First demonstration of O(1 ns) timing resolution in the MicroBooNE liquid argon time projection chamber

XX International Workshop on Neutrino Telescope

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Outline:

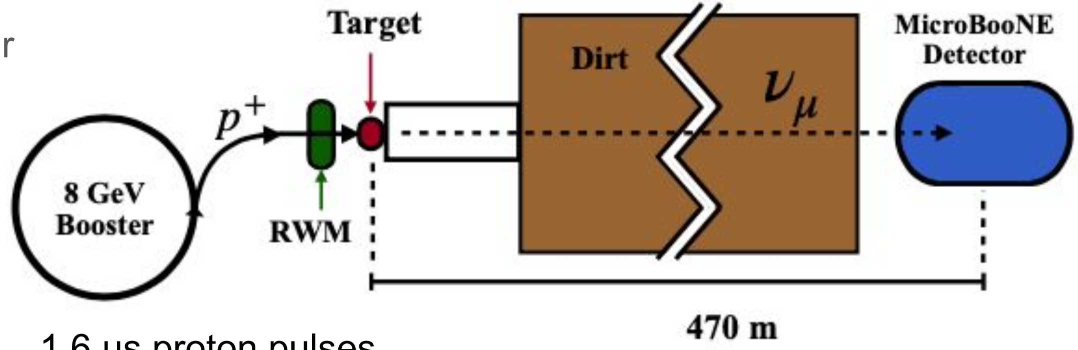
- MicroBooNE and the Booster Neutrino Beamline
- ν interaction time reconstruction
  - PDS,RWM, TPC
  - Empirical calibrations
- Detector timing resolution
- O(1 ns) resolution applications
  - Cosmic background rejection
  - Search for heavy neutral leptons

MicroBooNE and the Booster Neutrino Beamline (BNB)

MicroBooNE is a neutrino experiment consisting in a liquid argon TPC located near the surface on axis with the neutrino beam.

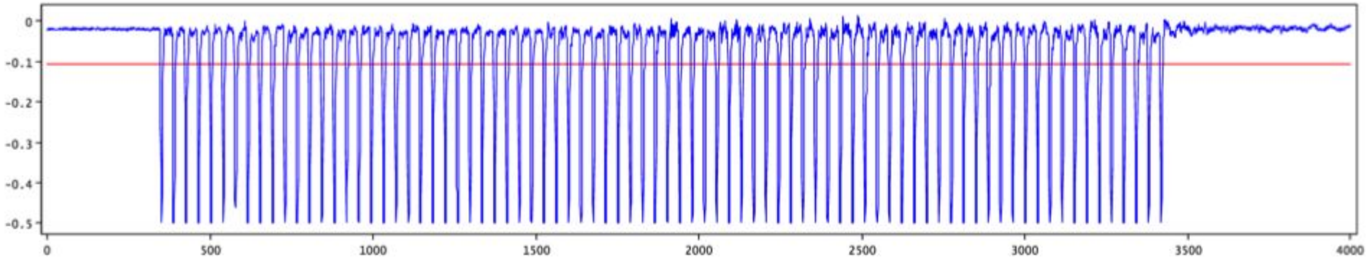
The main source of neutrinos is the BNB.

A resistive wall current monitor (RWM) measures the proton's pulse longitudinal profile [1,2]:



- 1.6 µs proton pulses
- 81 bunches per pulse
  - ~2 ns wide (**⟨σ_B⟩ ≃1.308 ns** [1,2])
  - 18.936 ns spaced

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



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

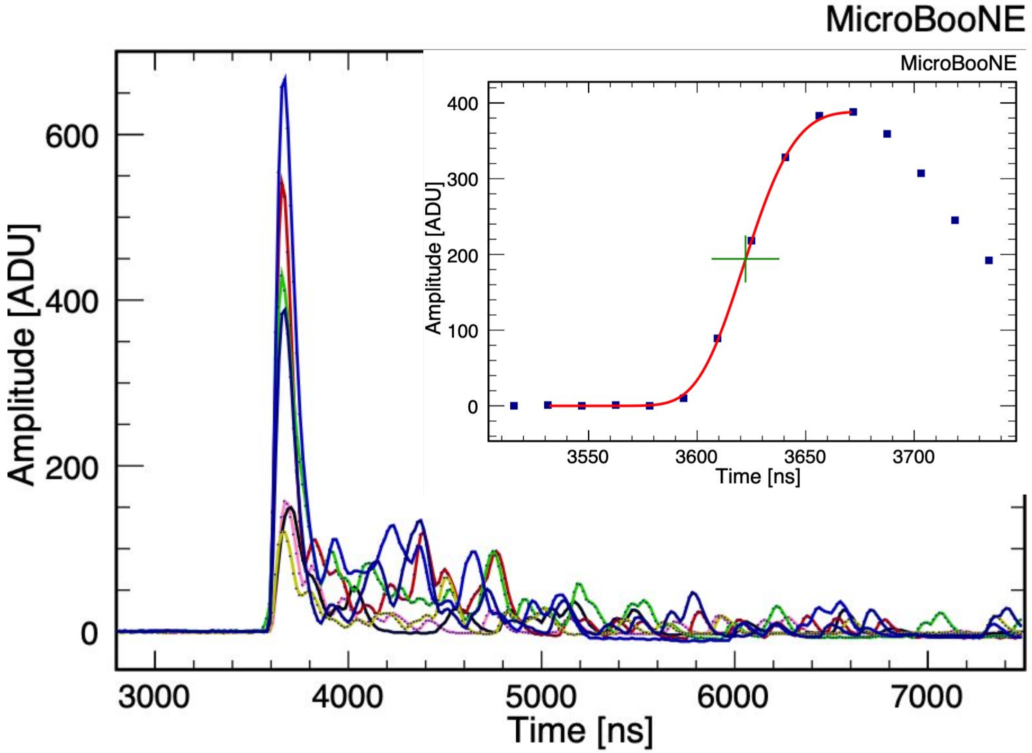
Reconstruction steps:

- Prompt signal provided by scintillation light
- RWM logic pulse to monitor the trigger jitter
- Protons time profile from RWM as reference
- Reconstruction of particles propagation inside the TPC
    - neutrino, daughter particles and scintillation light
- Neutrino arrival time reconstruction
    - “2nd order” corrections exploiting the reconstructed beam substructure

MicroBooNE's Photon Detection System (PDS)

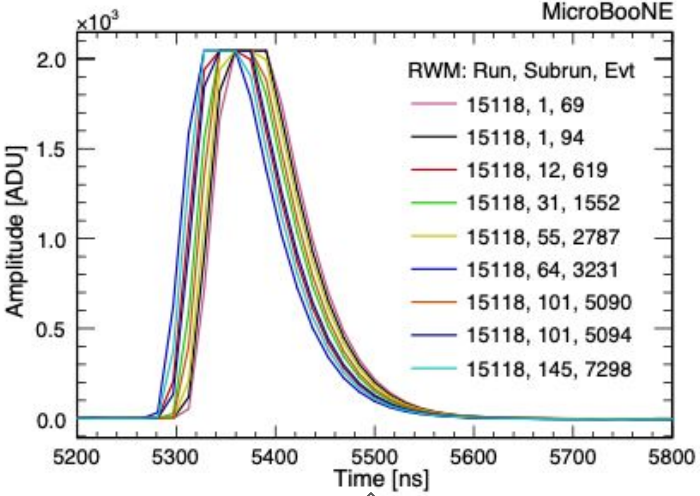
The MicroBooNE's PDS provides a prompt response to the scintillation light produced in neutrino interactions.

- 32 waveforms (of which 1 is a dead channel) are recorded in coincidence with the BNB trigger.
- Rising edge fit gives the PMT's signal timing.
  - **0.2 ns** smearing.
- The median of the PMT's timings is used to assign the neutrino interaction time.
  - Only waveforms with maximum amplitude (fast component) larger than 2 photons are considered

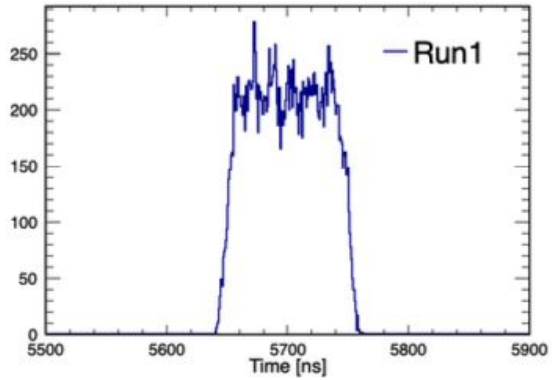


RWM monitors the BNB trigger

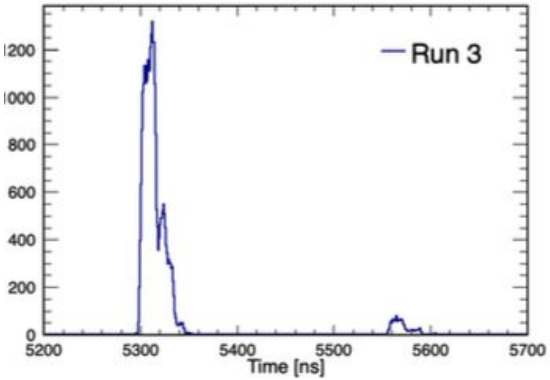
- The BNB trigger is subject to a fluctuation of tens of ns with respect to the proton pulse extraction time.
- An RWM logic pulse is sent to the MicroBooNE DAQ, where it is recorded for offline trigger monitoring.
- The timing of the RWM logic pulse is used to remove the measured BNB trigger jitter.



MicroBooNE



MicroBooNE



RWM timing from pulse rising edge fit.

RWM waveforms misalignment in time reflects the BNB trigger jitter:

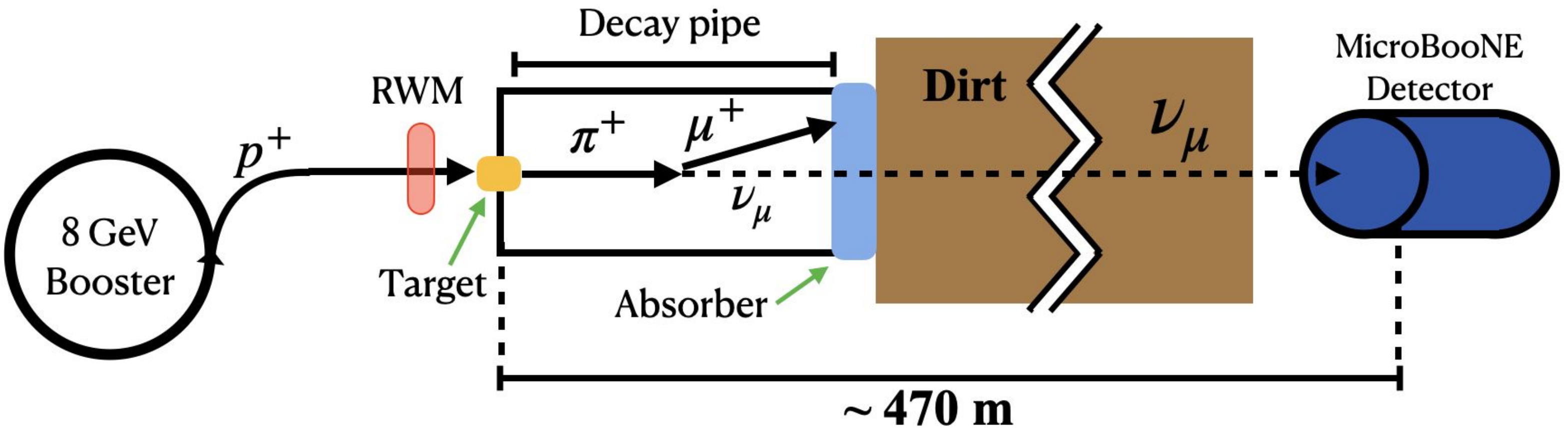
- 100s ns in Run 1
- 10s ns in Run 3

Neutrino time profile

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.

