Data-Driven Precision Charge-Light Matching

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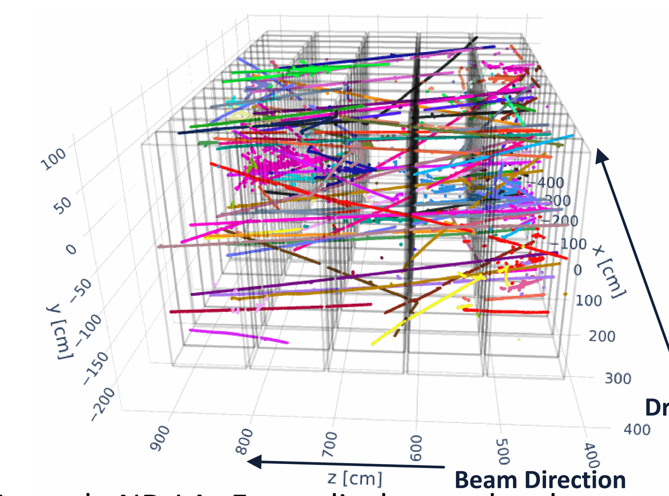
The DUNE Near Detector & 2×2 Demonstrator

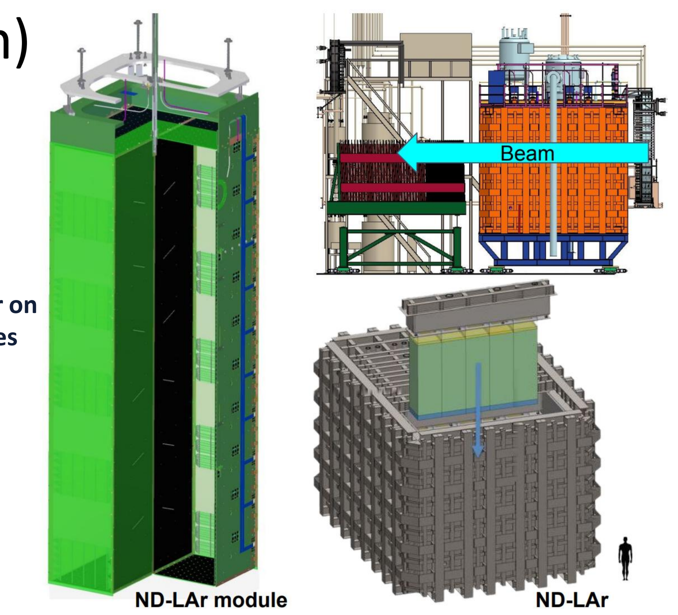
- Long-baseline oscillation experiment: Fermilab → Sanford Underground Research Facility (1300 km)
- Physics goals: mass ordering, CP violation, supernova ν, BSM
- **Near Detector (ND-LAr): Liquid Argon TPC, 7×5 = 35 modules**[1]
  - Pixelated charge readout
  - High-coverage readout for scintillation light
- **2×2 Demonstrator: 4 modules, same in design but smaller scale to those of ND-Lar, placed in the NuMI neutrino beam**[2]

Challenge for ND-LAr Analysis

- **Extremely high pile-up:** ~20 ν events, energy from ~100 events in 10 µs spill (2 MW beam)



Example ND-LAr Event display: each color represents charge hits with the same timestamp



(Event displays courtesy of the SPINE group)

