Deep Neural Networks for Energy and Position Reconstruction in EXO-200

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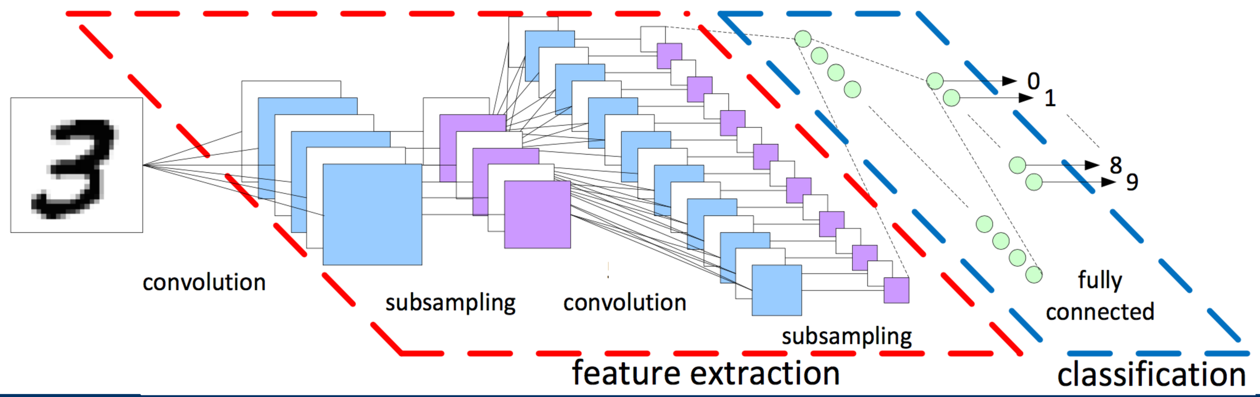
Neutrinoless Double Beta Decay

- $0\nu\beta\beta$ decay is a hypothetical decay forbidden in the Standard Model where a nucleus undergoes a double beta decay w/o emitting neutrinos
- Only possible in few nuclei, e.g. ^{76}Ge, ^{116}Cd, ^{130}Te, ^{136}Xe
- Theoretical implications:
  - Neutrinos are Majorana particles $(\nu = \bar{\nu})$
  - Violation of Lepton number conservation

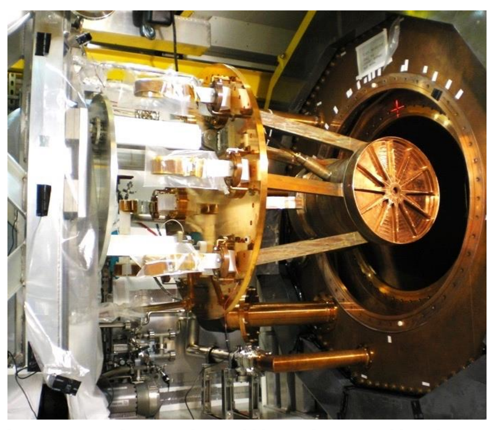
$$^{136}\mathrm{Xe} \xrightarrow{0\nu\beta\beta} {}^{136}\mathrm{Ba}^{++} + 2e^{-} + 2.457\,\mathrm{MeV}$$

Deep Learning

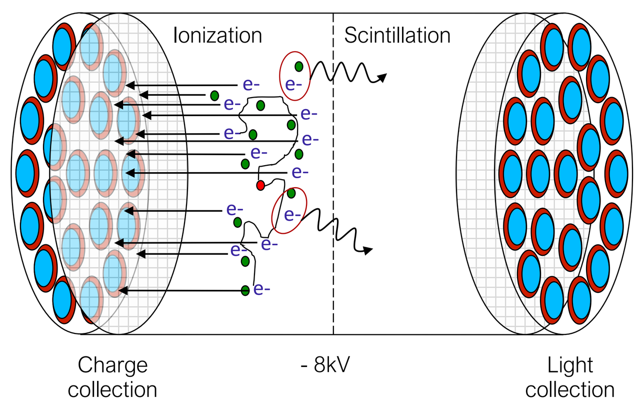
- Machine learning technique based on representation learning via multiple successive layers of units with an increasing level of abstraction and complexity
- Many architectures exist each with certain advantages
- Convolutional Neural Networks suited for image recognition by applying a convolution operation to the previous layer and a receptive field (feature map)
- Training by adjusting the unit weights
- Done by minimizing the discrepancy of network output and target value via backpropagation



