Deep learning based reconstruction for DUNE

QML for $0\nu\beta\beta$

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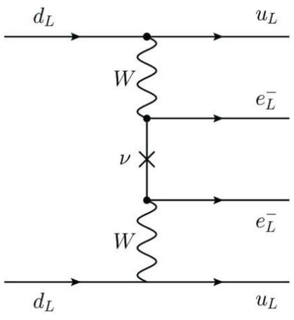


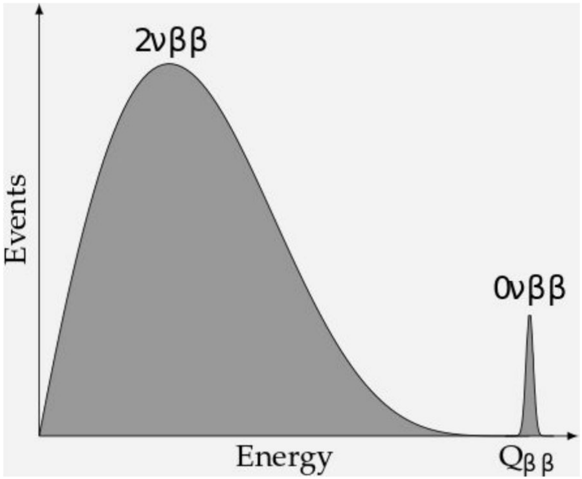
Feynman diagram

The 0νββ decay of ^{136}Xe isotope

Hypothetical BSM decay process: $(A, Z) \to (A, Z+2) + 2e^- + \cancel{2\bar{\nu}_e}$

Consequences:

- Neutrino and anti-neutrino coincide (Majorana fermions)
- Lepton number violation
- High Q-value, above natural radiation energies: $Q_{\beta\beta}$ = 2.458 MeV



Energy spectrum

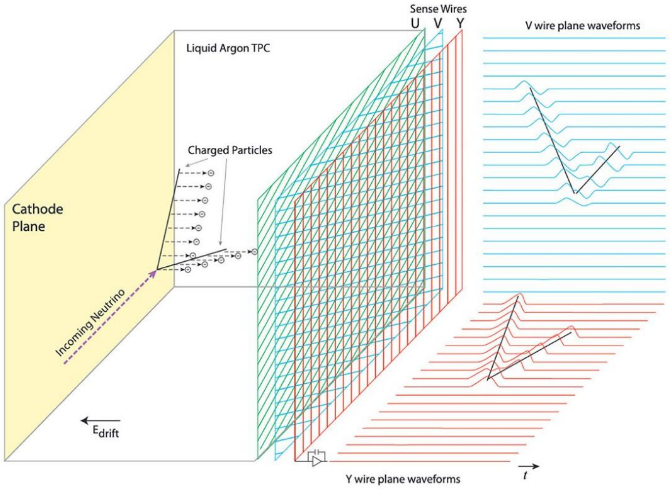
0νββ searches at DUNE experiment

DUNE main goals:

- CP violation in the neutrino sector
- Neutrino mass hierarchy
- Supernova neutrino bursts
- Proton decay

