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First demonstration of $\mathcal{O}(1\,\mathrm{ns})$ timing resolution in the MicroBooNE liquid argon time projection chamber

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MicroBooNE is a neutrino experiment located in the Booster Neutrino Beamline (BNB) at Fermilab, which collected data from 2015 to 2021. MicroBooNE's liquid argon time projection chamber (LArTPC) is accompanied by a photon detection system consisting of 32 photomultiplier tubes used to measure the argon scintillation light and determine the timing of neutrino interactions. Analysis techniques combining light signals and reconstructed tracks are applied to achieve a neutrino interaction time resolution of $\mathcal{O}(1\,\mathrm{ns})$. The result obtained allows MicroBooNE to access the ns neutrino pulse structure of the BNB for the first time. The timing resolution achieved will enable significant enhancement of cosmic background rejection for all neutrino analyses. Furthermore, the ns timing resolution opens new avenues to search for long-lived-particles such as heavy neutral leptons in MicroBooNE, as well as in future large LArTPC experiments, namely the SBN program and DUNE.

I. INTRODUCTION

The Standard Model (SM) of particle physics has demonstrated remarkable success in describing the interactions between observed fundamental particles; yet clear gaps remain in our ability to address questions such as the nature of dark matter or the matter-antimatter asymmetry in our universe. The study of neutrino properties and oscillations provides a compelling avenue both to complete our understanding of the SM and to explore physics Beyond the Standard Model (BSM). An extensive experimental program comprised of the Deep Underground Neutrino Experiment (DUNE) [1] and Short Baseline Neutrino (SBN) program [2] intends to make precision measurements of neutrino oscillations using liquid argon time projection chambers (LArTPCs). These detectors offer the ideal environment in which to search for BSM physics in the sub-GeV energy regime. Yet, fully exploiting the potential of such detectors for BSM searches requires dedicated advances in analysis tools and techniques. While millimeter-level accuracy and detailed calorimetric information have enabled the delivery of precision neutrino physics measurements with TPCs [3–8], the use of scintillation light signals has not yet been exploited as extensively.

This paper presents the first demonstration of $\mathcal{O}(1\,\mathrm{ns})$ timing resolution for neutrino interactions in a LArTPC utilizing the MicroBooNE detector. This work significantly improves on MicroBooNE's previously reported [9] timing resolution of $\mathcal{O}(100\,\mathrm{ns})$. A correction to the reconstructed interaction time is applied by introducing four developments: incorporating more precise beam timing signals from the accelerator, improving the reconstruction of signals from MicroBooNE's photon detection system, considering the particle and light propagation in the detector, and, finally, including an empirical calibration to correct for non-uniformities in detector response and particle propagation time.

The significance of this analysis has strong implications for searches for BSM physics that exploit differences in time-of-flight (ToF) to detect massive long-lived particles arriving at the detector delayed with respect to neutrinos. The techniques described in this article will allow improved searches for heavy neutral leptons (HNLs) beyond those already achieved with MicroBooNE data [10, 11] by increasing the sensitivity to both HNL coupling strength with neutrinos and HNL mass. Furthermore, improved timing can add a new tool for cosmic background rejection in surface LArTPCs, orthogonal to existing techniques [8, 12, 13].

The remainder of this paper is arranged as follows: Section II provides an overall description of the MicroBooNE detector and the Booster Neutrino Beamline (BNB). Section III describes the analysis developed to demonstrate MicroBooNE's $\mathcal{O}(1\,\mathrm{ns})$ timing resolution. Section IV summarizes the analysis results. Section V presents two applications in which the timing resolution achieved can improve MicroBooNE's capability of studying neutrino interactions: introducing a new tool for cosmic background rejection and improving the performance for BSM physics searches.

II. BOOSTER NEUTRINO BEAMLINE AND MICROBOONE DETECTOR

MicroBooNE [15] is a neutrino experiment at Fermilab that collected data from 2015 to 2021. The detector consists of a LArTPC located near the surface, on axis with the neutrino beam, and 468.5 m downstream of the proton target. Figure 1 shows a schematic of the BNB and

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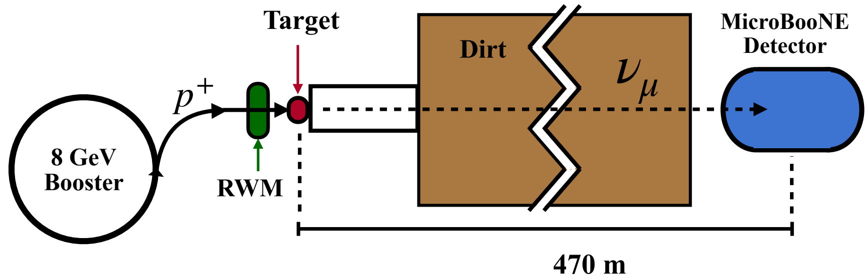


FIG. 1. Schematic of the BNB and MicroBooNE detector. MicroBooNE's detector is in the path of the BNB, on axis with the beam direction, 468.5 m downstream of the proton target (red). The RWM (green) records the proton pulse shape immediately before protons hit the target. For events selected in this analysis, the time for protons to hit the target, the propagation and decay of mesons, and the travel time of neutrinos to the detector upstream wall is assumed the same for each event.