EXO-200 Experiment [1]



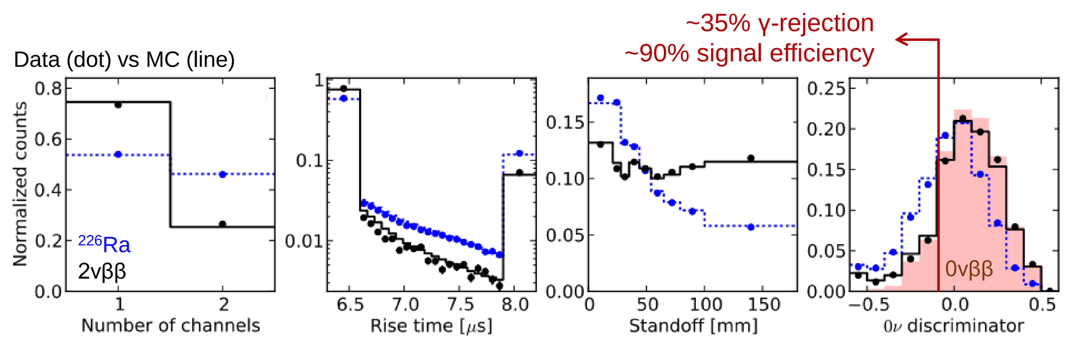
- Located in the Waste Isolation Pilot Plant (WIPP), Carlsbad, NM, US
- Detector is a double-sided single phase ultra-low-background time projection chamber
- 175 kg of liquid Xe enriched in ^{136}Xe (~80%)

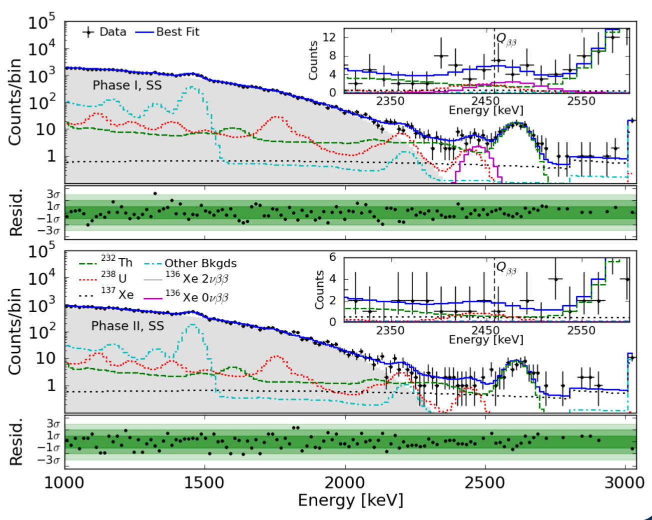


- Simultaneous detection of scintillation light (by APDs) and ionization charge (by crossed induction and collection wire grids)
- Complementary energy and full 3D position reconstruction
- Multi-parameter analysis

EXO-200 Recent Results (Phase I+II) [2]

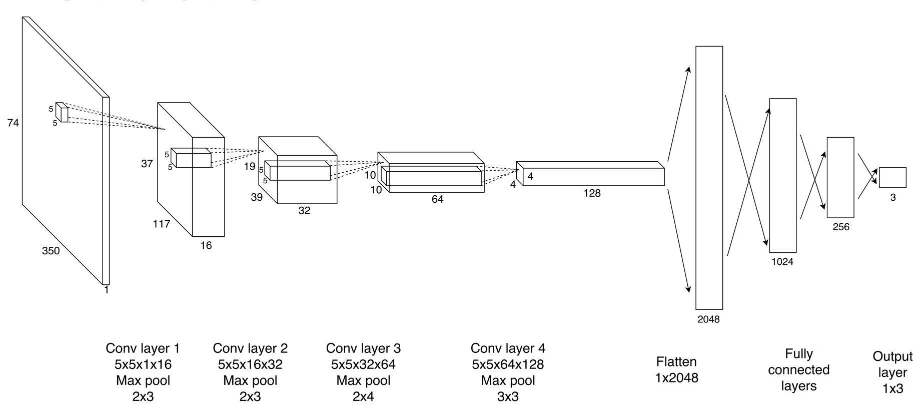
- Background model + data → maximum likelihood fit
- Fit in parallel Energy + SS/MS + BDT$_{SS}$ (15% improvement)
- Combine Phase I + Phase II profiles (total exposure: 177.6 kg yr)
- Sensitivity of $3.7 \cdot 10^{25}$ yr (90% CL)
- Limit: $T_{1/2}^{0\nu\beta\beta} > 1.8 \cdot 10^{25}$ yr (90% CL)