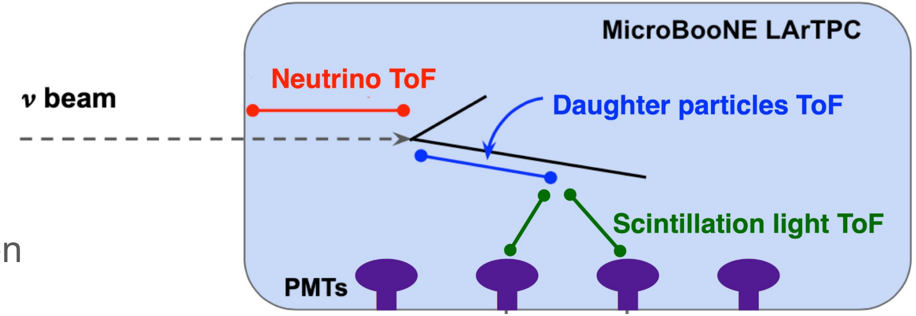
Treated as a constant offset for all the events



Neutrino vertex and reconstructed tracks

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

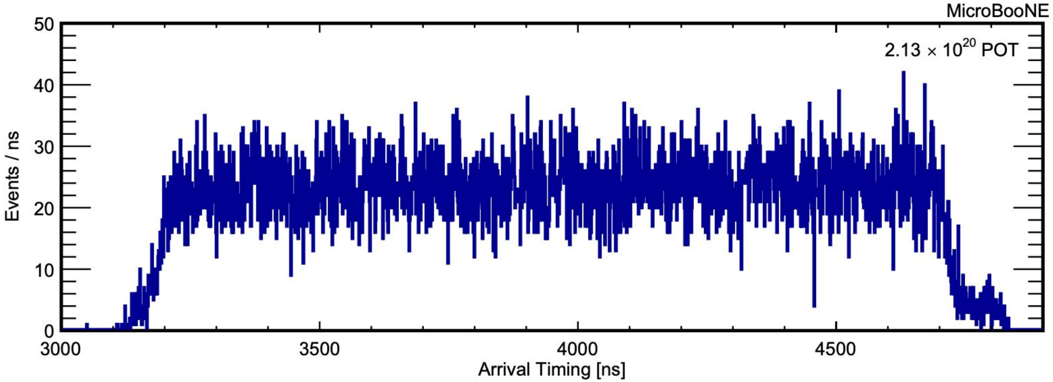
- **Neutrino ToF inside the TPC:**
  $\boldsymbol{\nu}$-vertex coordinate along the beam direction divided by the speed of light.
- **Daughter particles ToF**
  Distance from the neutrino vertex to a given space-point* divided by speed of light.
- **Scintillation light ToF**
  Distance from the space-point* to PMT divided by speed of light in liquid Argon.



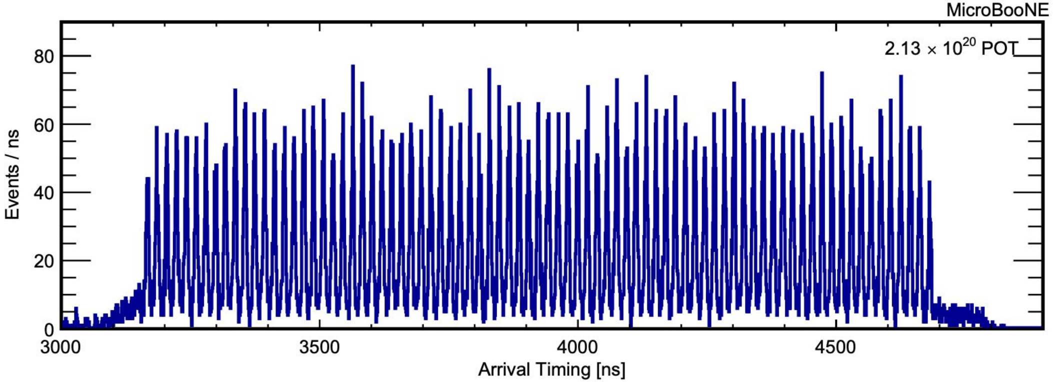
*The source of the first photons arriving to each PMT is located along the track by "minimizing" the daughter particle and shitilaltion light propagation from $\boldsymbol{\nu}$-vertex to PMT.

The contributions of the three processes are obtained leveraging the neutrino interaction vertex and the 3D tracks geometry provided by the TPC reconstruction (Pandora/Wire-Cell).

Neutrino arrival time reconstruction



(a) Neutrino arrival time distribution before the propagation reconstruction.



(b) Neutrino arrival time distribution after the propagation reconstruction.

The neutrino interaction timing provided by PMTs does not have enough resolution to recognize the beam substructure.