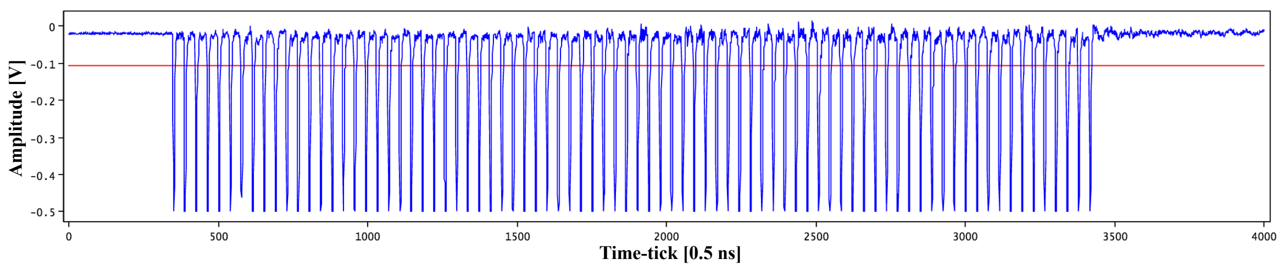


FIG. 2. Trace of a single BNB RWM waveform showing the BNB ns substructure. The red line shows the discriminator threshold used by the oscilloscope. The horizontal axis shows units of time-ticks (1 time-tick=0.5 ns). The vertical axis is the induced charge on the RWM in volts. Each BNB proton pulse is composed of 81 bunches spaced at $\Delta = 18.936 \pm 0.001$ ns. The average bunch width is $\langle\sigma_{BNB}\rangle = 1.308 \pm 0.001$ ns. The RWM time structure shown in this figure is obtained through the instruments and methods described in [14].

MicroBooNE detector, which will be briefly described in this section.

Booster Neutrino Beamline. The primary source of neutrinos for the MicroBooNE experiment is the neutrino beam produced by the BNB [16], where 8 GeV (kinetic energy) proton pulses are extracted from the Booster accelerator and delivered to the target. Each proton pulse has a 52.81 MHz substructure with 81 bunches spaced at 18.936 ± 0.001 ns. The average bunch width is $\langle\sigma_{BNB}\rangle = 1.308 \pm 0.001$ ns [14]. This characteristic substructure is key to leveraging ns-scale timing resolution for neutrino interactions, as it leads to wide gaps between neutrino bunches [17].

Resistive wall current monitor. The MicroBooNE trigger for the BNB is a signal in coincidence with the proton pulse extraction from the Booster accelerator. That signal is subject to a relatively large jitter, which is a fluctuation of tens of ns with respect to the proton pulse extraction time. To improve on the timing accuracy of the MicroBooNE beam trigger this analysis makes use of the resistive wall current monitor (RWM) [14] signal. Charged particles traveling through a conductive metallic pipe induce an image current on the pipe wall. In the BNB, the RWM is located just before the proton target and measures the image current produced by the beam protons. The RWM current reproduces accurately the proton pulse's longitudinal time profile. A typical waveform from the BNB RWM, digitized at 2 GHz, is shown in Fig. 2. The first bunch of this signal is used to send a thresholded logic pulse to the MicroBooNE readout electronics where it is recorded for offline monitoring. Figure 3 shows examples of RWM logic pulses recorded with MicroBooNE's electronics. Misalignment between the pulses reflects the jitter of the BNB trigger.

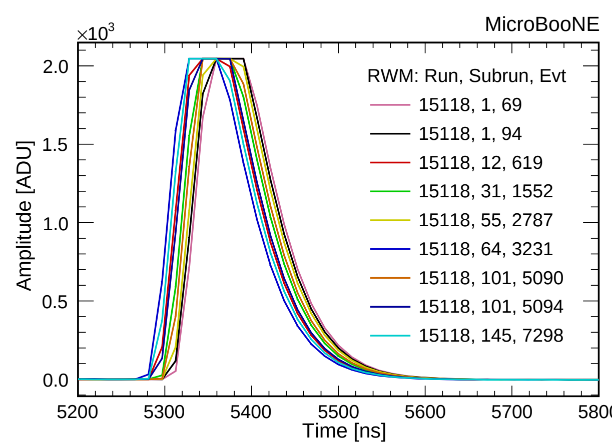


FIG. 3. RWM logic pulses in coincidence with the first proton bunch from the accelerator as recorded by the MicroBooNE DAQ. Misalignment between the pulses reflects the main trigger jitter.

MicroBooNE's photon detection system. A photon detection system [18] is installed behind the TPC anode plane to detect scintillation light emitted by the argon atoms that are excited by charged particles passing through the argon. Liquid argon is a high-performance prompt scintillator with a yield of about 30,000 photons/MeV at MicroBooNE's nominal electric field of 273 V/cm [19, 20] with ∼23% of the total light emitted within a few ns [21]. The MicroBooNE photon detection system consists of 32 8-inch cryogenic Hamamatsu photomultiplier tubes (PMTs) equipped with wavelength-shifting tetraphenyl butadiene (TPB) coated acrylic front plates [18]. MicroBooNE's readout electronics [22] record 23.4 μs long waveforms starting at the beam trigger. PMT pulses are smoothed by an analog unipolar shaper with a 60 ns rise time and then digitized at 64 MHz (16.625 ns samples). One of the 32 PMT channels became unresponsive starting in the summer of 2017. Figure 4 shows example PMT waveforms of scintillation light produced by a candidate neutrino interaction recorded with the MicroBooNE photon detection system.

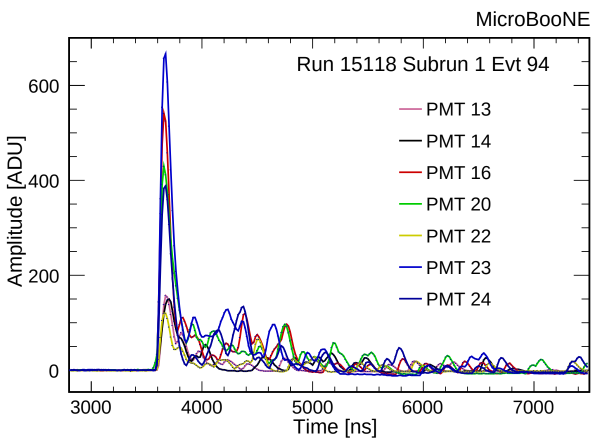
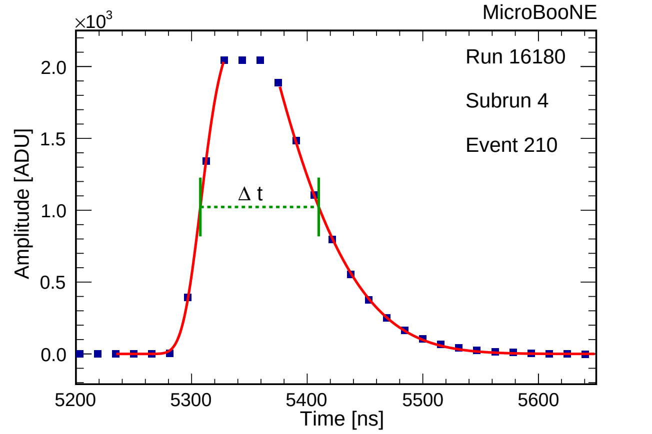