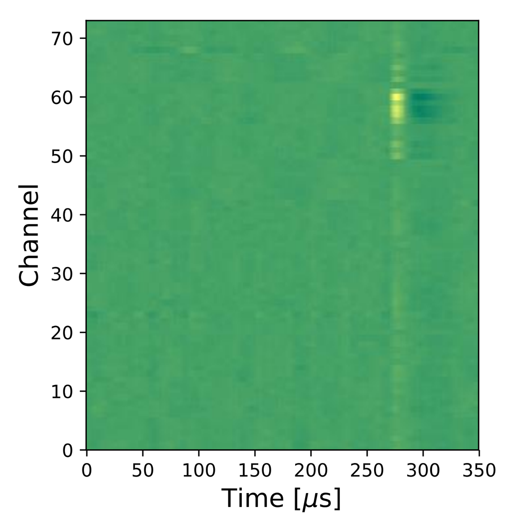


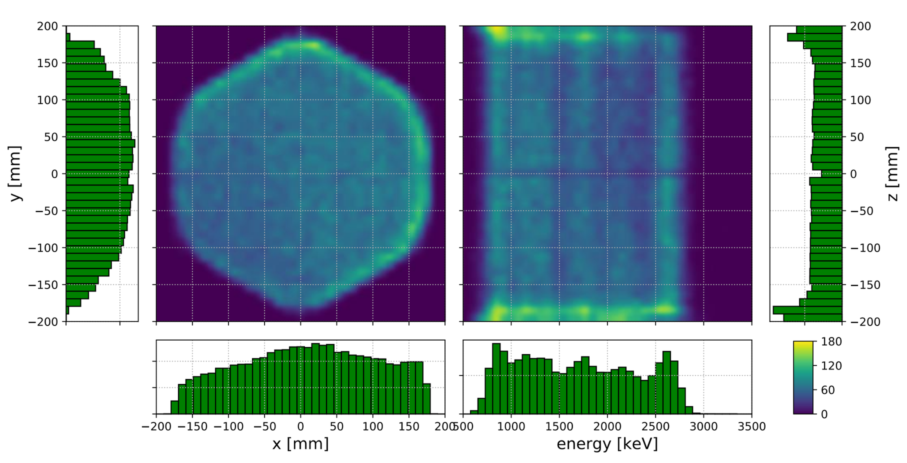
Data driven position reconstruction [3]

- Position reconstruction using raw light waveforms from recombination and excitation
- Approach solely based on data without reliance on a MC simulation



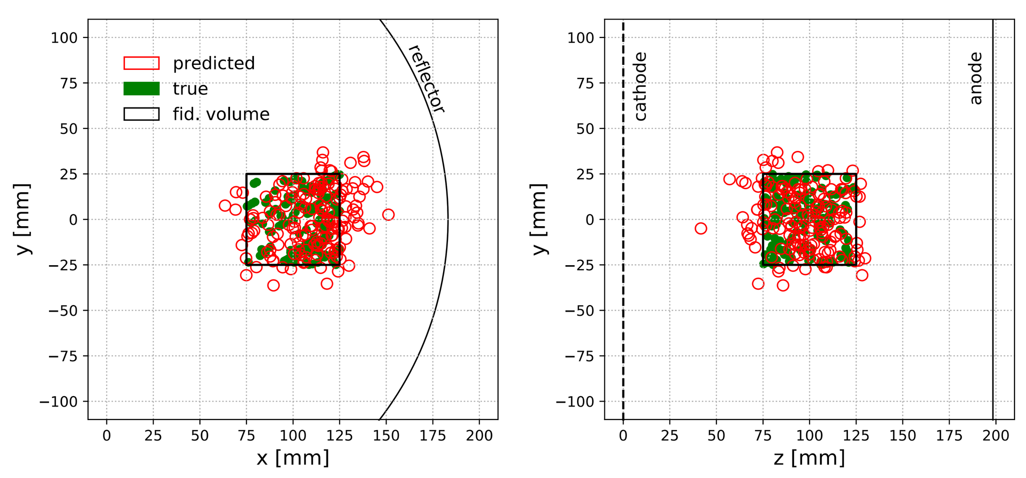
- Valuable for events with insufficient charge collection (i.e. near PTFE reflectors)
- Training on real data waveforms with single charge deposits in the detector against the position extracted from the ionization signal (X-Y) and timing difference of light and charge (Z)