Charge-Light Matching

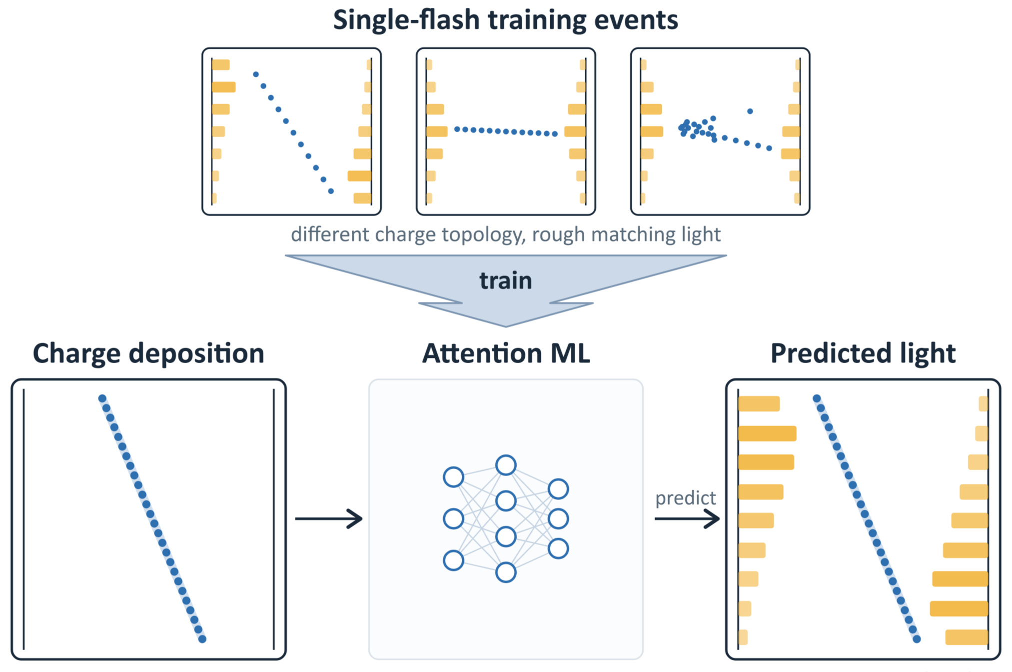
- **Complementary readout systems**
  Charge: excellent spatial imaging; spill interactions may overlap
  Light: nanosecond-level timing; clean signal even when multiple interactions occur in the same 10 spill µs time window
- **Associating light (timing) info to charge energy deposits is essential to reconstruct displaced interactions and help address pile-up**
- **Specifically useful when dealing with**
  1. Connecting spatially displaced energy deposits
  2. Discovering low-energy depositions
  Ex: small neutron interactions may leave tiny charge energies (hard to find spatially), but leave clear light signals.