FIG. 4. PMT waveforms for a typical neutrino candidate. A subset of the 31 waveforms recorded and a reduced time window around the event is shown.

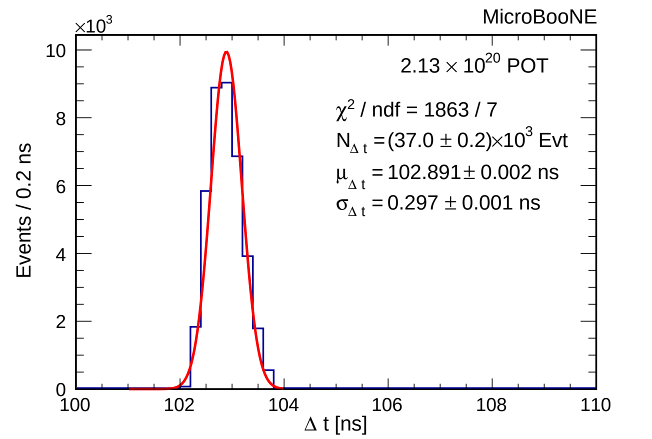
III. DATA ANALYSIS

The $\mathcal{O}(1\,\text{ns})$ timing resolution in MicroBooNE is achieved through four analysis steps. First, the RWM logic pulse is used to remove the BNB trigger jitter. Second, an accurate pulse-fitting method is implemented to extract the arrival time of the first photons detected by MicroBooNE's PMTs. Third, the propagation times of particles and scintillation photons inside the detector are corrected by leveraging the TPC's 3D reconstruction. Finally, an empirical calibration is used to apply corrections on the daughter particles' and scintillation light's propagation times. The dataset used in this analysis is an inclusive selection of ν_μCC interactions candidates [23] from MicroBooNE's BNB collected in 2016–17. Events are reconstructed with the Pandora multipurpose pattern-recognition toolkit [24]. This selection yields an $\mathcal{O}(80\%)$ pure sample of neutrino interactions, and $\mathcal{O}(20\%)$ cosmic-ray background. The MicroBooNE timing resolution is evaluated by comparing the reconstructed BNB ns substructure with the waveform provided by the RWM, shown in Fig. 2. The timing resolution achieved by this analysis resolves for the first time in MicroBooNE the substructure of the BNB beam spill [17]. This section will describe in detail the analysis steps developed to achieve this result.

RWM timing. The RWM logic pulse recorded at MicroBooNE is shaped and digitized through the same PMT readout electronics. The signal timing (T_{RWM}) is extracted with the fitting method described in the next paragraph. The RWM timing is used to replace the BNB trigger which contains a jitter of tens of ns. The RWM recorded signal is a logic pulse and, therefore, its shape is expected to be stable over time. Because of this, the RWM pulse is used to evaluate the intrinsic timing resolution of the PMT electronics by measuring the stability of the RWM pulse half height width (Δt), shown



(a) The RWM pulse amplitude (Δt), shown with the green dotted line, is the distance between the half-height of the rising and falling edges, shown with red curves.



(b) Gaussian fit of the Δt distribution. The parameters $N_{\Delta t}$, $\mu_{\Delta t}$ and $\sigma_{\Delta t}$ are respectively the amplitude, the mean and the standard deviation of the Gaussian fit.

FIG. 5. The intrinsic PMT pulse timing uncertainty is obtained measuring the stability of the RWM pulse amplitude (Δt), shown in (a). The Δt distribution is fitted with a Gaussian function, shown in (b), and the parameter $\sigma_{\Delta t}/\sqrt{2}$ is used to evaluate the intrinsic PMT pulse timing uncertainty.

in Fig. 5 (a). The uncertainty of Δt is obtained fitting the Δt distribution with a Gaussian function, shown in Fig. 5 (b). The width of the Gaussian ($\sigma_{\Delta t}$) gives the uncertainty of Δt, which is $\sigma_{\Delta t} \simeq 0.3\,\text{ns}$. This uncertainty is on the difference between the rising and falling edges of the RWM pulses, both obtained with the same fitting method. Therefore the uncertainty on the single rising edge timing is given by $\sigma_{\Delta t}/\sqrt{2} \simeq 0.2\,\text{ns}$, negligible compared to the overall resolution achieved.

PMTs Pulse Fitting. MicroBooNE's PMTs provide a prompt response to the scintillation light produced in neutrino interactions. In order to extract $\mathcal{O}(1\,\text{ns})$ timing resolution the 60 ns shaping response of the MicroBooNE PMT electronics must be accounted for. This is achieved by fitting the rising edge of the PMT trace with the function

$$f(t) = A \cdot \exp\left(-\frac{(t-t_M)^4}{B}\right). \quad (1)$$

Multiple functions have been tested for fitting the PMT waveform rising edge. The one which gives the lowest χ^2 has been chosen. An example of this fit is shown by the red line in Fig. 6. The parameters A and B in the fit function are left free and t_M is fixed to the time-tick with the maximum ADC value. The measured half-height value (green cross in Fig. 6) is used to assign the arrival time of the first photons at the PMT. Despite the relatively low sampling frequency of the PMT digitization, a $\simeq$0.2 ns resolution for the intrinsic PMT pulse timing is achieved using this method as demonstrated with the RWM pulse. To account for variation in signal propagation time due to electronics response, signal transmission, or other intrinsic delays, the time distribution given by each PMT is analyzed to check for PMT-by-PMT offsets. Offsets between different PMTs were found to be of order 2.5 ns. Each PMT timing measurement has been corrected for this offset, aligning each PMT mean value to the average across all the PMT means.

