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Electromagnetic shower reconstruction in the ICARUS liquid argon time projection chamber detector

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The ICARUS-T600 liquid argon time projection chamber (LArTPC) detector is taking data at shallow depth as the far detector of the Short Baseline Neutrino (SBN) program at Fermilab, to search for a possible sterile neutrino signal at $\Delta m^2 \approx 1$ eV^2 with the Booster (BNB) and Main Injector (NuMI) neutrino beams at ≈ 0.8 GeV and ≈ 2 GeV average energies respectively. The LArTPC technology, developed by the ICARUS collaboration and now a standard in neutrino physics, offers impressive charged-particle imaging capabilities with ≈ 1 mm spatial resolution, enabling efficient discrimination between track-like signatures (e.g., from muons, pions, and protons) and electromagnetic showers (from electrons and photons). Moreover, electron and photon signatures can be distinguished both with the calorimetric measurement of local energy depositions at the shower start and with the cm-scale conversion gap signature of photons. This contribution discusses event reconstruction at ICARUS focusing on Pandora, a multi-algorithm pattern recognition software widely used in LArTPC experiments. Over a hundred Pandora algorithms and tools are used to reconstruct cosmic rays and neutrino interactions in the ICARUS detector. Recent developments have focused on the reconstruction of electromagnetic shower signatures, crucial to ensure a robust and efficient reconstruction of charged-current ν_e interactions, which serve as a key signature of sterile neutrino oscillations at SBN. In this contribution, recent improvements to the reconstruction are discussed, focusing on the discrimination between tracks and electromagnetic showers using neutrino simulations and data.

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

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https://pos.sissa.it/

PoS(EPS-HEP2025)185

1. ICARUS at Fermilab's Short Baseline Neutrino program

The ICARUS liquid argon time projection chamber (LAr-TPC) detector [1] is currently taking data as the far detector of the Short Baseline Neutrino (SBN) program at Fermilab [2], searching for sterile neutrinos with muon and electron neutrinos from the 0–2 GeV Booster Neutrino Beam (BNB) and the off-axis 0–5 GeV Neutrinos at the Main Injector (NuMI) beam.

In recent years, several anomalous neutrino oscillation results at very short baselines (e.g., from LSND [3] and MiniBooNE [4]) have been interpreted by hypothesizing a fourth sterile neutrino state associated with a large $\Delta m^2 \sim 1$ eV^2 mass splitting, which would produce neutrino oscillations at the $L/E_\nu \approx 1$ m/MeV scale. Several constraints on sterile neutrinos exist, including measurements from data collected until 2013 with the ICARUS detector at the INFN Gran Sasso National Laboratories in Italy [5], before the detector was refurbished at CERN and INFN in view of the operation at a shallow depth within SBN [1].

The ICARUS detector consists of two identical modules filled with 476 t of active liquid argon, each hosting two LAr-TPCs sharing a common semi-transparent cathode and with a drift length of 1.5 m, corresponding to a drift time of roughly 1 ms at the nominal 500 V/cm electric drift field (fig. 1). Charged particles traversing the liquid argon ionize the medium, and ionization electrons are drifted by the field towards the TPC anodes. Each anode consists of three readout planes 3 mm apart, consisting of wires with a 3 mm pitch oriented at 0 and ±60° with respect to the BNB direction, where the first two Induction planes measure an induced charge non-destructively, and the last Collection plane collects the charge with the highest signal-to-noise ratio [6].