METHOD & RESULTS

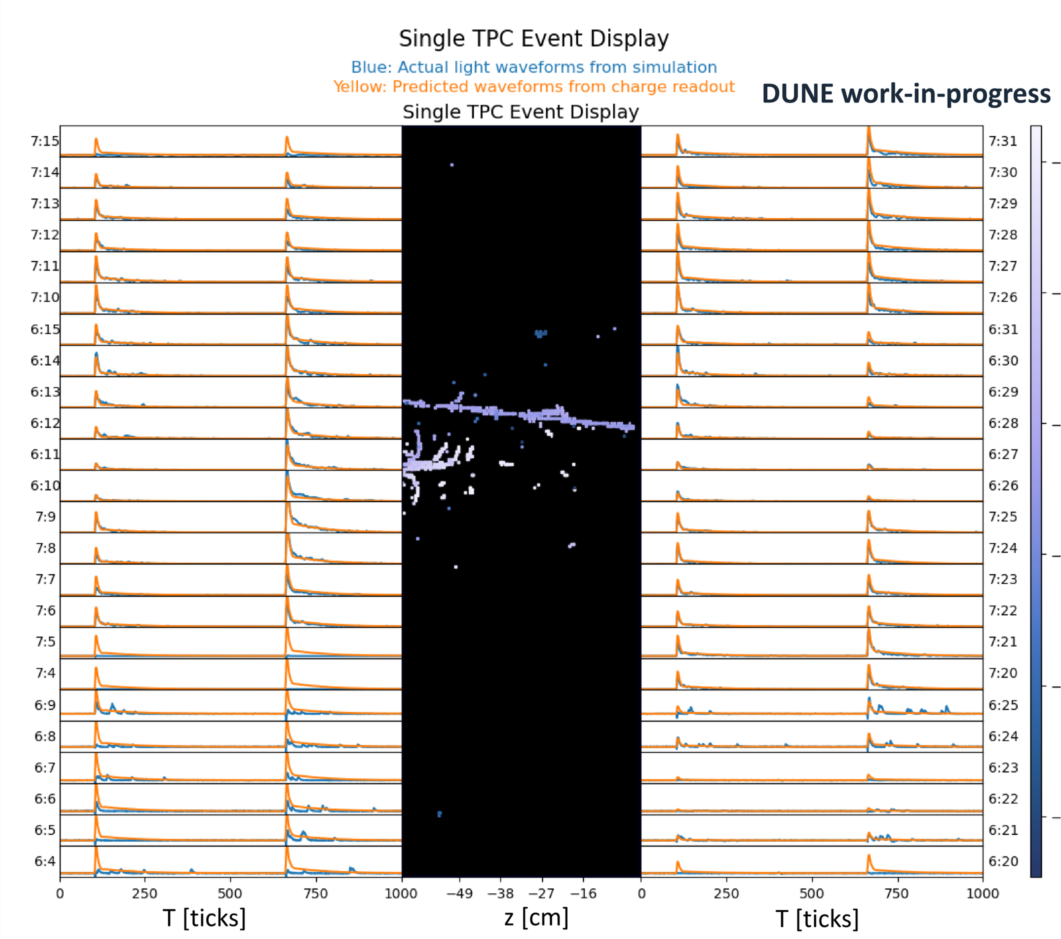
Prepare: Data-Driven Charge–Light Relation

Train 3DNN + attention-based ML to predict light flash patterns from charge signals
-> Automatically obtain data features

- Select single-interaction events
- Use ML algorithm to train on these events and obtain charge to light relation



REAL 2×2 Data Implementation



REAL data — 2×2 Demonstrator

Each Event Step 1: Cluster + Predict Light

Group pixelated hits that likely belong to the same T_0 through hit topology

- RANSAC-based track finding
- DBSCAN-based clustering
- Inter-TPC matching

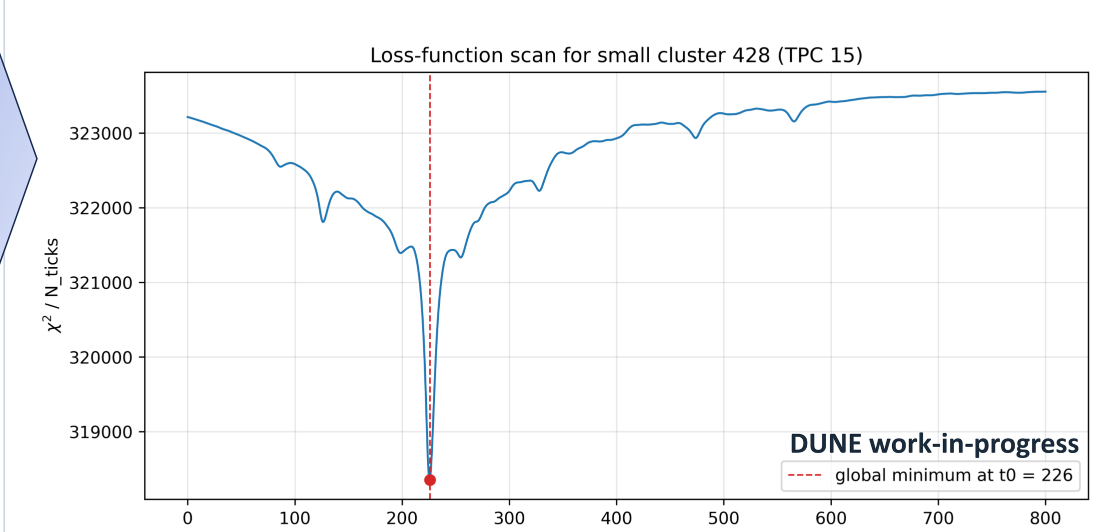
For each cluster, predict the signals expected in the light readout using ML techniques (above)

