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Neutrino identification with scintillation light in MicroBooNE

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Abstract: MicroBooNE is a neutrino experiment which employs a liquid argon (LAr) time projection chamber (TPC) to record neutrino interactions from Fermilab's neutrino beamlines. The experiment's primary objective is to study low-energy ν_e interactions from the Booster Neutrino Beamline (BNB). Located on the surface, the detector is affected by a continuous rate of cosmic-rays. This leads to one neutrino interaction for every 10^4 cosmic rays observed in the TPC, making it difficult to isolate neutrino interactions in the detector using charge alone. MicroBooNE's trigger makes use of prompt scintillation light and plays an essential role in both performing strong background rejection and significantly reducing data-rates. Furthermore, a series of novel techniques relying on scintillation light are used to isolate beam-induced activity. This document briefly presents MicroBooNE's scintillation-light based trigger and novel Flash-Matching pattern recognition techniques for cosmic-rejection. This work serves as the foundation of neutrino analyses in LArTPC detectors and is therefore of interest to the broader short- and long-baseline neutrino programs being launched at Fermilab.

Keywords: Neutrino detectors; Noble liquid detectors (scintillation, ionization, double-phase); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Trigger concepts and systems (hardware and software)

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1 MicroBooNE: physics goals and detector description

The MicroBooNE experiment [1] aims to study neutrino interactions of $O(1)$ GeV from the Booster Neutrino Beamline (BNB) with the goal of investigating and determining the nature of the excess of low-energy electromagnetic events observed on the same beamline by the MiniBooNE collaboration [2]. At the same time, MicroBooNE is carrying out a rich ν − Ar cross-section program [3–5]. In order to resolve the full details of neutrino interactions, MicroBooNE employs the Liquid Argon Time Projection Chamber (LArTPC) detector technology to obtain high resolution images which enable the detection and identification of different final-state particles with low (few to tens of MeV) thresholds. The LArTPC technology enables this by recording with *mm* accuracy the 3D pattern of ionization charge produced from final-state particles. The slow drift of electrons used to create such images leads to a significant background of cosmic-ray interactions for a surface detector. These backgrounds dominate over the neutrino signal from the beam by a factor of 10^4:1.

Two major challenges need to be overcome in order to suppress cosmic backgrounds to the level needed to perform precise neutrino measurements:

1. The slow drift of ionization electrons (1.1 meters/millisecond for MicroBooNE) washes out the powerful benefit of the BNB's μs pulsed beam structure, making it challenging to discern whether any given event contains activity in time with the neutrino beam.

2. Even in events triggered by neutrino interactions, a pile-up of $O(10)$ cosmic-ray interactions get superimposed over the neutrino image, as can be seen in figure 1, making the task of isolating charge from the neutrino interaction challenging.

2 MicroBooNE's light collection system

Scintillation light, produced copiously in the detector, propagates through the detector volume in nanoseconds and can be used to recover the timing information that the ionization signals recorded by the TPC lack. Scintillation light is used both to determine if there is activity coincident with the

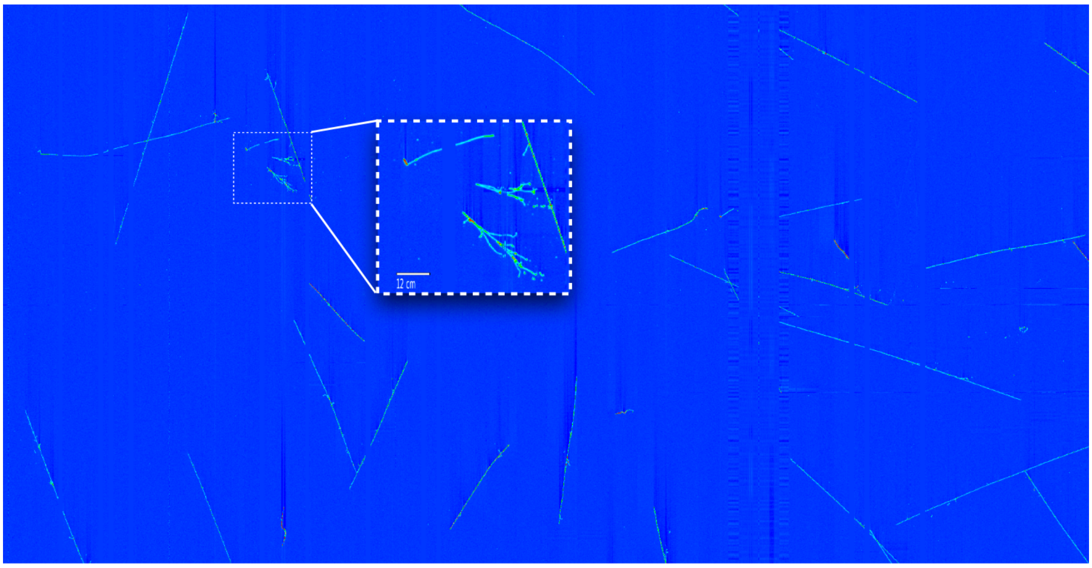

Figure 1. Full view of a recorded MicroBooNE event display. The neutrino interaction, highlighted in the image, is recorded together with ~20 accidental cosmic-ray interactions which are out of time with respect to the beam but occur in the same 2.3 ms TPC readout window due to the slow electron drift.