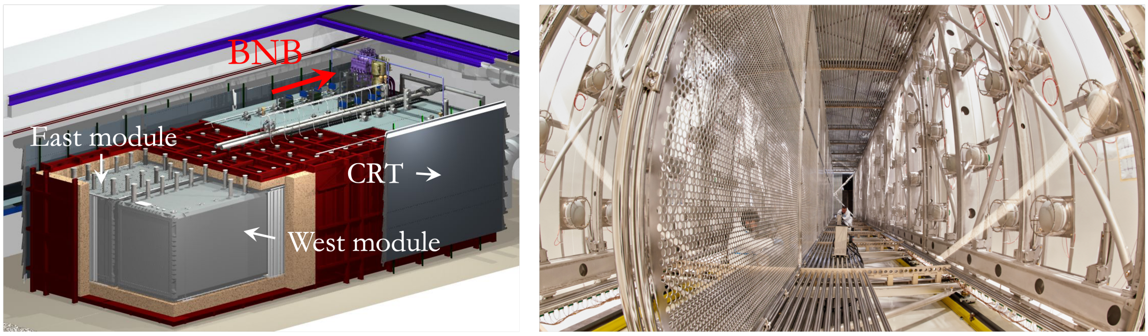

Figure 1: (left) Diagram of the two ICARUS modules inside the warm vessel, surrounded by the cosmic ray tagger. (right) View of an ICARUS TPC during the overhauling activities, with the semi-transparent pierced cathode visible in the middle. On the right, the 8" PMTs are installed behind the anodic wire planes.

To face the ≈ 11 kHz cosmic ray rate at the Earth's surface, the detector is surrounded by a segmented plastic scintillator Cosmic Ray Tagger (CRT) system providing nanosecond-scale timing of crossing particles [7], and covered by a 3 m concrete overburden to reduce the hadronic and soft cosmic ray components. Scintillation light is also produced abundantly in liquid argon, and is detected by 360 8″ photo-multiplier tubes (PMTs) located behind wires [8], providing a prompt nanosecond-scale signal that can be used for triggering, neutrino identification, and cosmic ray veto. Light signals from the PMTs are combined with timing from Fermilab's accelerator complex within an online trigger system, which produces a trigger based on a multiplicty of signals in limited TPC spatial regions, prompting the acquisition of TPC, CRT, and PMT signals [9].

2. Electromagnetic shower reconstruction in liquid argon time projection chambers

Particles traversing the liquid argon lose energy via collisions and stochastic radiative processes. For electrons and photons from tens of MeV energies, energy loss is dominated by the radiative processes, producing electromagnetic showers characterized by complicated topologies that are challenging to automatically reconstruct and identify. Fig. 2 (left) shows a high-energy electron shower from a NuMI electron neutrino interaction, in the Collection wire plane. Raw wire signals from the TPC are filtered from noise and *deconvolved*, to ideally recover the original current of drift electrons upstream of drift field and electronics distortions. A threshold-based algorithm identifies the regions of interest along each wire, performing Gaussian fits to extract TPC *hits*, characterized by the channel, amplitude, integral and RMS from the fit [10].