- Use attention-based ML to predict light amplitude given each charge cluster
- Form one predicted light "image" for each cluster

Each Event Step 2: Align + Likelihood

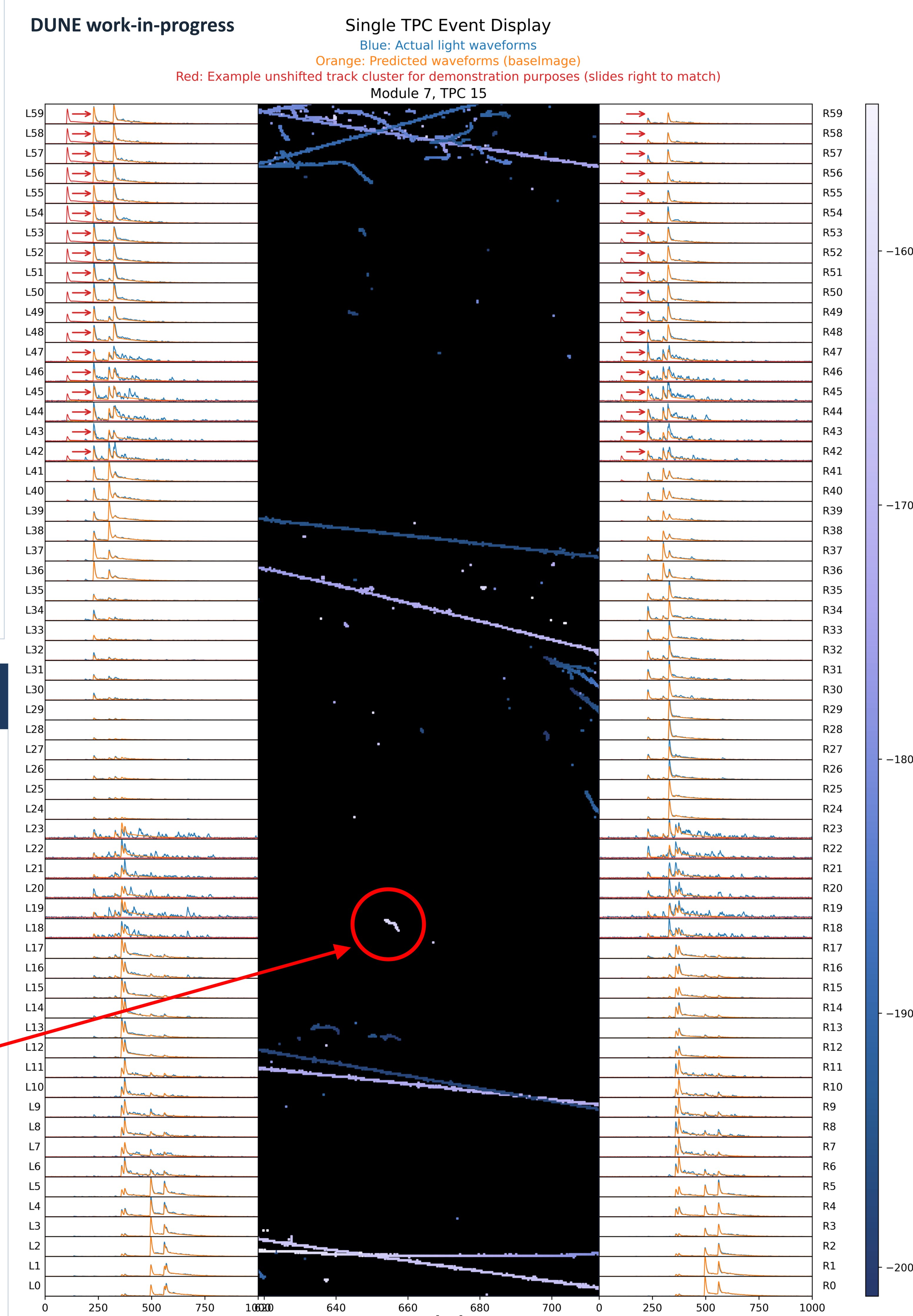
Shift the predicted waveform along the time axis to match actual data