neutrino beam (triggering, see section 3) and to perform pattern-recognition by associating light information to TPC charge in order to discern the in-time neutrino interaction from out-of-time cosmic-ray activity in any given recorded event (flash-matching, see section 4). The rest of this section provides a brief description of MicroBooNE's light collection system.

The detector is equipped with 32 8-inch R5912-02mod cryogenic Hamamatsu PMTs which are placed behind an acrylic plate coated with tetraphenyl-butadiene (TPB) used to shift the 128 nm wavelength emitted in argon to the visible range in which the PMTs are sensitive. The PMT array is placed behind the anode-plane on which the TPC readout wires are mounted, leading to a strong drift-position dependent light collection efficiency.

Signals from MicroBooNE's PMTs are digitized and recorded through custom readout boards responsible for shaping, digitizing, and triggering of light signals. Each PMT is read out via two channels with high and low gain, allowing for a dynamic range spanning 0.1 to 1000 photo-electrons (PEs). Signals are then shaped with a 60 ns rise-time and digitized at 64 MHz frequency (15.625 ns time-tick).

Two different readout modes are used to record signals out-of-time and in-time with the neutrino beam. Signals arriving out-of-time with respect to the neutrino beam are recorded through a trigger scheme which stores waveforms from any given PMT provided a signal of seven PEs or more is observed. If this condition is met, a 40-tick (625 μs) waveform is recorded. This readout mode is used to collect light associated with out-of-time cosmic-ray interactions which are recorded in each TPC event. For signals in-time with the beam, an unbiased 23.4 μs readout window (wide enough to comfortably contain the BNB and NuMI beam-spills) is recorded for each PMT in coincidence with the trigger time. Figure 2 shows an example of the recorded light signals from MicroBooNE's PMT system in time-coincidence with the beam. Time-coincident activity on multiple PMTs, associated with a candidate neutrino interaction, can be seen on several PMTs.

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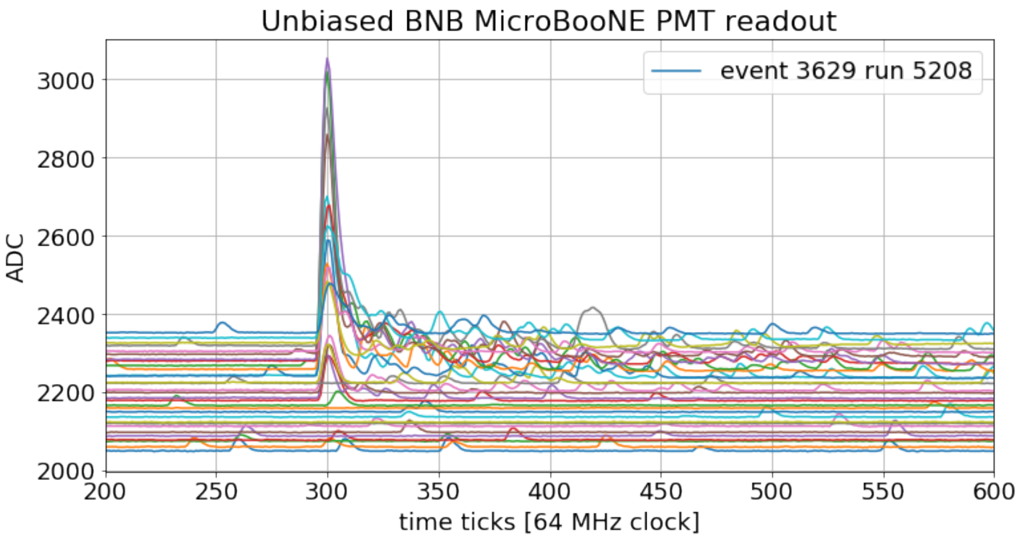

Figure 2. An example of the recorded light signal from MicroBooNE's 32 PMTs in the 23.4 μs unbiased readout window coincident with the neutrino beam spill. The baseline of the waveforms from the 32 PMTs is shifted sequentially by 10 ADC for graphic purposes.