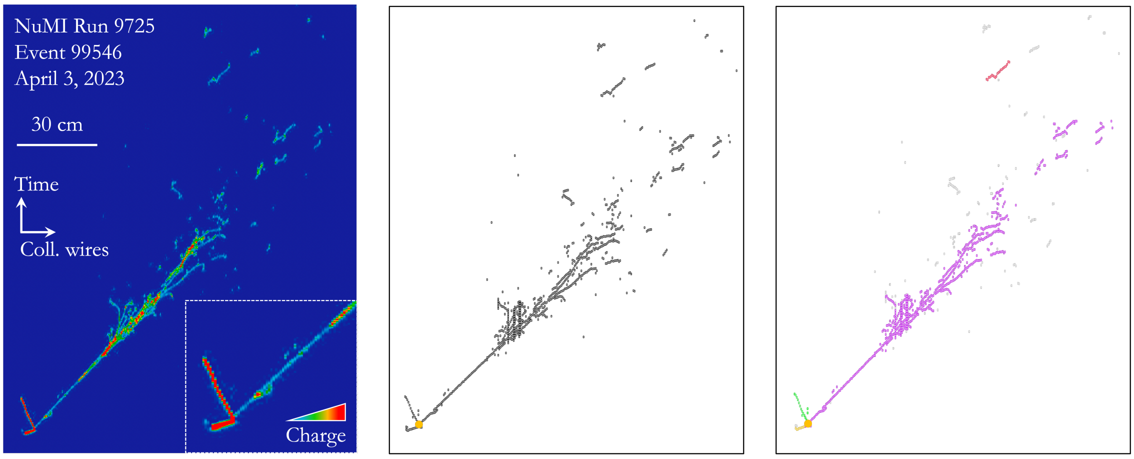

Figure 2: Event display of an electron neutrino interaction with a high-energy electron and two visible protons in the final state from NuMI data collected in 2023, showing the deconvolved signals in the Collection plane (left), the reconstructed hits along with the vertex identified by Pandora (center), and the final Pandora event reconstruction (right).

Event reconstruction in ICARUS builds upon the reconstructed hits in the three wire plane views, and relies on two parallel software packages, SPINE [11] and Pandora [12, 13]. Pandora, the focus of this analysis, is a framework with hundreds of traditional and machine learning algorithms which gradually build up a hierarchy of fully-reconstructed particles within an event. To mitigate the high cosmic ray rate, a first-pass track-oriented reconstruction path identifies evident cosmic ray interactions, from associated charge deposits occurring out of time with respect to the expected beam window, or from tracks that are through-going and clearly cross the detector boundaries. Hits associated with clear cosmic rays are removed from subsequent reconstruction steps, simplifying the task. The remaining hits are clustered into *slices*, each representing a single neutrino or non-obvious cosmic interaction, and are then processed with neutrino-oriented algorithms. Vertexing is one of the first and most critical stages: after an initial clustering, all cluster endpoints are considered vertex candidates. A boosted decision tree (BDT) selects the best candidate using features such as the number of hits upstream and downstream, the relative coordinate along the beam, and the local energy deposition pattern. Fig. 2 (center) shows the reconstructed electron neutrino interaction hits, along with the vertex identified by Pandora.

A series of algorithms build and refine clusters in each wire plane, e.g., by splitting clusters at the vertex position or in the case of evident kinks, and then match clusters across different wire planes based on the common drift time. Tracks are reconstructed in 3D by performing sliding linear fits of the matched clusters. Reconstructing electromagnetic showers is a much harder task, having to deal with ever-changing and crowded topologies. First, the track-like *spine* of the shower is identified in each plane, and the surrounding shower branches are merged based on geometrical and topological arguments. The clusters in the three views are matched based on the common time and showers are further refined in 3D, where algorithms recursively grow the leading shower with remnant branches, further improving the particle completeness. Finally, the hierarchy of the interaction is defined: the vertex is associated to primary particles, which in turn can be associated to daughter particles. Fig. 2 (right) shows the fully reconstructed electron neutrino, where two short track-like and one large shower-like objects emerge from the vertex.

Externally to Pandora, track particle identification is performed by comparing the energy deposition along the track with the expected Bethe-Bloch prediction. In this way, the two short highly-ionizing stubs at the vertex in fig. 2 can be identified as protons.

2.1 Track and shower discrimination

Toward the end of the reconstruction, a BDT is used to discriminate between track and shower objects based on a set of 13 reconstructed features encapsulating the development of a particle in liquid argon. Some of the variables arise from geometrical arguments, specifically from a sliding fit and from a principal component analysis (PCA) of the hits associated to each particle, whereas other variables use calorimetry, relying on the deposited charge distribution and its development within the cluster. To avoid biases in the discrimination of tracks and showers, data and Monte Carlo agreement is ensured for all the BDT features. The BDT was optimized and trained with a large BNB sample, with the shower component complemented by a BNB ν_e-only sample, consisting of roughly 55,000 tracks (balanced between protons, muons, and pions) and 55,000 showers (balanced between photons and electrons) with a true energy larger than 30 MeV.