- Form likelihood metric to characterize goodness of fit



Loss min → cluster T_0 alignment

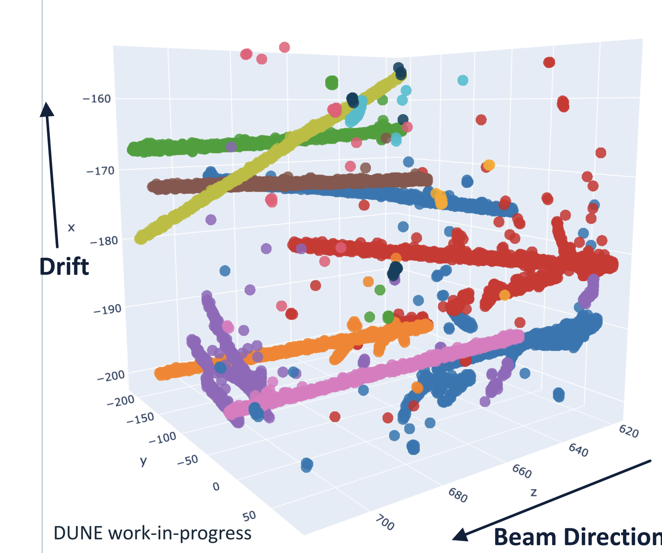
Simulated ND-Lar Implementation



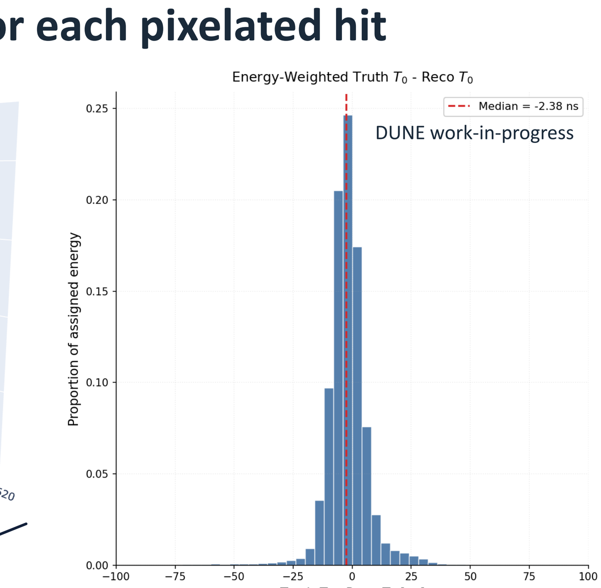
ND-LAr Simulation Performance

Handles high pile-up regime very well

O(~10ns) timing precision for each pixelated hit



Example ND-LAr TPC display : same color represents charge hits with the same time