Far Detectors (FD): four 10 ktons fiducial mass LArTPCs

A 10kt FD module doped at **~2% ^{136}Xe** could allow for 0νββ search

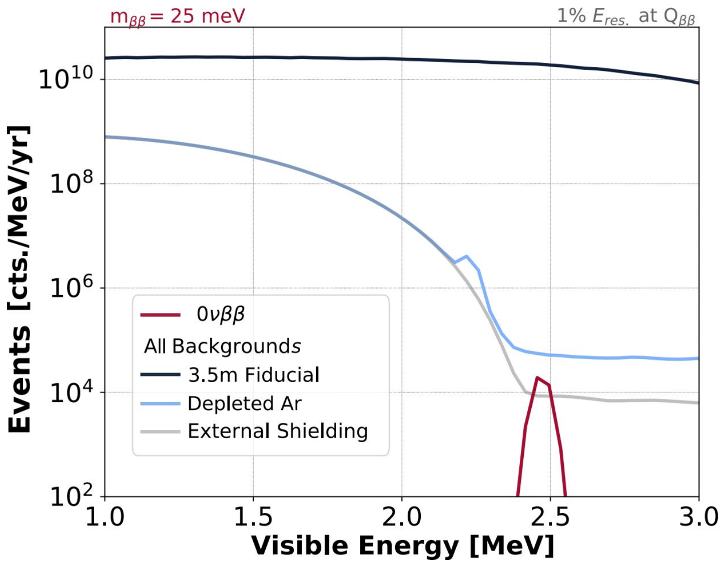


source

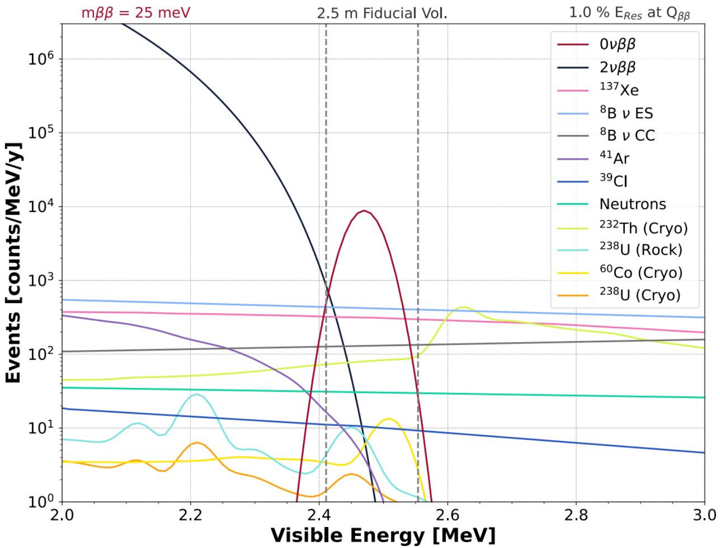
Background sources - Mitigation strategies

- Environmental radioactivity → VOLUME FIDUCIALIZATION
- Neutrons from (α, n) reactions → PASSIVE SHIELDING
- **Single β emission with Q_β~2.5 MeV in $^{42}Ar \rightarrow {}^{42}K \rightarrow {}^{42}Ca$ → USE OF DEPLETED ARGON**
- Solar neutrinos (CC and ES interactions) → PHOTON COINCIDENCE TAG
- Cosmogenically-activated radioisotopes (^{41}Ar, ^{137}Xe, ^{39}Cl ...) → COINCIDENCE MUON TIMING VETO
- ^{136}Xe 2νvββ → IRREDUCIBLE BACKGROUND

Mitigation strategies impact



Signal and Background spectra after mitigation



0νββ vs ^{42}Ar single-β Classification

IN FACT DEPLETED ^{42}Ar CANNOT BE PRODUCED IN HIGH QUANTITIES

NEED OF DIFFERENT STRATEGY → MACHINE LEARNING

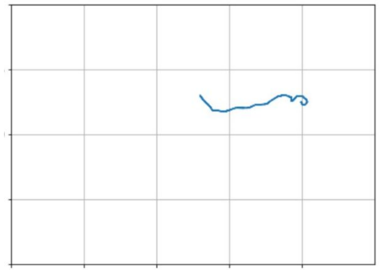
Generate Toy dataset:

- Geant4 simulated high resolution β and ββ tracks at Q=2.458 MeV (11k and 10k events respectively)
- DUNE resolution: 3D track voxelization with 5x5x1 mm^3 bins.
- No detector effects taken into account

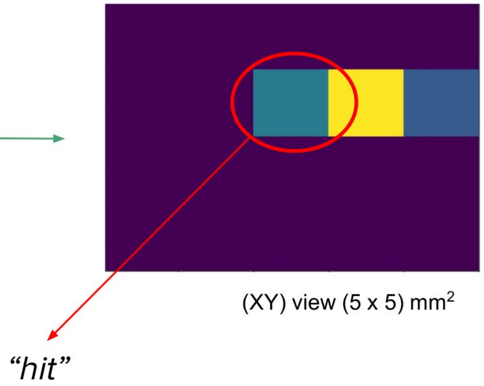
Issues:

- Low energy resolution: ~1 MeV
- Short tracks ~1.2 cm
- Too few pixels for pattern recognition