The track–shower classification accuracy improved to 96%, with a significantly enhanced separation between track and shower particles (fig. 3). The updated BDT model places greater emphasis on calorimetric variables, allowing for further discrimination between electron and photon showers, where electrons are identified with the highest confidence. This improvement was found to result in over a 10% increase in the purity of selected charged-current electron-neutrino interactions in ICARUS, substantially reducing confusion with low-energy charged-current muon-neutrino events and interactions containing π^0 decays.

2.2 Electromagnetic showers in neutrino interactions

Track–shower discrimination is a key component in improving event reconstruction, enabling the use of dedicated algorithms for particles identified as showers, and for the selection of electron-neutrino or neutrino-induced π^0 decay candidates.

Fig. 4 demonstrates the data and Monte Carlo agreement for the leading shower opening angle and the gap between the vertex and the shower start (conversion gap), using a shower-enhanced neutrino sample in which the biggest reconstructed shower particle, identified thanks to the track score, has an energy above 200 MeV.

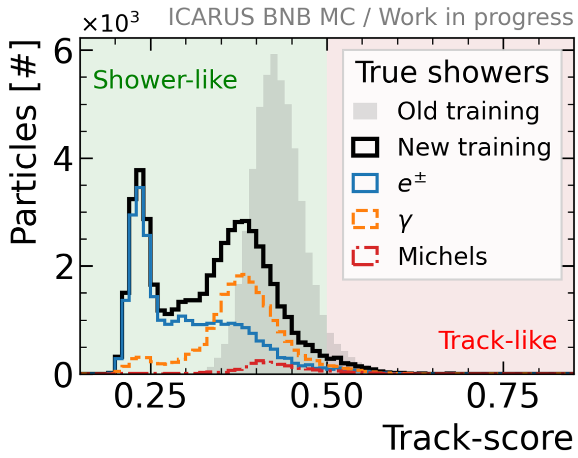

Figure 3: BDT track score distribution for true showers, split across the primary electron, photon, and Michel electron categories. The updated training substantially improves on track-shower separation and classification accuracy. Moreover, it enables for discriminating between electrons and photons.

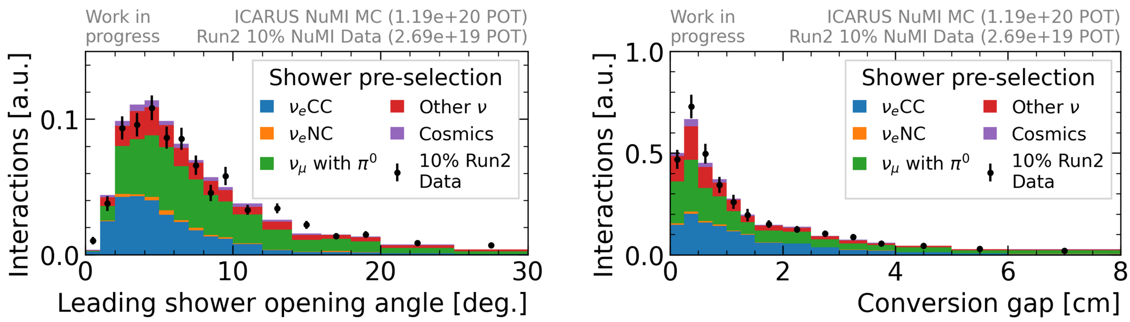

Figure 4: Area-normalized leading shower opening angle (left) and conversion gap (right) distributions with a selected neutrino sample enhanced in electromagnetic showers, consisting mostly of charged-current electron neutrino interactions and π^0 decays, using ICARUS NuMI data and Monte Carlo.

3. Conclusions

Electromagnetic showers in liquid argon are characterized by complex topologies, yet their accurate reconstruction is essential for electron neutrino and other shower-based analyses. This work discussed algorithmic shower reconstruction in LArTPCs using Pandora, and showcased recent improvements implemented in ICARUS, specifically in the track–shower discrimination. Ongoing efforts aim to further enhance shower reconstruction, e.g., through the integration of graph neural network–based approaches.

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