The neutrino arrival time at the upstream detector wall is reconstructed by correcting for the trigger jitter and the propagation time inside the TPC of

- neutrino
- daughter particles
- scintillation light

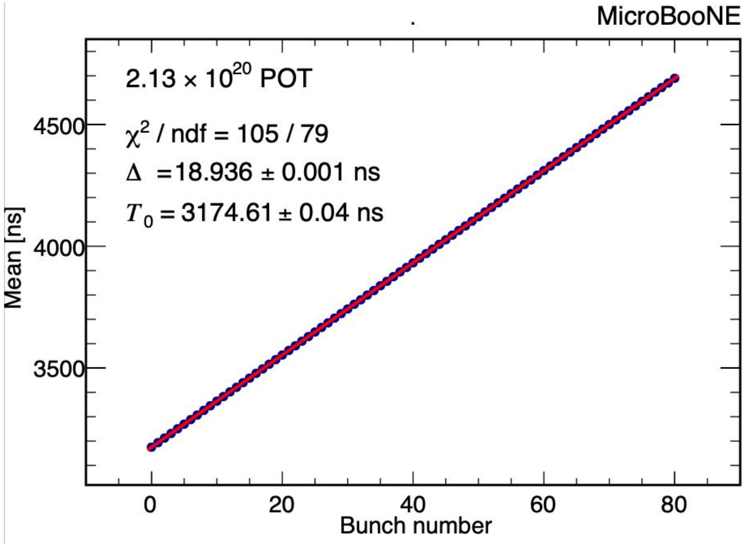
The 81 bunches composing the beam pulse substructure are easily visible after the reconstruction.

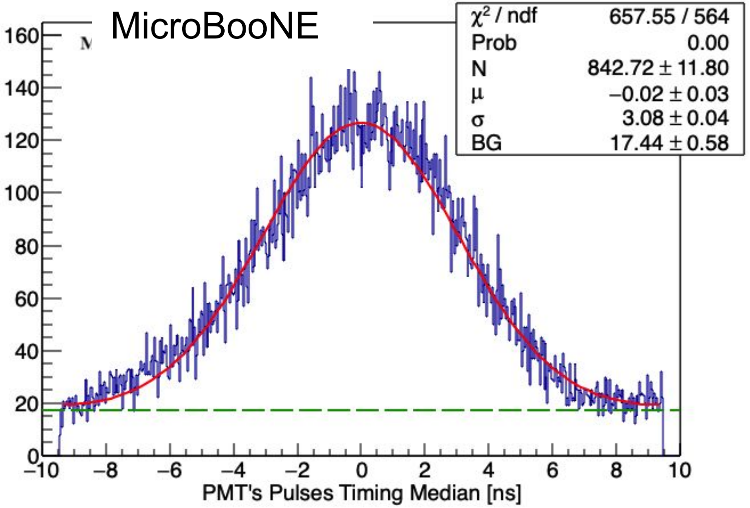
Beam bunch structure

Once bunches can be recognized the substructure is analyzed:

- Gaussian fit of the 81 bunches
- Bunch mean vs. bunch number linear fit
- Buch separation: Δ = 18.936 ± 0.001 ns
- Common offset T_0 ~ 3.2 μs

- The 81 peaks are merged in a single one
- The superimposed peak is centered at 0
- Gaussian + Constant term fit.
- Peak width is given by $\boldsymbol{\sigma}$





Empirical corrections

The superimposed peak is leveraged for further corrections:
(using timing from each single PMT and not the median)

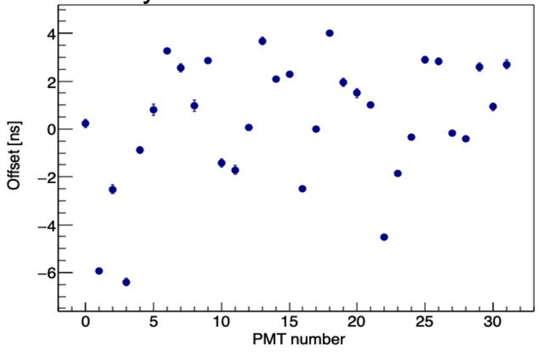
PMT by PMT offset:

- Timing mean obtained for each PMT
- All PMTs aligned to the average value

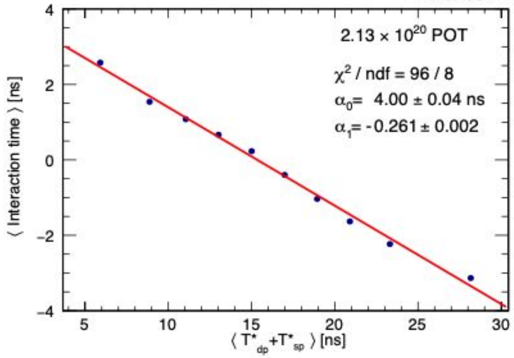
Propagation re-calibration:

- Interaction timing is studied as function of:
  - ν vertex to PMT path
  - Number of photon detected
- Correction using linear fit
- Process is iterated multiple times

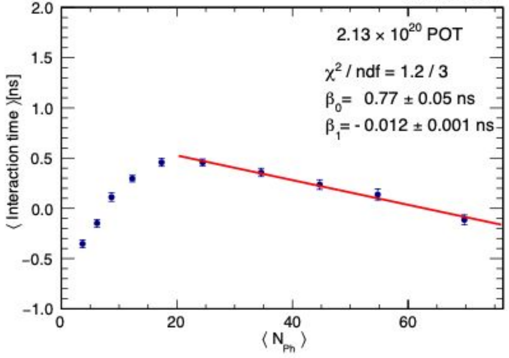
PMT by PMT offset



ν interaction timing vs.
ν vertex to PMT path



ν interaction timing vs.
number of photon detected



Detector timing resolution

Neutrino interaction time resolution in BNB events:

- Gaussian fit gives σ = 2.53 ± 0.02 ns
- The intrinsic beam spread is σ_B = 1.308 ns
- Overall resolution: **2.16 ± 0.02 ns.**