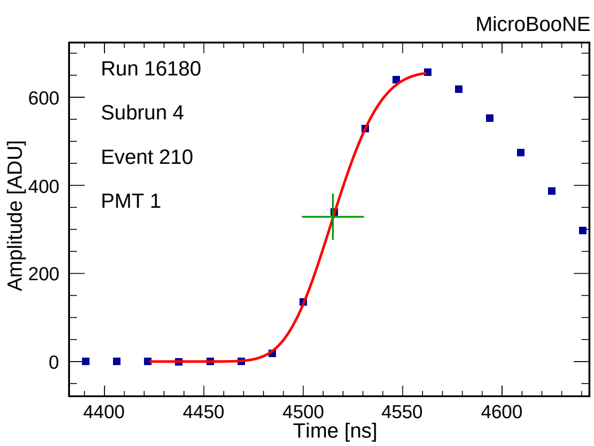


FIG. 6. Single PMT pulse timing extraction. The red curve shows the pulse rising-edge fit, and the green cross marks the rising-edge half-height point used to assign the timing to the PMT pulse.

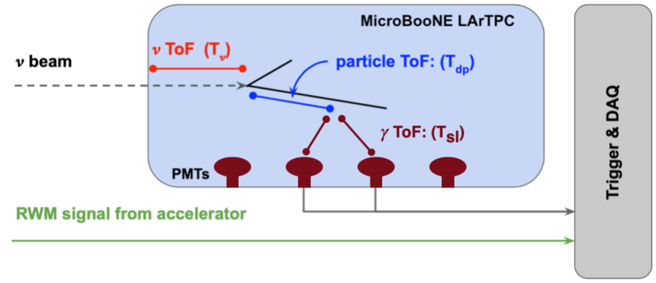


FIG. 7. Schematic of the MicroBooNE LArTPC (light blue). PMTs are represented in maroon. The tracks reconstructed in the TPC (black solid lines) are used to measure the paths of the particles and scintillation photons inside the detector. The three paths, red for the neutrino in the TPC, blue for a daughter particle, and maroon for scintillation photons, are used to evaluate the time between the neutrino entering the TPC and scintillation photons reaching the PMTs: $T_\nu + T_{dp} + T_{sl}$.

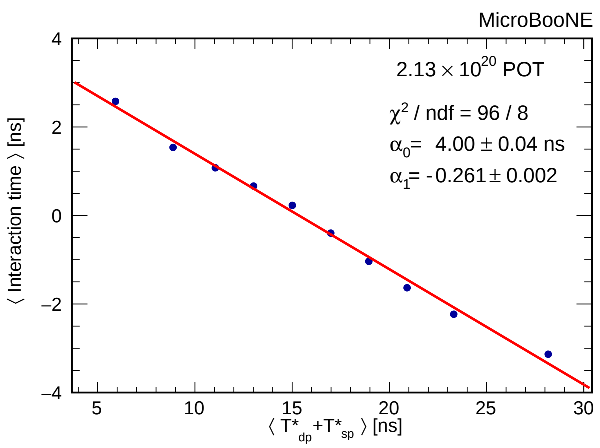
Particle and scintillation photon propagation. Between the signal induced by protons at the RWM and the signal provided by PMTs, there is a complex chain of processes to take into account in order to extract the neutrino interaction timing. The time for protons to hit the target, the propagation and decay of mesons, and the travel time of neutrinos to the detector (illustrated in Fig. 1) is treated as a constant offset for all interactions. Therefore, the neutrino time profile at the upstream detector wall is assumed the same as the proton time profile provided by the RWM. Once neutrinos enter the detector, three processes, shown in Fig. 7, impact the observed neutrino interaction time in the PMTs:

1. The neutrino ToF inside the TPC (T_ν);
2. The daughter particle ToF from the neutrino interaction vertex to the space-point where photons are produced (T_{dp}); and
3. The scintillation light ToF from the space-point where photons are produced to the PMT where photons are detected (T_{sl}).

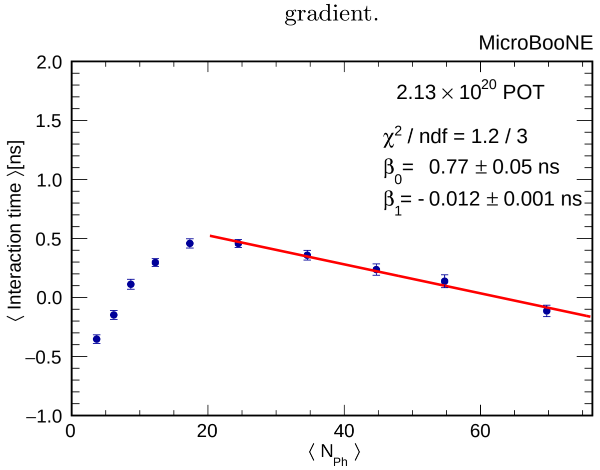
Leveraging the neutrino interaction vertex position and the daughter particle's track geometry reconstructed with the TPC signals [24], the times for each of these three processes can be extracted. Since the beam is on-axis with the detector, and neutrinos are nearly massless, T_ν is given by the neutrino interaction vertex coordinate along the beam direction divided by the speed of light. T_{dp} and T_{sl} are calculated together for all 3D spacepoints along the trajectory of all visible daughter particles from the neutrino interaction. At each 3D spacepoint, T_{dp} is given by the distance from the neutrino interaction vertex divided by the speed of light, and T_{sl} is given by the distance to the TPB coated plate in front of each PMT divided by the group velocity for scintillation light in liquid argon, v_g ($1/v_g = 7.46 \pm 0.08\,\text{ns/m}$ [25]). The minimum value of $T_{dp} + T_{sl}$ among all reconstructed 3D spacepoints is chosen as the daughter particle and scintillation light propagation time for the first photons arriving on the PMT. This quantity is denoted $(T^*_{dp} + T^*_{sl})$. Note that this calculation is performed independently for each PMT.

