SPINE for DUNE Far Detector & the Prototypes

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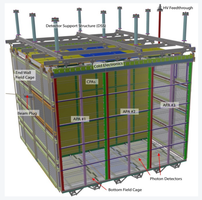
Introduction

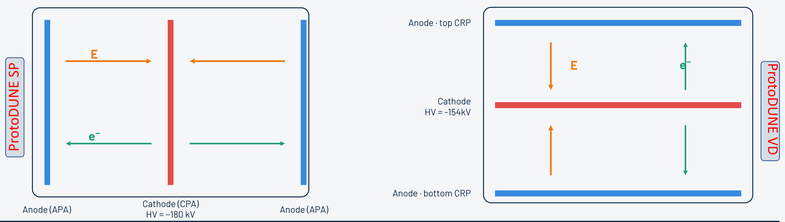
- ❑ **DUNE** → **D**eep **U**nderground **N**eutrino **E**xperiment
  - Long-baseline neutrino oscillation experiment
  - Measure various parameters of the PMNS matrix
  - Search for CP violation in the leptonic sector
  - Determine the neutrino mass hierarchy
- ❑ **SPINE** → **S**calable **P**article **I**maging with **N**eural **E**mbeddings
  - ML-native, end-to-end LArTPC reconstruction with sparse CNNs + GNNs on 3D space points.
  - segmentation → clustering → vertex → PID
  - Trained on generator-agnostic samples (MPV-MPR):
    - MPV (Multi-Particle Vertex) — particles from a common vertex (beam-like)
    - MPR (Multi-Particle Rain) — particles scattered across the volume (cosmic-like)
    - Realistic, overlapping topologies for robust training

ProtoDUNEs

CERN hosts two large-scale prototypes of the DUNE Far Detector, implementing the Horizontal Drift (SP - left) and Vertical Drift (VD - right) designs, the technologies of FD modules 1 and 2. ProtoDUNE-SP took beam and cosmic data in 2018, and ProtoDUNE-VD collected beam and cosmic data in 2025.

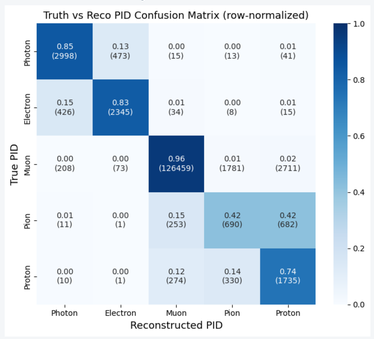
CERN neutrino platform (protodune – SP TPC)



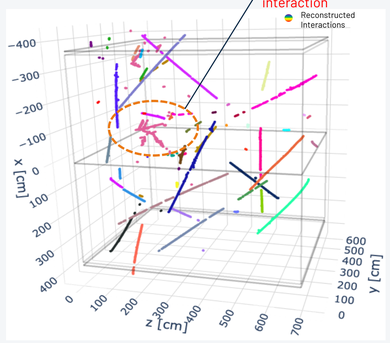


Single Phase (SP)

ProtoDUNE-SP training simulation

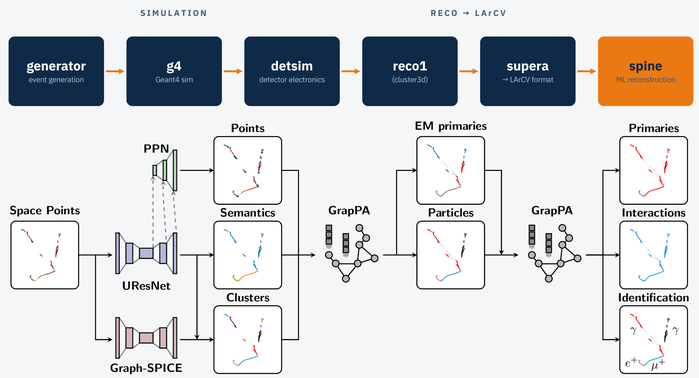


ProtoDUNE-SP beam data



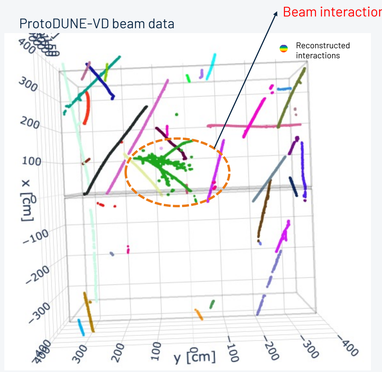
- π/p: Pions and protons mis-reconstructed as each other frequently
- Hadron PID limited by short tracks and missing Bragg / end-point information → key target for improvement

End-to-end reconstruction chain

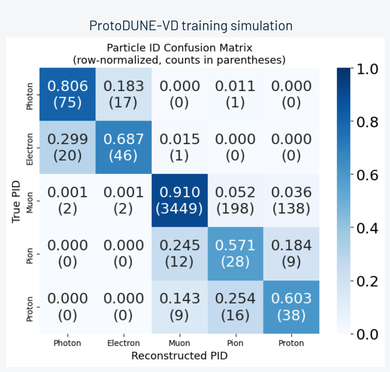


Vertical Drift (VD)