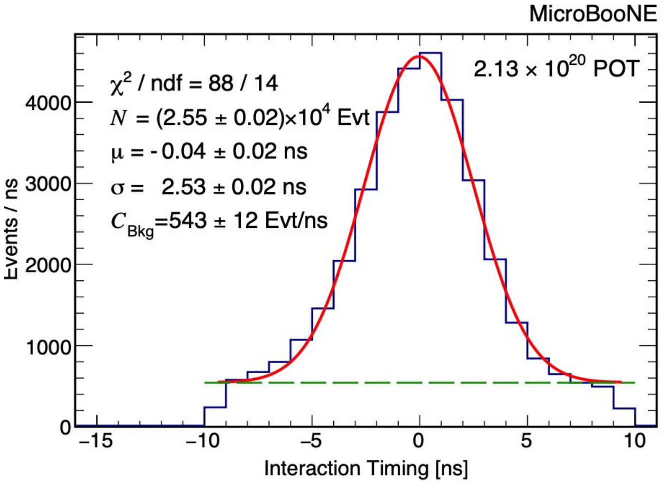
Detector intrinsic time resolution for neutrino interactions:

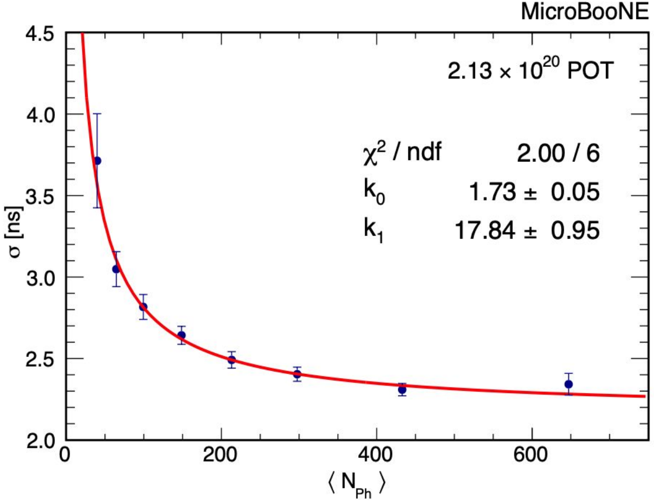
- Superimposed peak broken off for the number of photons detected.
- BNB intrinsic spread is subtracted
- Fit of the resolution vs. number of photons detected

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

- **Detector intrinsic resolution k_0 = 1.73 ± 0.05 ns**

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.108.052010

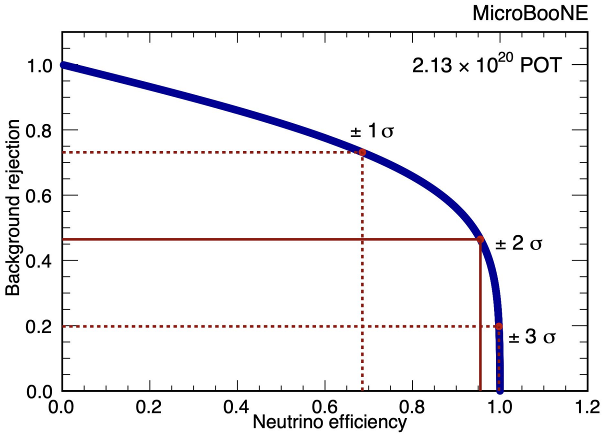


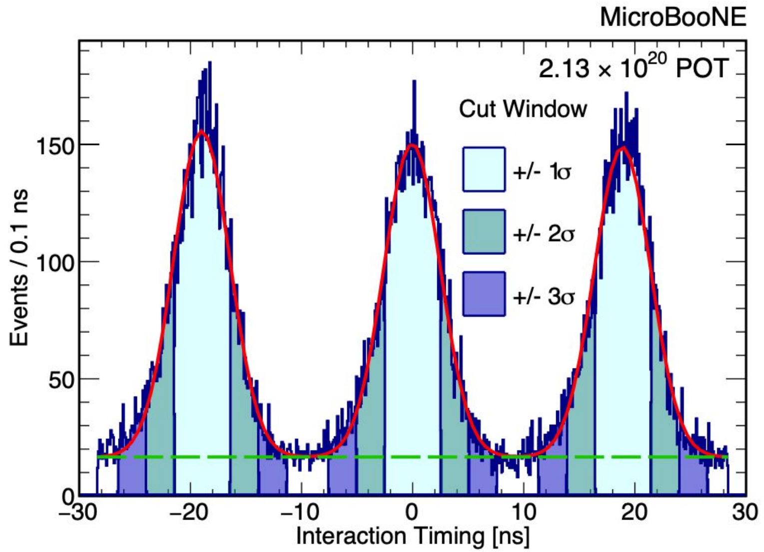


Applications I: Cosmic background rejection

A selection time window around the BNB bunches reduces the fraction of cosmic background events since cosmic-rays arrive uniformly in time while BNB neutrinos are peaked.

The width of the cut determines the background rejection and the neutrino efficiency.