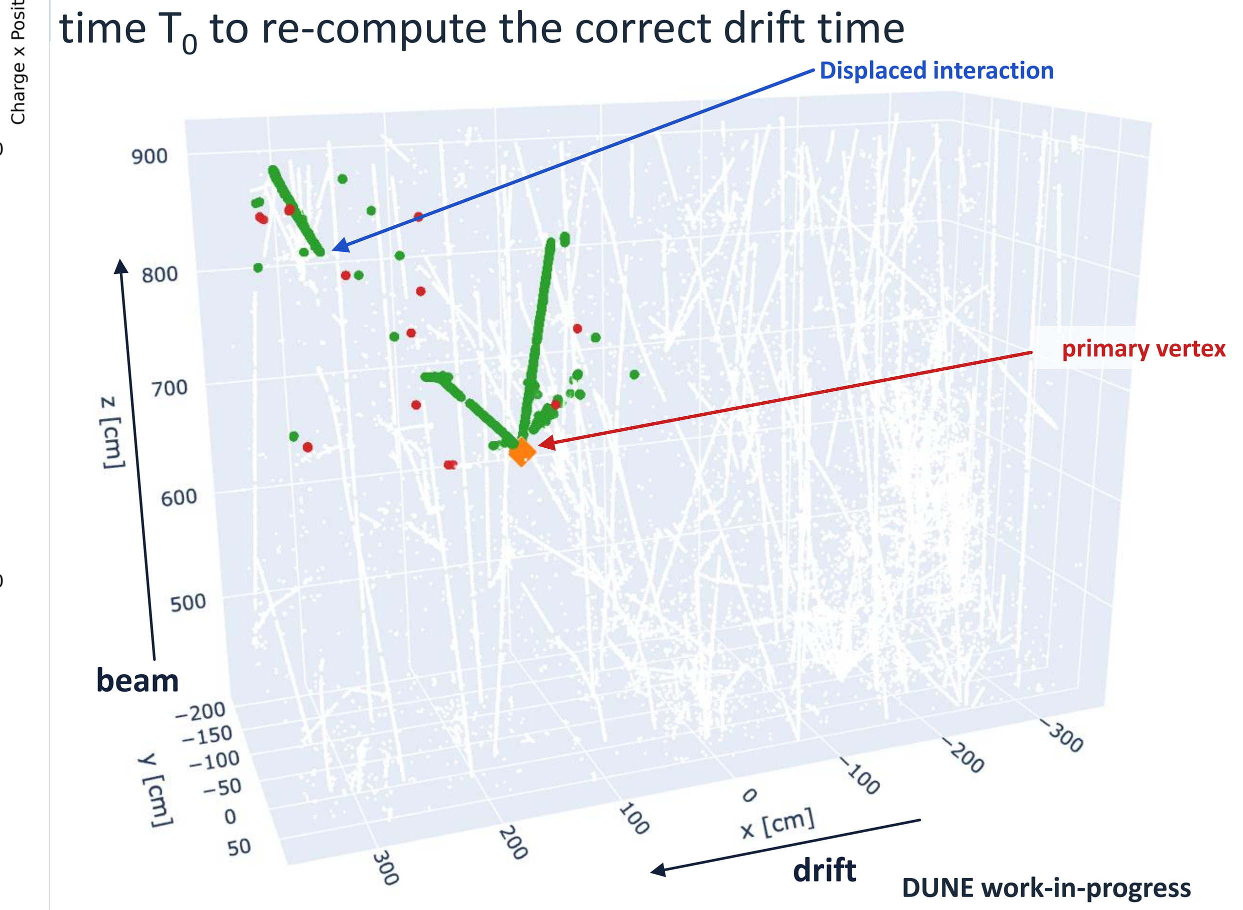


T_0 residual plot

Applications

Higher Reconstruction efficiency
- Connecting displaced activities back to original vertex

Corrections to electron drift time
- Nanosecond time-stamp accurately predicts the starting time T_0 to re-compute the correct drift time



Example displaced ND-LAr event captured by CL-matching: A neutron produced from the main interaction traveled invisibly and produced a displaced hadronic cascade

References
[1] DUNE Collaboration, "Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report," Instruments 5 (2021) 31, arXiv:2103.13910.
[2] DUNE Collaboration, "Operation of a Modular 3D-Pixelated Liquid Argon Time-Projection Chamber in a Neutrino Beam," Instruments 10 (2025) 18, arXiv:2509.07012.