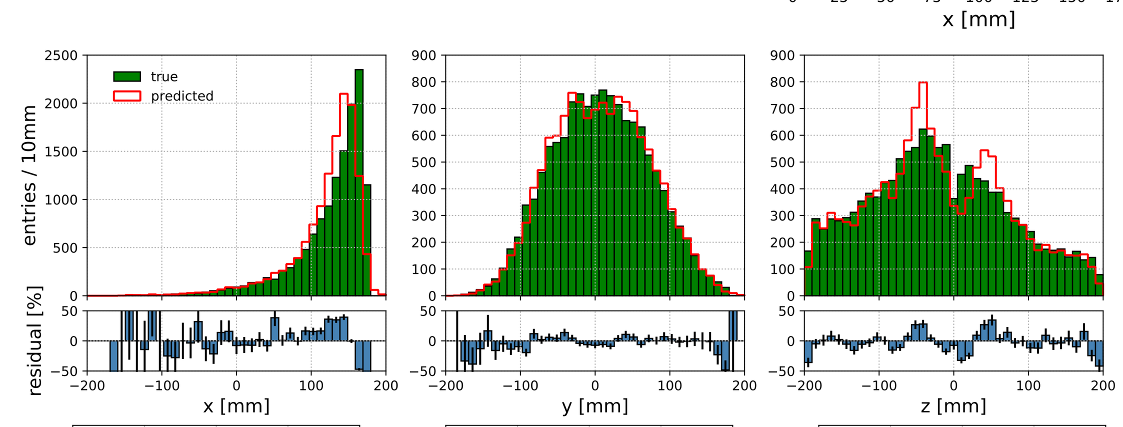


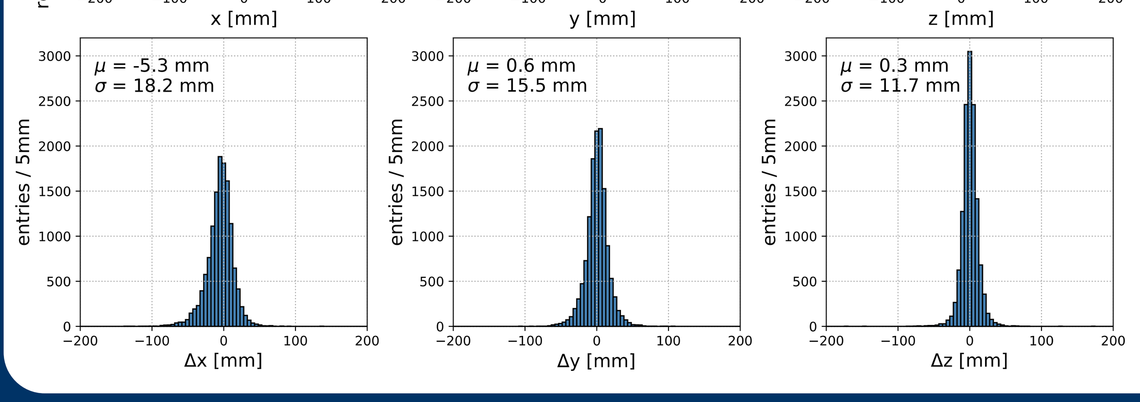


- Events from source calibration runs (^{228}Th, ^{226}Ra, ^{60}Co) at different source positions
- Event image is fed to deep convolutional neural network