σ = 2.53 ± 0.02 ns   **Bunch gap= 18.936 ns**

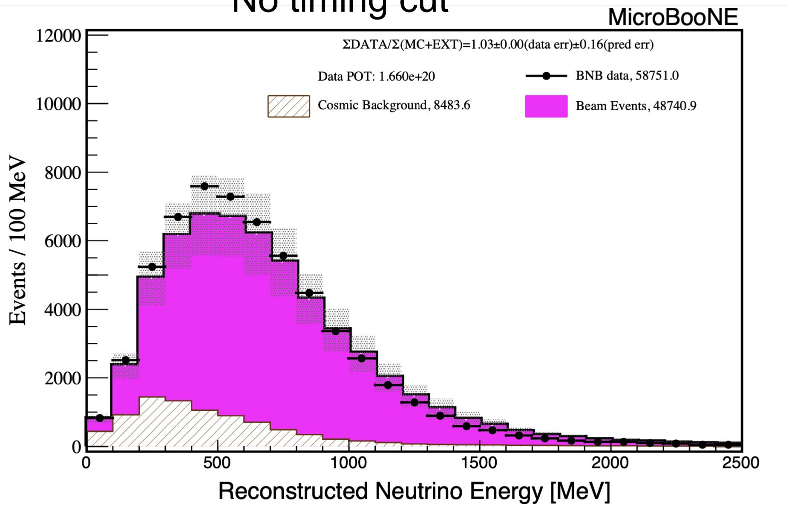
Cut	BG_{Tot} (%)	ν_{eff} (%)	BG_{rej} (%)
No cut	27.1	100	0
$\pm 3\sigma$	21.7	99.7	19.8
$\pm 2\sigma$	15.2	95.5	46.6
$\pm\sigma$	10.6	68.3	73.3

Applications I: Cosmic background rejection

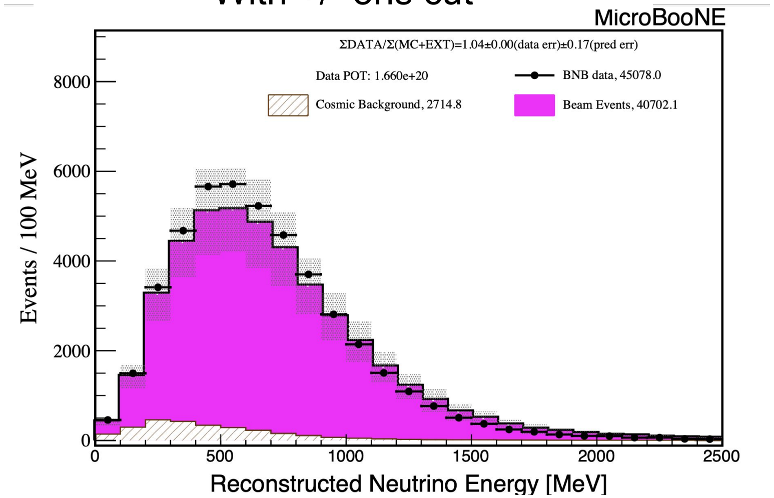
Initial implementation in MicroBooNE's inclusive single photon LEE analysis
(see Photon Analyses in MicroBooNE talk by Xiao Luo)

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

No timing cut

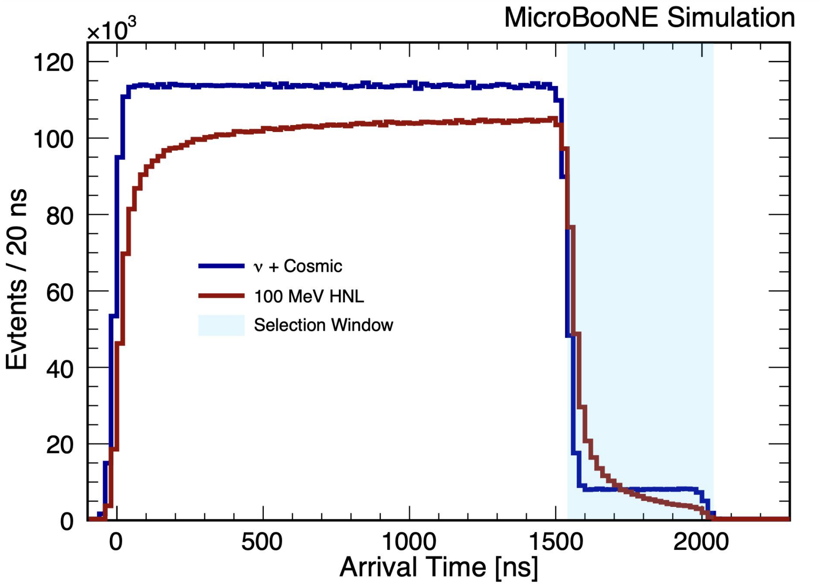


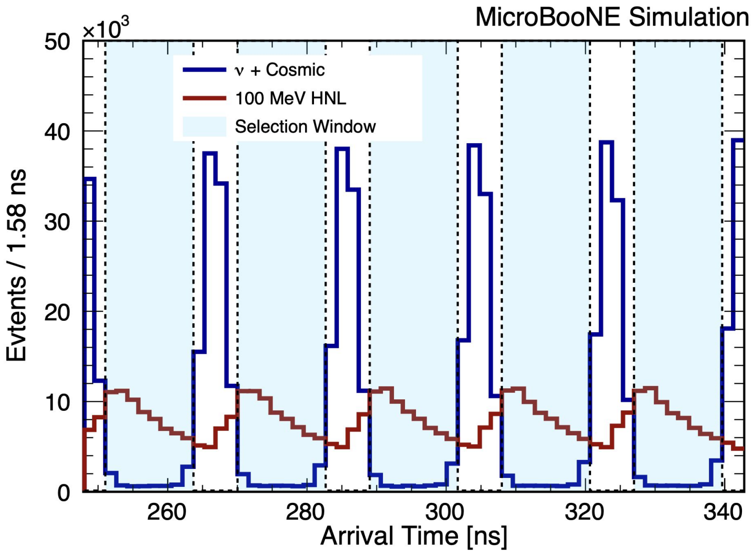
With +/- 5ns cut



Applications II: BSM search

The beam bunches' resolution can significantly expand LArTPC's capability of studying neutrino interactions and searching for long-lived massive particles, as heavy neutral leptons (HNL), that have a longer ToF and reach the detector delayed with respect to neutrinos.