3 Scintillation light triggering

MicroBooNE makes use of scintillation light in its online trigger by requiring that in an event there be light in coincidence with the beam spill. Beam timing is determined with a 100 ns resolution through the measurement of reconstructed optical flashes in on-beam and off-beam events, as shown in figure 3. The regions with excess activity associated with the beam are referred to as the *beam-spill window*. An online trigger, implemented in the DAQ, is issued if the amount of PEs observed in any 100 ns time-window in the identified beam-spill window passes a certain threshold. No multiplicity condition is required on the light from the 32 PMTs, but a given PMT will contribute to the total PE only if it was found to have more then half a PE above baseline. The charge on a PMT at a given time is calculated by taking the ADC difference between time-tick N+4 and time-tick N to account for the 60 ns (4 time-tick) rise-time of the shaper. A threshold of ~4 PE is applied to trigger an event from the BNB.

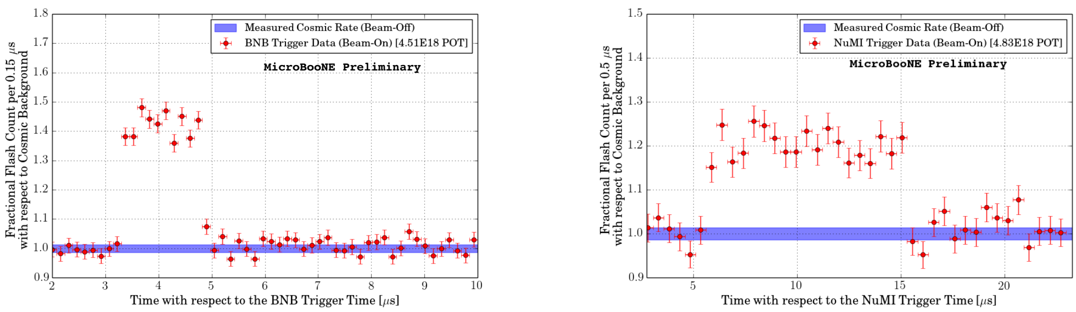

Figure 3. Ratio of the number of reconstructed flashes for BNB (left) and NuMI (right) events recorded in a zero-bias readout mode over the rate in off-beam cosmic events.

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By rejecting 96% of events, MicroBooNE's online trigger provides a first powerful step in cosmic rejection, and drastically reduces data transfer rates from 13 TB/day to 500 GB/day, reducing stress on computing and network resources. Yet, even with the implementation of MicroBooNE's online trigger, offline data-processing (reconstruction and analysis) faces a significant challenge in the ability to load in a timely fashion large datasets – $\mathcal{O}$(PB/year) – from tape. Therefore, an additional offline filter is applied to the data, imposing the same logic applied in the online trigger, but with an increased threshold of 20 PEs. This additional filter further reduces dataset volumes by a factor of three, while maintaining high efficiency for low-energy neutrino interactions.

MicroBooNE's trigger efficiency is strongly position dependent due to the asymmetric location of the PMT array in the cryostat. The number of recorded PEs of prompt-light (in the first 100 ns) per MeV of deposited energy, drops to $\mathcal{O}(0.1)$ for energy deposited at the cathode. With a 20 PE offline filter threshold, this can impact the efficiency for $\mathcal{O}(100\,\text{MeV})$ energy deposition, potentially impacting MicroBooNE's signature ν_e analysis. By relying on cathode-piercing tracks externally tagged through the Cosmic Ray Tagger [6], MicroBooNE can perform a data-driven measurement of its triggering efficiency. This work, currently underway, will provide necessary input to MicroBooNE's low-energy physics program. Preliminary results give greater then 97% efficiency for more then 200 MeV of deposited energy at the Cathode.

4 Flash-matching: cosmic rejection through the use of scintillation light

After MicroBooNE's scintillation-light based trigger and offline filters have been applied, more then 98% of beam spill signals have been rejected; and yet, cosmic interactions still dominate the data by $\mathcal{O}(200)$:1. For each surviving event, roughly nine out of ten are triggered by cosmic activity which coincidentally occurs in time with the beam, and for each in-time interaction, ~20 cosmic-ray interactions in the full TPC readout window are recorded in the same event. Identifying out of the many TPC interactions which one occurred in time with the beam-spill is another task for which scintillation light is used in MicroBooNE. By correlating the charge and position of reconstructed TPC interactions to the reconstructed optical information in time with the beam-spill (the *beam-flash*) cosmic backgrounds are further reduced by an order of magnitude. Remaining backgrounds ($\mathcal{O}(10)$:1) are associated with in-time cosmic activity which happens to trigger an event, and are dealt with through topological (i.e. stopping muon) or geometrical (i.e. through-going muon) cuts.