- Produce uniform position and energy distribution of training events (70,000)
- Performance limit is charge position resolution (σ_{3D} = 3mm)



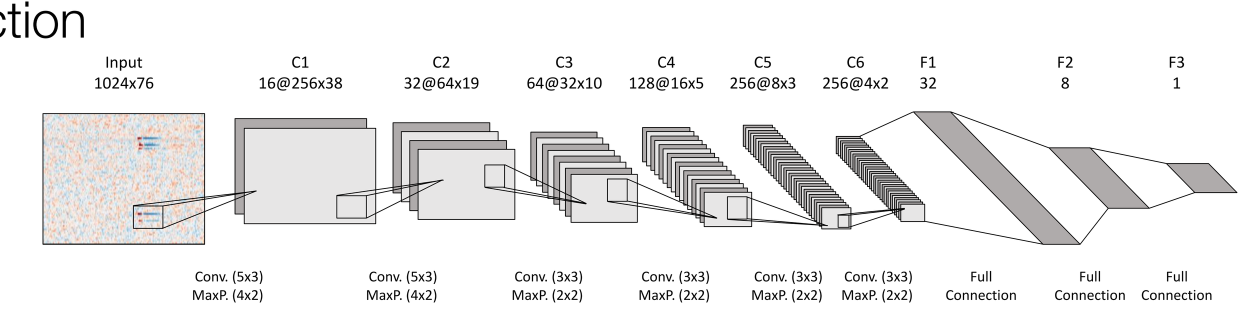


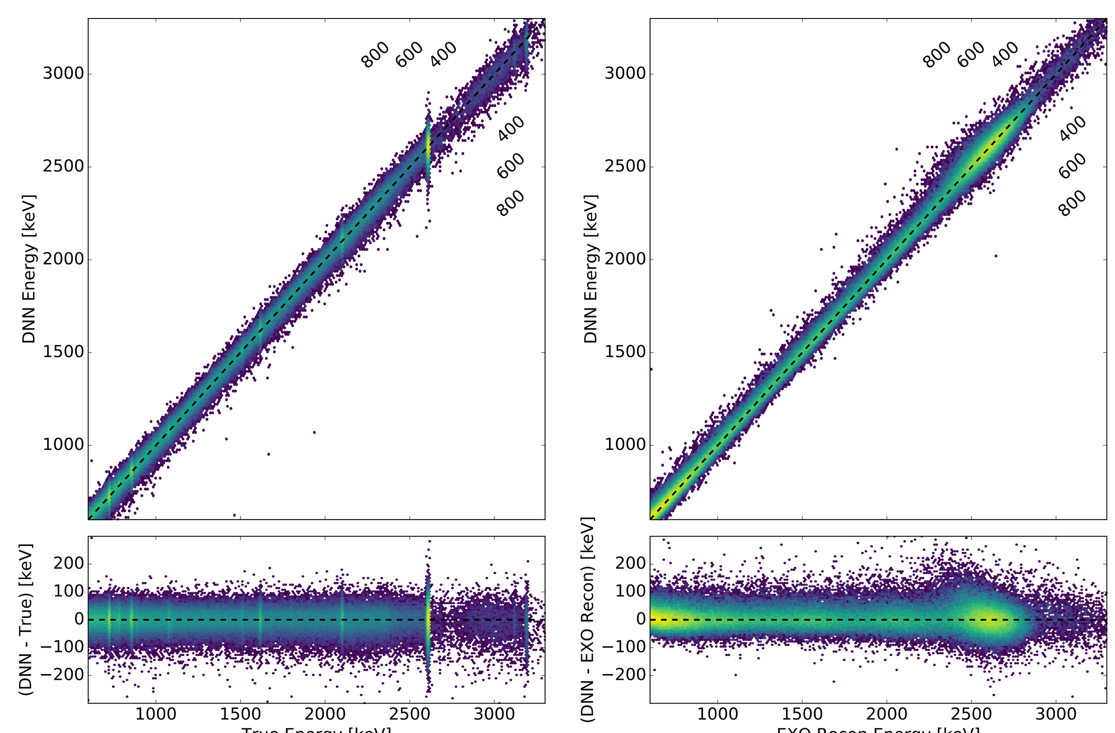


- Position resolution of light channel only (after 200 epochs): σ_{3D} = 24.5mm

Charge-only energy reconstruction [3]