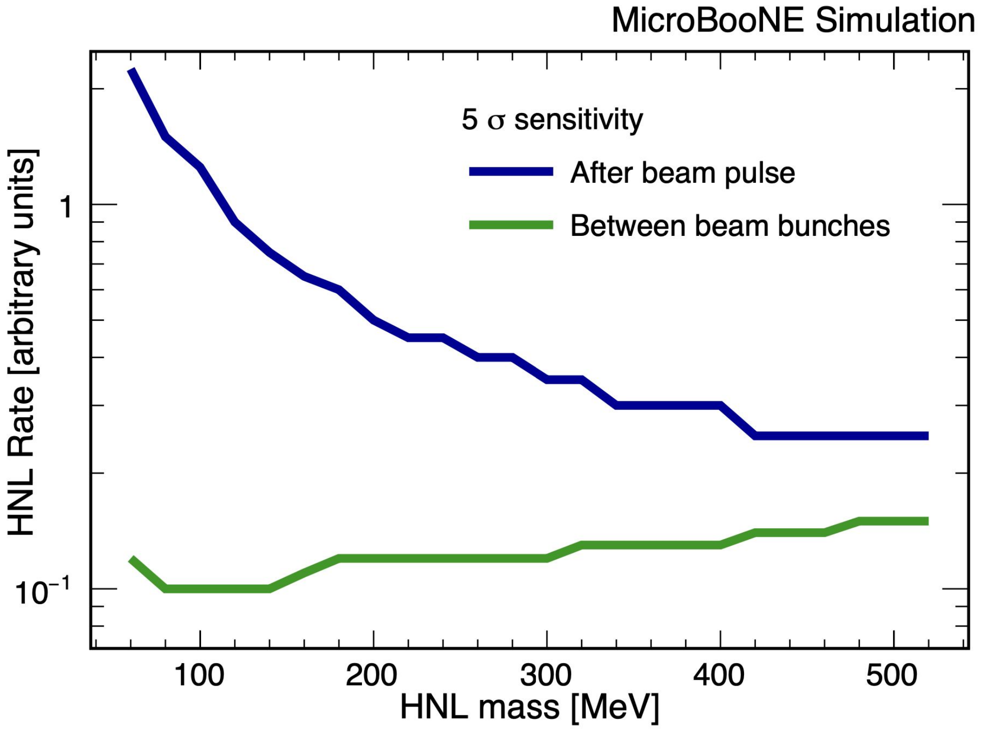




Applications II: BSM search

The substructure resolution allows to investigate event between bunches offering significant improvement for long-lived massive particle search in the range of 10s to 100s of MeV, especially for lower masses.

Lines of 5σ sensitivity* using only events after the beam pulse (blue line) compared to only events between beam bunches (green line), as function of the HNL mass.



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

Summary

MicroBooNE demonstrates for the first time the O(1 ns) timing resolution for reconstruction ν_μCC interaction time in a LArTPC.

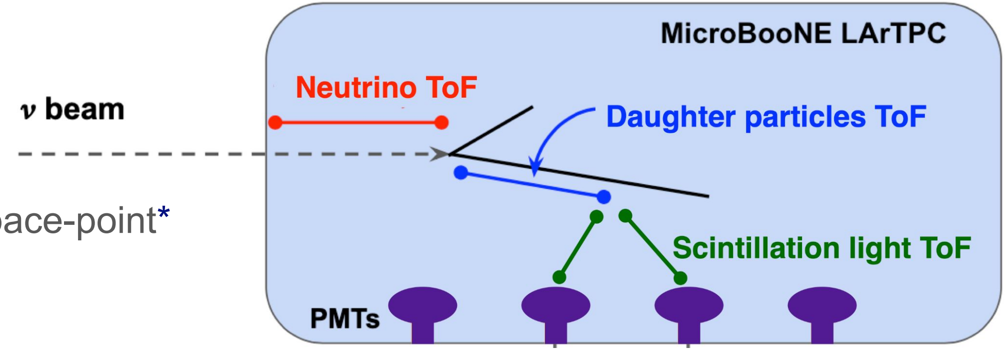
This result allows for the resolution of the pulse time structure of the BNB that, in turn, introduces a new powerful handle for physics measurements:

- 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

Backup Slides

Neutrino vertex and reconstructed tracks

- **Neutrino ToF inside the TPC:**
  ν-vertex coordinate along the beam direction divided by the speed of light.
- **Daughter particles ToF**
  Distance from the neutrino vertex to a given space-point* divided by speed of light**.
- **Scintillation light ToF**
  Distance from the space-point to PMT*** divided by speed of light in liquid Argon.



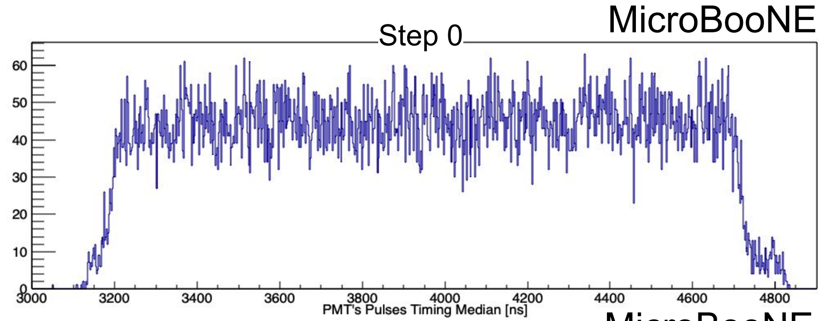
Notes:

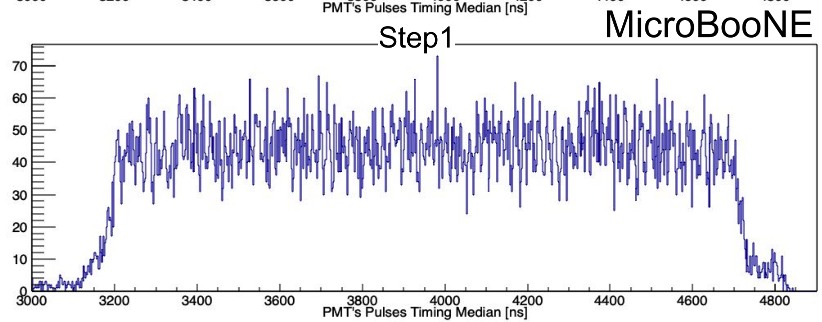
*Each track's space point is a source of light. The daughter particle and scintillation light propagation time is calculated for each space-point. Since PMT's timing is sensible to the first arriving photon, the space-point which gives the quickest path from neutrino vertex to PMT is chosen.