Empirical calibration. After correcting for the time delays caused by daughter particle and scintillation light propagation, a residual smearing still persists. This effect manifests itself as a non-uniform distribution of the measured neutrino interaction time as a function of the propagation time from the neutrino vertex to a given PMT, $(T^*_{dp} + T^*_{sl})$, and the total number of photons collected, N_{Ph}. This smearing comes from approximating the daughter particle propagation speed to that of the speed of light and by position-dependence in light collection response. To further improve the timing resolution, an empirical calibration is applied to correct for these approximations. The dependence of the neutrino interaction time on these two quantities is shown in Fig. 8. A linear fit to the response as a function of these quantities is used to extract two calibration factors: α_1 and β_1. The two calibration factors are combined in an effective empirical correction (C_{Emp}) given by $C_{\mathrm{Emp}} = (T^*_{dp} + T^*_{sl}) \cdot \alpha_1 + N_{Ph} \cdot \beta_1$, which is applied to correct the photon arrival time given by each PMT. To limit the fit to be linear, points for small N_{Ph} values are not included. Since the calibration factors are obtained using the mean values from time distributions of events in given $(T^*_{dp} + T^*_{sl})$ and N_{Ph} windows, after the first correction the initial residual smearing decreases but still persists. Fits and corrections are applied recursively until no more reduction is visible in the smearing of the mean values. After these steps the spread of the mean values shown in Fig. 8 (mean interaction time as function of $\langle T^*_{dp} + T^*_{sl}\rangle$ and $\langle N_{Ph}\rangle$) is reduced below 0.5 ns in both cases.

Neutrino interaction timing measurement. The neutrino interaction time is calculated by removing the trigger jitter (T_{RWM}), by subtracting from each PMT's measured time the neutrino ToF inside the TPC (T_ν) and the daughter particle and photon propagation time $(T^*_{dp} + T^*_{sl})$, and by applying the empirical correction (C_{Emp}). For each of these terms the spreads and the ranges of values are reported in Table I. It is important to note that a significant impact on improving the timing resolution comes from applying corrections that make use of TPC reconstructed information emphasizing the importance of the analysis choice of leveraging both precise PMT timing and topological information from the TPC. Precise PMT timing is not alone sufficient to extract $\mathcal{O}(1\,\mathrm{ns})$ interaction timing resolution. The median of the obtained values across all PMTs with more than two detected photons is taken as the neutrino interaction time for the event. Figure 9 shows the neutrino interaction timing before (a) and after (b) applying the neutrino interaction time reconstruction. The 81 bunches composing the beam pulse sub-structure are well visible after the reconstruction as seen in Fig. 9 (b) and reproduce the 52.81 MHz substructure of the RWM waveform of Fig. 2.



(a) Linear fit of the mean of the neutrino interaction time as a function of the average propagation time from the neutrino vertex to a given PMT $\langle T^*_{dp} + T^*_{sl}\rangle$. The parameters α_0 and α_1 are respectively the offset and the gradient.

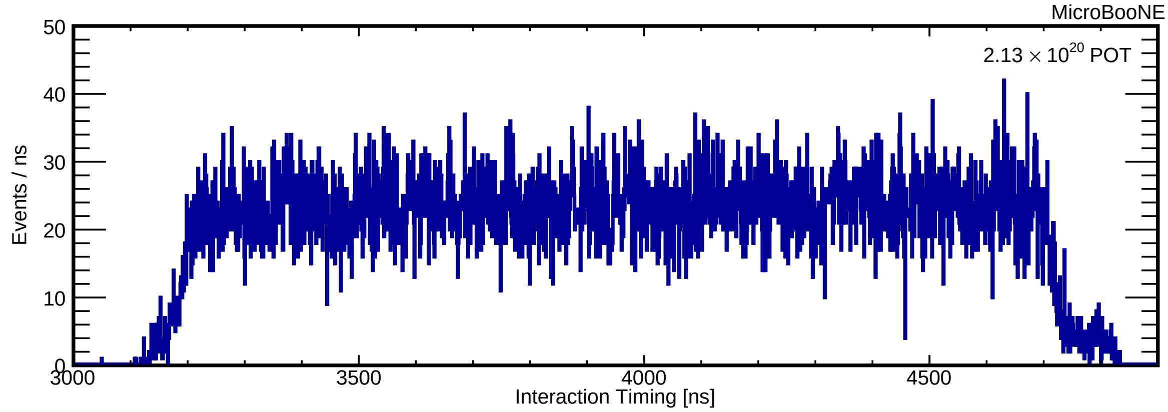


(b) Linear fit of the mean neutrino interaction time as a function of the average of number of photons collected by a given PMT $\langle N_{Ph}\rangle$. The parameters β_0 and β_1 are respectively the offset and the gradient.