Geant4 track



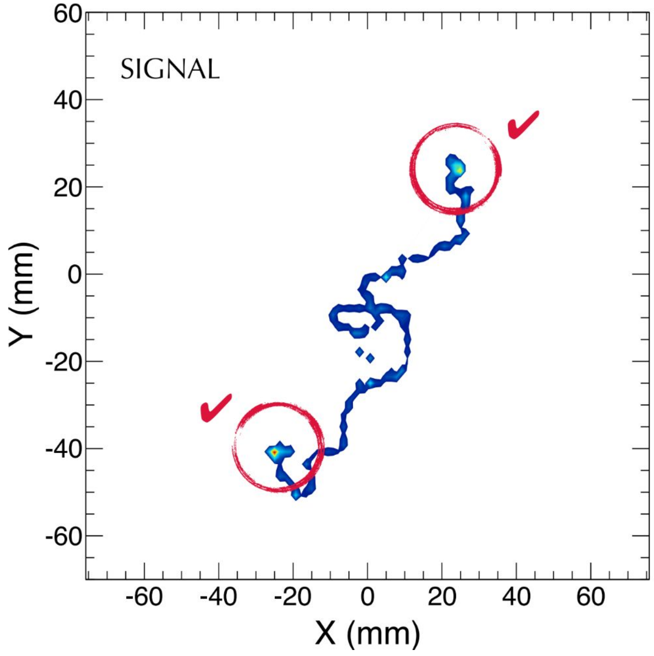
Voxelized projection

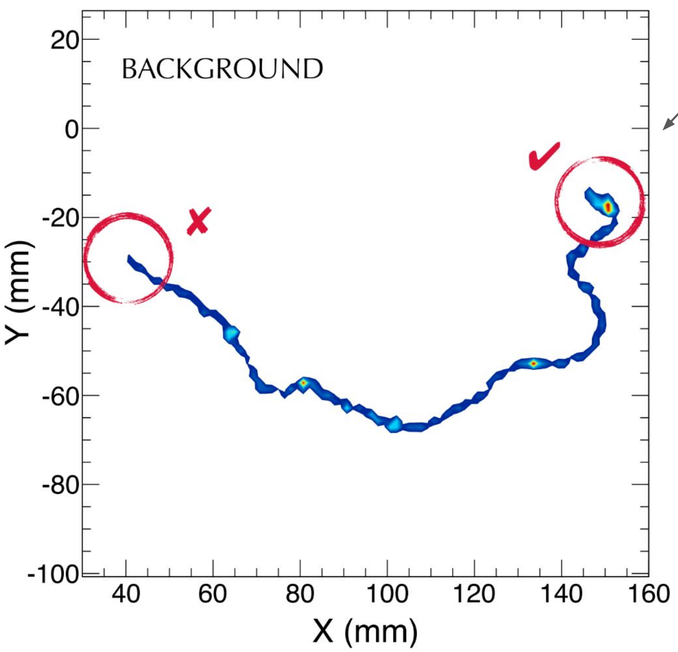


(XY) view (5 x 5) mm^2

Signal vs background

Single β:
Only one blob of energy deposition at track end

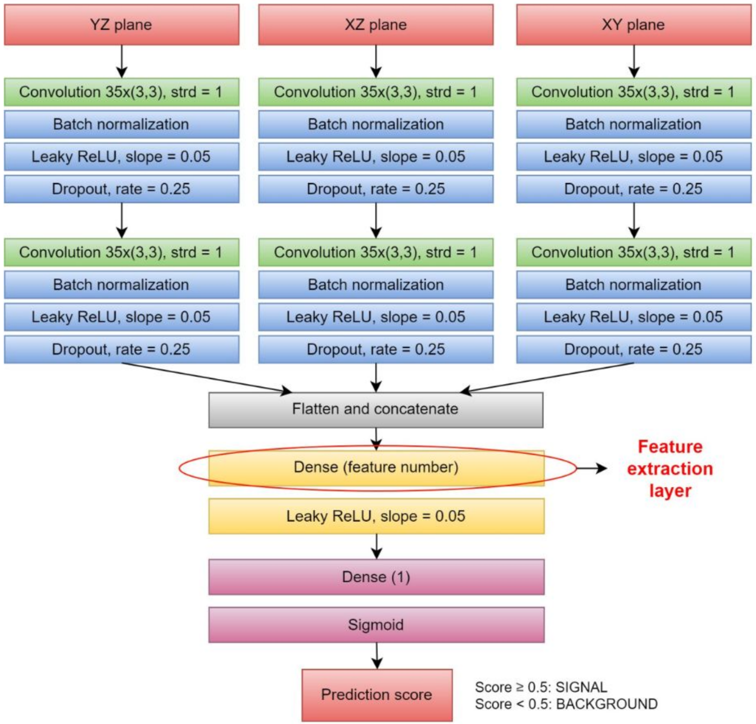




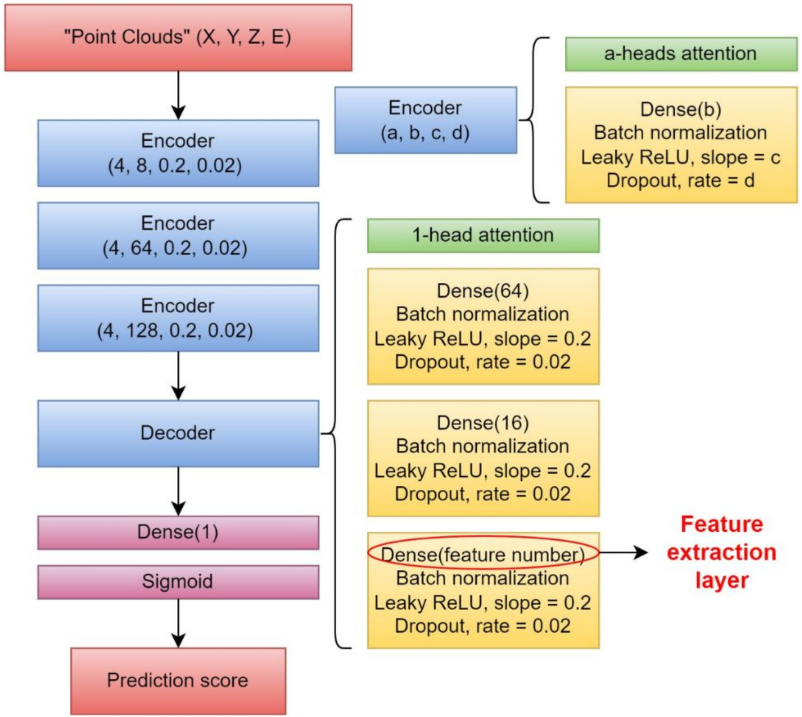
0νββ:
Two blobs of energy deposition at both ends