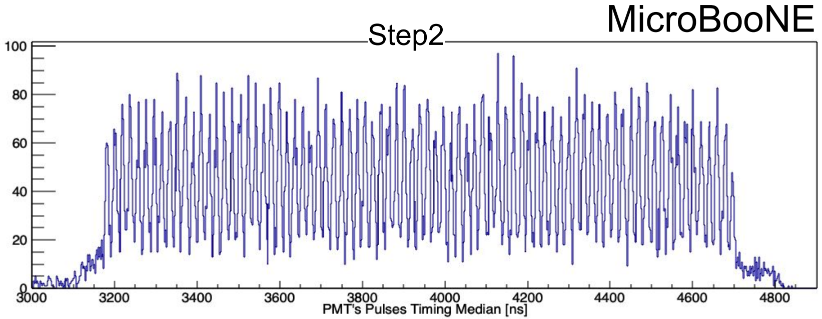
**The speed of light in vacuum is used for the daughter particles propagation. Empirical corrections will be applied to take care of this approximation. Including information about daughter particle ID and dE/dX in each space point could improve the propagation reconstruction and the overall timing resolution.

***Daughter particle and scintillation light ToF is calculated independently PMT by PMT (different PMTs have different locations).

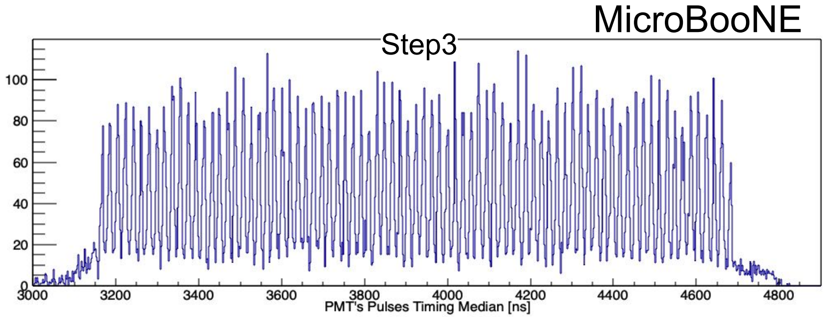
Beam pulse reconstruction steps [0,1,2,3]:



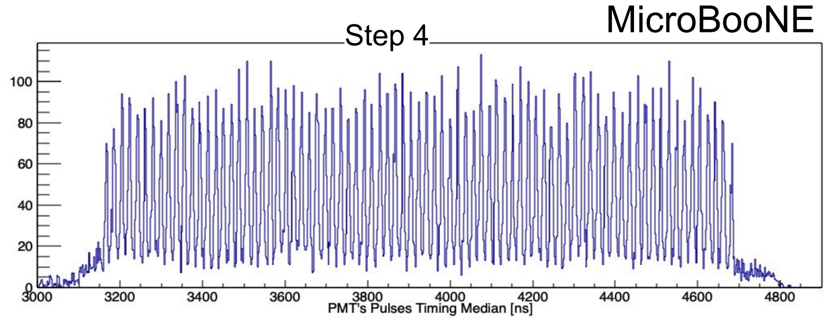


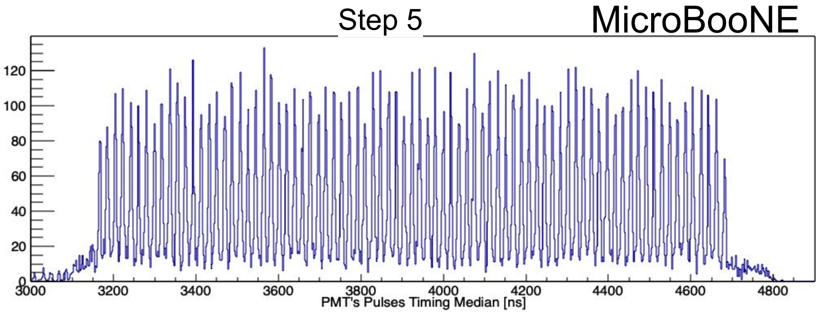


- **Step 0:** PMTs give a prompt signal,
  - Fit resolution : σ_{fit} < 0.2 ns
  - t = Median of PMTs
- **Step 1:** RWM removes the BNB tigger jitter,
  - Jitter is 10s of ns
- **Step 2:** ν ToF inside the TPC,
  - Up to 33 ns
- **Step 3:** daughter particles and scintillation light propagation time,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



Beam pulse reconstruction steps [4,5]:





Reconstruction step summary:

Steps:	Superimposed peak width:
0. PMTs median	-
1. Trigger→RWM	-
2. $\boldsymbol{\nu}$ ToF inside the TPC	σ = 4.7 ± 0.2 ns
3. $\boldsymbol{\nu}$-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

The dataset used in this analysis is an inclusive selection of $\boldsymbol{\nu}\mu$CC iteration candidates from MicroBooNE's BNB, Run3 (2016-17)