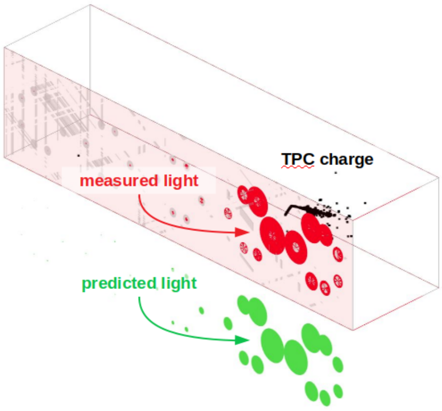
MicroBooNE relies on several reconstruction techniques for different analyses, each using scintillation light in different ways for cosmic rejection. Here we describe the *flash-matching* technique as a means to demonstrate how scintillation light is used for cosmic rejection. For details on how cosmic rejection is carried out for specific analyses please refer to the reports employing the PANDORA [7] and WireCell [8] frameworks. These methods are being furher refined for upcoming MicroBooNE analyses.

The flash-matching technique aims to quantify the compatibility in charge and position between the beam-flash and each reconstructed TPC interaction. The flash-matching algorithm compares, PMT by PMT, recorded light signals (PE^{reco}) to the light signal expected from the collection of 3D energy deposition points associated with a reconstructed 3D intreaction in the TPC ($\text{PE}^{\text{hypothesis}}$). For a given PMT and a given TPC interaction, the amount of light predicted is calculated through the use of a photon visibility map:

$$\mathrm{PE}_{\mathrm{n}}^{\mathrm{hypothesis}} = \sum_{m=0}^{M} Q_m \times \alpha \times \mathrm{Visbility}\,(\vec{r}_m, n)\,, \tag{4.1}$$

where the sum is performed over all reconstructed 3D energy-deposition points in the interaction, Q_m is the charge and $\vec{r}_m$ the coordinate associated with each reconstructed 3D energy deposition point, α is a constant conversion used to scale from charge to number of photons, and the function Visbility $(\vec{r}, n)$ returns the visibility for PMT n of coordinate $\vec{r}$ and takes into account geometric acceptance, scattering, and reflection effects, calculated relying on a `Geant4` simulation of the MicroBooNE detector, in addition to a PMT's global quantum efficiency.

The TPC-based expectation produced for each PMT is quantitatively compared to the measured light signal. This method is visually described in figure 4.



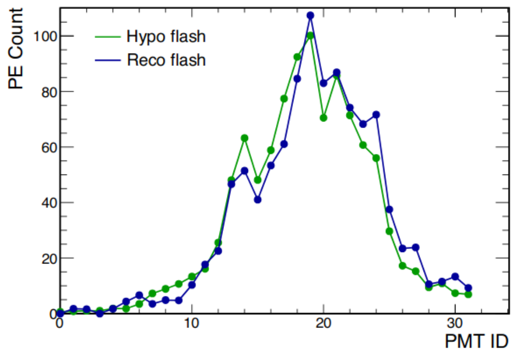


Figure 4. The Flash-Matching technique displayed visually. Left, a comparison of expected and recorded light for a given TPC interaction, reproduced from ref. [8]. Right: the comparison of the PMT spectrum for hypothesized and reconstructed light signal at the basis of the Flash-Matching method, reproduced from ref. [7].

Finally, a test statistic to quantify this level of agreement is computed and defined as:

$$\chi = \sum_{n=0}^{32} \frac{\left[\mathrm{PE}^{\mathrm{hypothesis}}\,(n) - \mathrm{PE}^{\mathrm{reconstructed}}\,(n)\right]^2}{\sigma_{\mathrm{PE}}}. \tag{4.2}$$

Based on this test-statistic, compatibility between light information and each reconstructed TPC interaction can be tested, enabling to isolate the interaction that is time-coincident with the beam-spill and further suppress backgrounds by an order of magnitude.

The Flash-Matching technique strongly relies on an accurate modeling of the light response in the MicroBooNE cryostat. An active analysis program has been developed in order to provide the needed calibrations aimed at understanding and describing the light response in the MicroBooNE detector both spatially in the TPC and as a function of time. This work will be discussed in future publications.

5 Conclusions

MicroBooNE has developed important techniques for triggering, calibration, and pattern-recognition using scintillation light for the purpose of neutrino identification of large-scale surface LArTPC experiments. Triggering in MicroBooNE allows to recover the benefits of a pulsed μs accelerator neutrino source which is otherwise washed out by the ms-long electron drift time. Triggering reduces datasets and data-rates by close to two orders of magnitude, allowing for an efficient data-transfer and processing while maintaining high efficiency for recording low energy neutrino interactions. Pattern recognition using charge and topological information from the PMT arrays allows for further cosmic rejection. MicroBooNE has developed the *flash-matching* technique to identify which of the many cosmic-ray interactions in a given event is associated with the light produced in time with the beam-spill. In order to make this step in the analysis successful, an extended light calibration program has been developed. These topics will be further elaborated in a future technical article.

Acknowledgments

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