Feature Extractors

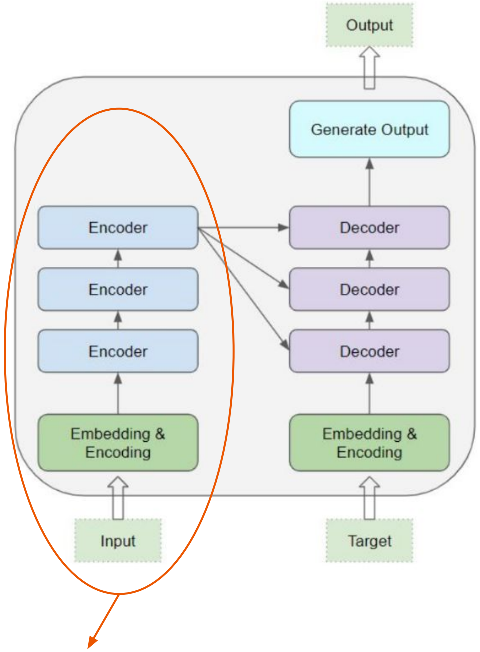
CNN

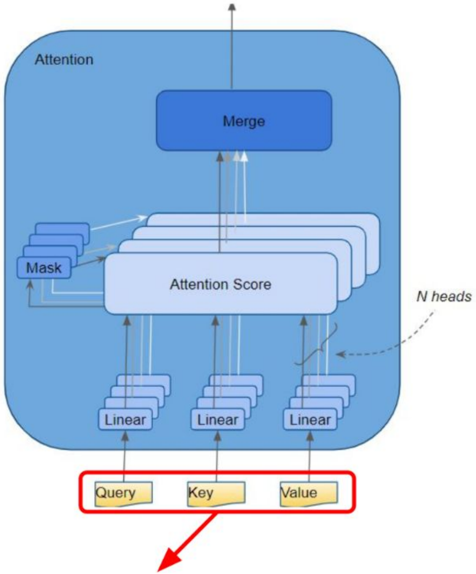


ATN



Transformer Block



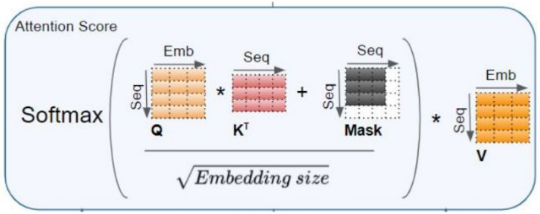


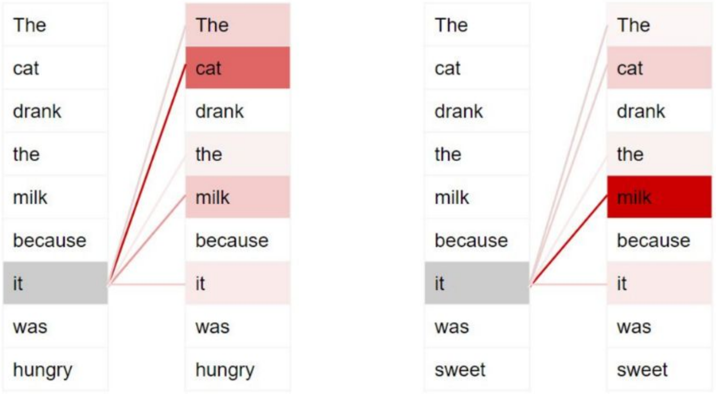
Transformer Encoder

Trainable weights

Attention Mechanism

$\mathbb{R}^{qxh} \mapsto \mathbb{R}^{qxh'}$ (self)





Evaluation - Resolution study

Consideration for ProtoDUNE geometry

- DUNE wire pitch is 5 mm on x, y axis and 1 mm on z axis
- DUNE energy sensitivity is ~0.1 MeV per voxel
- 0νββ events activate very few hits: classification accuracy is poor ~68% with CNN

What if we could build a more efficient detector?

- Increase spatial resolution to 1 mm on all axes
- Increase energy sensitivity: up to 10x factor

Evaluation - Resolution study

Spatial resolution correlates more than energy resolution

Low resolution (1mm ≤ pitch ≤ 5 mm):

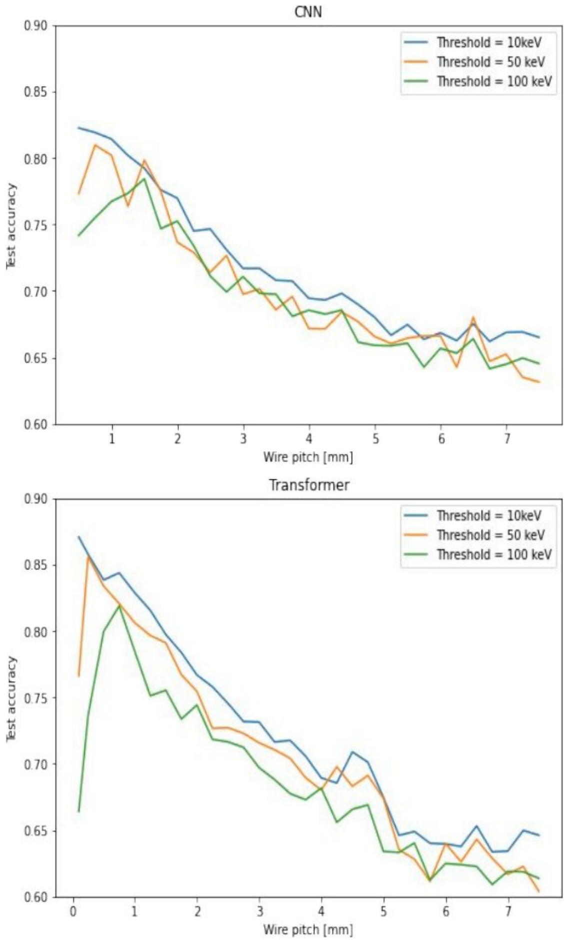
- less voxels
- few active hits

CNN performs better.

High resolution (pitch ≲1mm):

- more voxels
- more active hits
- accuracy drops for low energy resolution:
  energy threshold too high to activate the smaller voxels

ATN is **more efficient** and reaches higher accuracy



Thank you !

Questions?

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