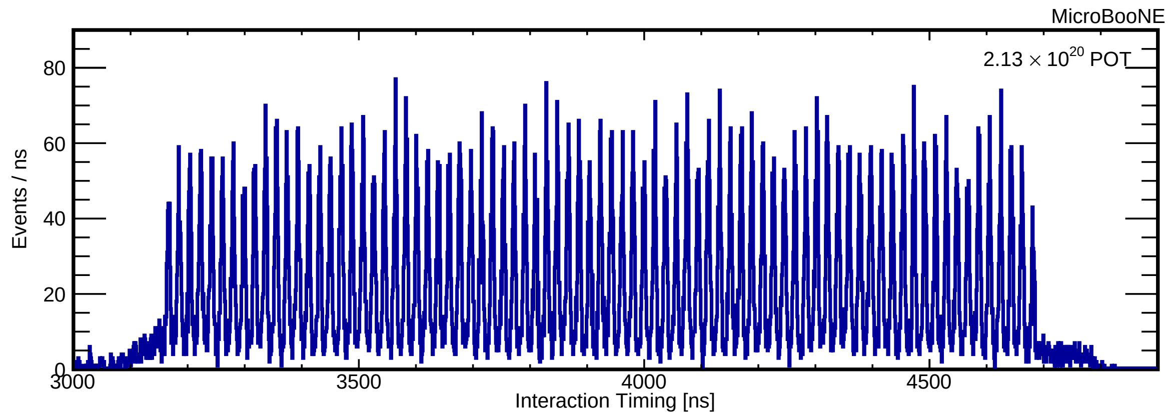
FIG. 8. Linear fits of the mean neutrino interaction time as functions of $\langle T^*_{dp} + T^*_{sl}\rangle$ (a) and $\langle N_{Ph}\rangle$ (b) are used to extract the two calibration factors α_1 and β_1, which are the gradients of the linear fits.

TABLE I. Terms analyzed in the reconstruction steps introduce different contributions to the event timing spread. This table summarizes the standard deviation and full range of the distribution of values of each term.

Term	STD [ns]	Range [ns]
T_{RWM}	$\simeq 9$	[-25,+25]
T_ν	$\simeq 9$	[0, 33]
$(T^*_{dp} + T^*_{sl})$	$\simeq 7$	[0, >50]
C_{Emp}	$\simeq 3$	[-10, 30]



(a) Interaction timing distribution before the propagation reconstruction.



(b) Interaction timing distribution after the propagation reconstruction.

FIG. 9. Neutrino candidate interaction timing distribution before (a) and after (b) the propagation reconstruction of the processes happening inside the TPC. The reconstruction includes the neutrino ToF inside the TPC, the daughter particle propagation and the scintillation light propagation, with the relative empirical correction included. The 81 bunches composing the beam pulse sub-structure are easily visible after the propagation reconstruction.

For each one of the 81 bunches a Gaussian fit is performed and the extracted mean values are used to obtain a linear fit as a function of the peak number, as shown in Fig. 10. The linear fit slope is used to measure the bunch separation (Δ). The value found of 18.936 ± 0.001 ns matches the expectation from the accelerator frequency parameter [17]. This is the first time the ns time-structure of a neutrino beam is detected with a LArTPC-based detector.

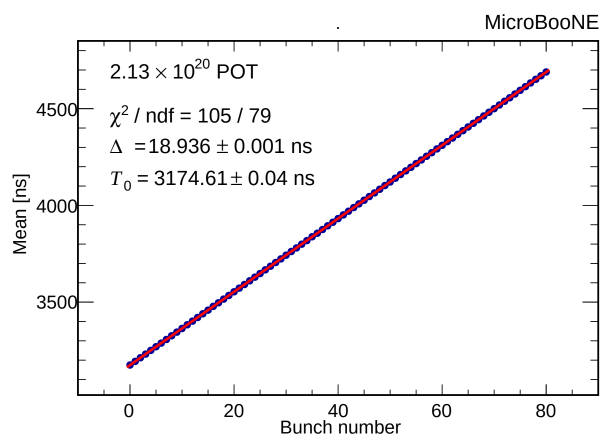


FIG. 10. For each of the 81 bunches observed in Fig.9 (b) a Gaussian fit is performed to the bunch peak and the extracted mean values are used to obtain a linear fit as a function of the peak number. The gradient (Δ) and the intercept (T_0) of the linear fit give respectively the bunch separation and the common constant offset due to the propagation time form the beam target to the TPC. The value found for the bunch separation is $\Delta = 18.936 \pm 0.001$ ns.

IV. RESULTS

Once all the reconstruction steps are implemented and corrections applied, the neutrino candidate timing distribution, reported in Fig. 9, is used to extract the detector timing resolution for neutrino interactions. The 81 bunches are merged in a single peak which is fit with the function:

$$f(t) = C_{\mathrm{Bkg}} + \frac{N}{\sqrt{2\pi\sigma^2}} \left\{ \exp\left[-\frac{1}{2}\left(\frac{t-\mu-\Delta}{\sigma}\right)^2\right] + \right.$$
$$\left. + \exp\left[-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{t-\mu+\Delta}{\sigma}\right)^2\right] \right\} \quad (2)$$

The fit function is composed of three Gaussians with identical width σ. The fit parameter σ is used to extract the timing resolution, while the two Gaussians offset by the bunch separation Δ are introduced to account for events from neighboring peaks. Finally an overall constant term, C_{Bkg}, accounts for a flat background from cosmic-ray events. Using this method the bunch width obtained is $\sigma = 2.53 \pm 0.02$ ns, from the fit shown in Fig. 11. Table II shows the reduction of the bunch width after each reconstruction step is included.

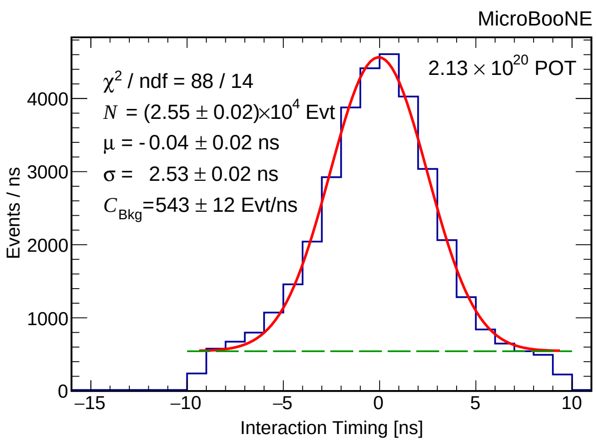


FIG. 11. Event timing distribution of the 81 beam bunches merged in a single peak after applying corrections. The green dashed line shows the constant term associated to the cosmic background uniform contribution.