ProtoDUNE-VD beam data



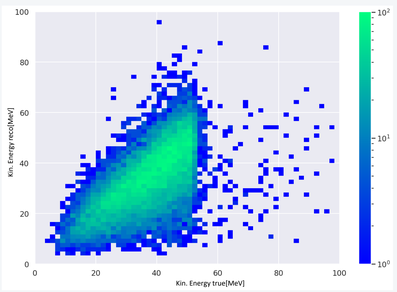
ProtoDUNE-VD training simulation



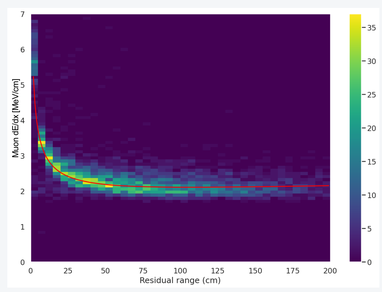
- μ/π/p: shared MIP dE/dx, separable only at track ends → confused when ends are short or missing
- e/γ: identical showers, split only by start dE/dx (~1 vs. 2 MIP) → confused at small conversion gaps

ProtoDUNE-VD Cosmic Simulation

Michel Identification

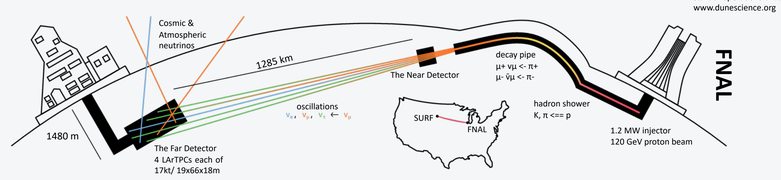


Muon dE/dx



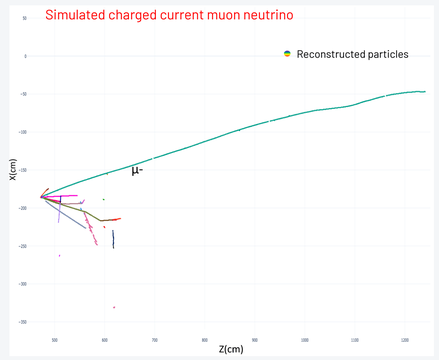
Muon dE/dx vs. residual range follows the expected Bragg curve → validated calorimetry
Michel e⁻: reco vs. true Kinetic Energy (KE), correlated to the 52.8 MeV endpoint → expected low-energy reconstruction

DUNE Far Detector



- Four 17-kt LArTPC modules (~70 kt total)
- ~1.5 km underground at SURF, 1300 km downstream of the Fermilab beam
- Far detector (FD) still under construction → all studies on full simulation
- SPINE trained on simulated MPV-MPR samples, **FD-HD sub-volume geometry**
- Towards robust reconstruction at full FD scale
- Dedicated FD-VD training underway

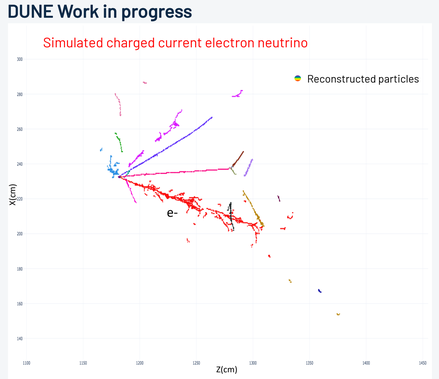
DUNE Work in Progress



FD observables

- UResNet (semantics) → track / shower separation
- PPN (key points) → vertex & end-point resolution
- GrapPA (GNN) → PID purity & efficiency; ν-interaction topology; selection efficiency
- kinematics (calorimetry) → energy resolution & linearity

DUNE Work in progress



Conclusions

- First end-to-end SPINE reconstruction implemented across DUNE detectors
- High-quality event reconstruction in dense topologies
- Standard observables reconstructed reliably → Michel-e⁻ tagging and muon dE/dx (Bragg curve) validate the charge/energy calibration
- PID requires improvement across both ProtoDUNE configurations
- ProtoDUNE performance to be improved with dedicated custom event-generator training and better space-point tagging
- Next: direct benchmarking vs standard reconstruction, domain adaptation, and full FD-scale deployment

Ref:
[1] F. Drielsma et al., NeurIPS 34 (2021) [arXiv:2102.01033]
[2] L. Dominé, K. Terao, PRD **102**, 012005 (2020)
[3] L. Dominé et al., PRD **104**, 032004 (2021)
[4] F. Drielsma et al., PRD **104**, 072004 (2021)
[5] Dune Collaboration: arxiv:2002.03005

SPINE GitHub repository