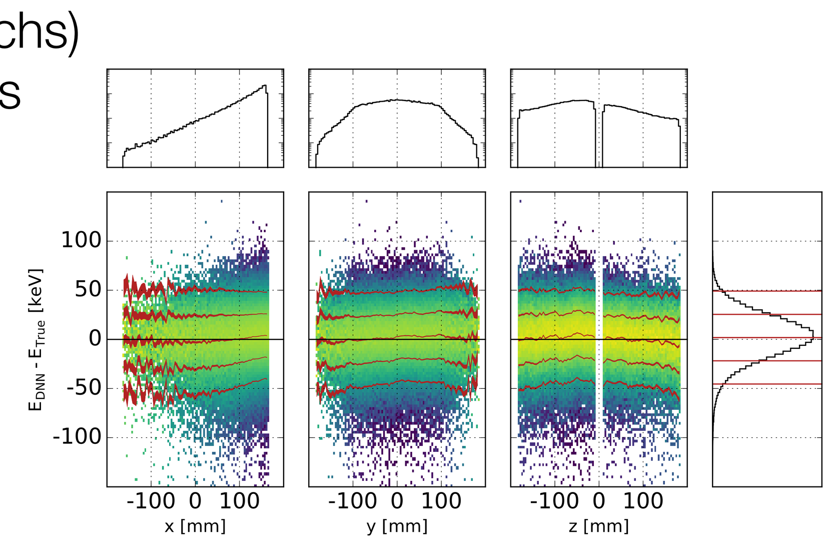
- Energy reconstruction using raw charge waveforms of all charge collection (U) wires



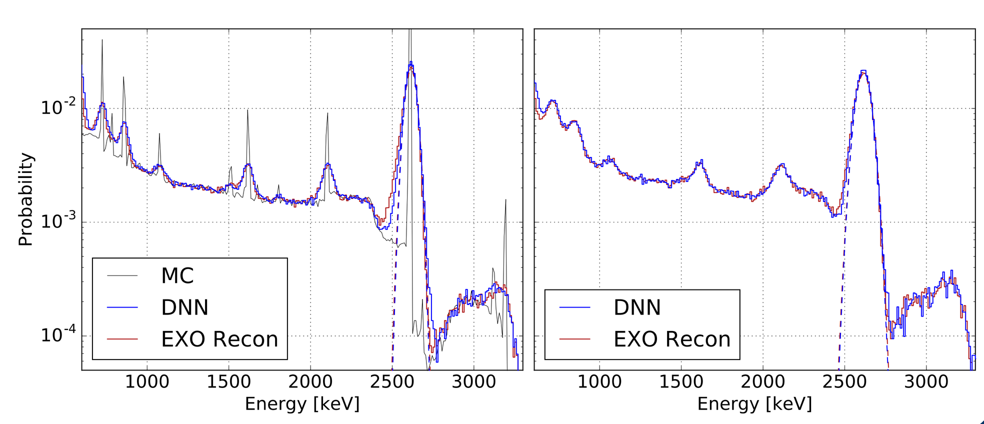


- Training on MC events (~750,000) with real noise including single and multiple scatters in the LXe against the total deposited energy that is distributed uniformly in energy
- Event image is fed to deep convolutional neural network

- Energy reconstruction (after 100 epochs) works w/o energy dependent features
- MC: Energy resolution (σ) at the ^{208}Tl full absorption peak (2615keV)
  DNN: 1.22% (Single Site: 0.94%)
  EXO-200 Recon: 1.29% (SS: 1.15%)
- No significant dependence on the event position



- Data (not MC): Energy resolution (σ) at the ^{208}Tl full absorption peak after combining with denoised light channel [4] from EXO-200 reconstruction
  DNN: 1.65% (SS: 1.50%)
  EXO-200 Recon:
  1.70% (SS: 1.61%)



References

[1] EXO-200 Collaboration, JINST 7 (2012), P05010
[2] EXO-200 Collaboration, Phys. Rev. Lett. 120 (2018), 072701
[3] EXO-200 Collaboration, arXiv:1804.09641
[4] EXO-200 Collaboration, JINST 11 (2016), P07015

Acknowledgements

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