Subtracting the intrinsic proton beam bunch width $\langle\sigma_{BNB}\rangle \simeq 1.308$ ns from the measured bunch width gives a value for the overall detector timing resolution of

$$R_{Tot} = \sqrt{\sigma^2 - \langle\sigma_{BNB}\rangle^2} = 2.16 \pm 0.02\,\mathrm{ns} \quad (3)$$

Finally, a characterization of the timing resolution versus the total number of detected photons is performed.

TABLE II. This table shows the decrease of the bunches width (σ) after each reconstruction step is applied. Applying singularly T_{RWM} or T_ν is not sufficient to separate the bunches and measure the width. The intrinsic 1.308 ns beam spread is included in the σ values reported in this table.

Correction included	σ [ns]
T_{RWM} or T_ν	-
T_{RWM} and T_ν	4.7 ± 0.2
T_{RWM}, T_ν, $(T^*_{dp} + T^*_{sl})$	2.99 ± 0.04
T_{RWM}, T_ν, $(T^*_{dp} + T^*_{sl})$, C_{Emp}	2.53 ± 0.02

The parameter σ is measured as a function of the total number of detected photons, as shown in Fig. 12. This distribution is fit using the function

$$\sigma\left(\langle N_{Ph}\rangle\right) = \sqrt{\langle\sigma_{BNB}\rangle^2 + k_0^2 + \left(\frac{k_1}{\sqrt{\langle N_{Ph}\rangle}}\right)^2}, \quad (4)$$

where k_0 is a constant term, k_1 is associated to the statistical fluctuation in the number of detected photons ($\propto \sqrt{N_{Ph}}$), and $\langle\sigma_{BNB}\rangle$ is the beam spread contribution to the resolution. The intrinsic detector timing resolution is associated with the constant term k_0 measured to be 1.73 ± 0.05 ns.

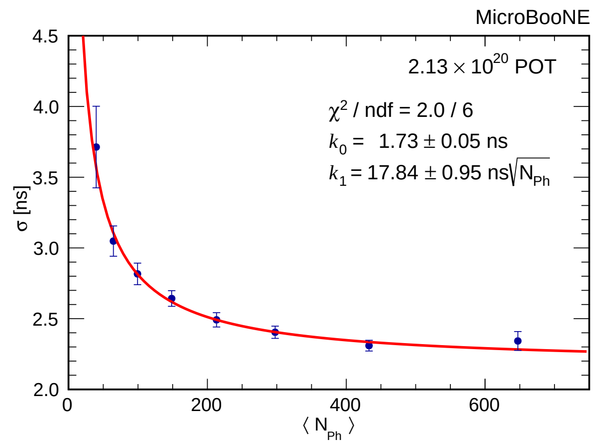


FIG. 12. Interaction timing resolution as a function of the total number of photons detected.

V. APPLICATION OF $\mathcal{O}$(1 NS) TIMING IN PHYSICS ANALYSIS

The $\mathcal{O}(1\,\mathrm{ns})$ timing resolution achieved can significantly expand MicroBooNE's capability of studying neutrino interactions and searching for BSM physics. An improved neutrino selection efficiency can be obtained by adding the $\mathcal{O}(1\,\mathrm{ns})$ timing as a new tool for cosmic background rejection in surface LArTPCs orthogonal to existing techniques [8, 12, 13]. Moreover, a $\mathcal{O}(1\,\mathrm{ns})$ timing resolution allows improvement in the performance of searches for heavy long-lived particles which will travel to the detector more slowly than the SM neutrinos. This method can in particular be applied to searches for heavy neutral leptons (HNLs), expanding the phase-space and sensitivity of HNL models being tested with current techniques [10, 11]. In this section we describe the potential that the precise timing has for improved cosmic background rejection and for searches for heavy long-lived particles such as HNLs.

Cosmic ray background rejection. The reconstruction of the BNB bunch structure makes it possible to exploit the timing of the neutrino interaction to remove a fraction of cosmic-ray background from the BNB neutrino candidates. This is possible because cosmic-rays arrive uniformly in time while BNB neutrinos are in time with the proton pulse structure of Fig. 2. Imposing a selection time window around the BNB bunches can be used to reduce the fraction of cosmic background events as shown in Fig. 13. Figure 14 shows the direct dependence of neutrino selection efficiency versus background rejection. The neutrino selection efficiency is defined as the fraction of neutrino events surviving the cut applied to remove the background. As a benchmark, a cut at $\pm 2\sigma$ around the peak gives a ν_μCC selection efficiency of 95.5% and a cosmic background rejection of 46.6% removing nearly half the cosmic-ray background with minimal efficiency loss. This method is complementary with respect to previously demonstrated cosmic rejection for LArTPCs which relies on charge-to-light matching.

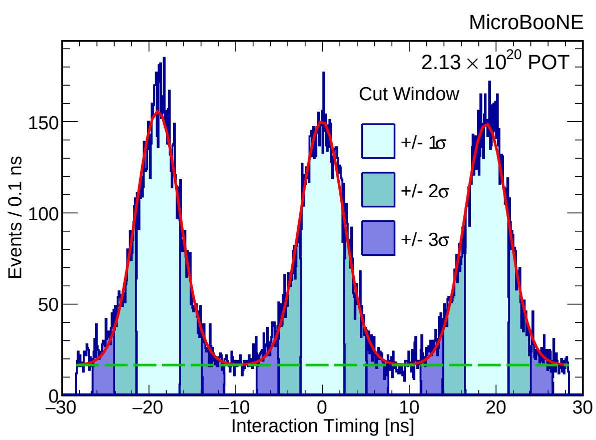


FIG. 13. Event timing distribution with selection cuts around the peaks. The dotted green line shows the cosmic background fraction. The initial 27.1% of total background reduces to 21.7%, 15.2%, 10.6% for the respective cuts of $\pm 3\sigma$, $\pm 2\sigma$, $\pm \sigma$ around the peak.

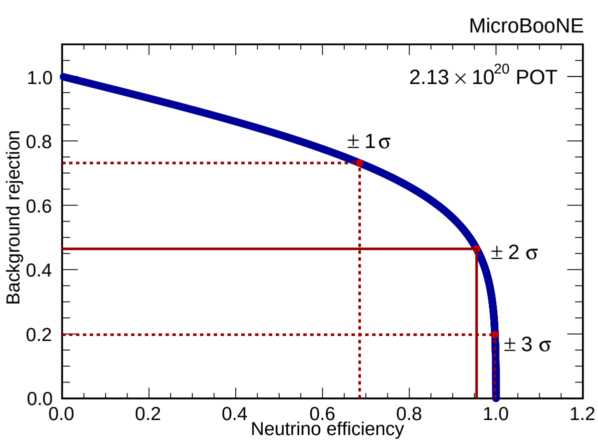


FIG. 14. Neutrino efficiency versus background rejection. Neutrino efficiency of 68.3%, 95.5%, 99.7% and background rejection of 73.3%, 46.6%, 19.8% are obtained for the respective cuts of $\pm \sigma$, $\pm 2\sigma$, $\pm 3\sigma$ around the peak (red points).

Heavy Neutral Lepton Searches. A set of models that can be tested with LArTPC neutrino experiments includes the production of HNLs through mixing with standard neutrinos [10, 11, 26–29]. HNLs may be produced in the neutrino beam from the decay of kaons and pions, then propagate to the MicroBooNE detector where they are assumed to decay to SM particles. The masses of these right-handed states can span many orders of magnitude, reaching the detector with a delay with respect to the nearly massless standard neutrinos [30]. This results in a distortion of the interaction time distribution when compared to the proton beam profile. To illustrate this delay, Fig. 15 shows the arrival time distribution of hypothetical HNLs with mass of 70 MeV (red line) overlayed on the regular BNB neutrino beam structure (black line) measured in this analysis. The HNL delay causes a distortion in the overall time distribution (blue line). Here the fraction, 10%, of HNLs has been overestimated to emphasize the effects of a massive particle superimposed on the nearly massless standard neutrino time distribution. The 70 MeV mass of the HNLs introduces a difference of ∼6 ns between the ToF of HNLs and standard neutrinos when calculated with an energy of 800 MeV, the mean BNB beam energy. The ability to resolve interaction timing with $\mathcal{O}(1\text{ ns})$ resolution introduces a new method to improve searches for long-lived particles (including HNLs) by rejecting neutrino backgrounds through the determination of the interaction time. This development will improve the sensitivity of and help expand the reach of BSM searches in the existing and upcoming accelerator-based neutrino physics program being carried out at Fermilab. In particular, the introduction of $\mathcal{O}(1\text{ ns})$ timing has the potential to allow model-independent searches for heavy long-lived particles for masses of 10s to 100s of MeV.

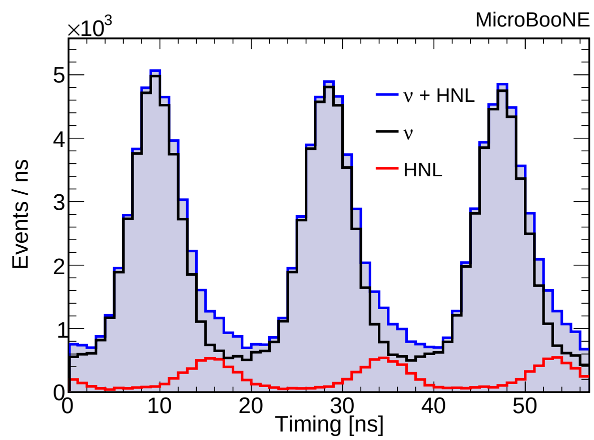


FIG. 15. Time distribution given by an hypothetical combination of HNLs and standard neutrinos. The toy model uses a sample of events populated by 10% of 70 MeV HNLs and 90% of nearly massless standard neutrinos. This introduces a difference of ∼6 ns between the ToF of HNLs and standard neutrinos, produced with an energy of 800 MeV, travelling from the BNB target to MicroBooNE.

VI. CONCLUSIONS

This work is the first demonstration of $\mathcal{O}(1\,\text{ns})$ timing resolution for reconstructing ν_μCC interaction times in a LArTPC with the MicroBooNE experiment. This result is achieved through the implementation of novel analysis methods that measure and correct the ToF of neutrinos and their interaction products, as well as scintillation photons propagating through the detector volume. This makes use of both precise photon detection system timing resolution as well as detailed reconstructed TPC information to account for various delays in particle propagation through the detector. Moreover, the RWM signal has been used to improve the precision of the beam trigger. The analysis finds an intrinsic resolution in measuring the neutrino interaction time of 1.73 ± 0.05 ns. 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 with LArTPC neutrino experiments. The method presented here can be applied to obtain $\mathcal{O}(1\,\text{ns})$ timing for any type of interaction occurring in the TPC. $\mathcal{O}(1\,\text{ns})$ timing resolution for neutrino interactions enables a new cosmic-rejection method to discriminate between neutrino interactions arriving in $\sim$2 ns pulses in the BNB versus the continuous flux of cosmic-rays that constitute a significant background for surface-based LArTPC detectors. Furthermore, $\mathcal{O}(1\,\text{ns})$ timing accuracy can be leveraged for searches of BSM particles such as HNLs that have a longer ToF and reach the detector delayed with respect to neutrinos. The development of this new handle for studying BSM signatures will expand the sensitivity reach and parameter space that can be explored for searching for BSM signatures in LArTPC detectors operating in neutrino beams, both within the SBN program [2] and in the DUNE near detector [31].

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