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

CIPANP 2018 - Palm Springs - 05/29/18

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Double Beta Decay and the EXO-200 Experiment

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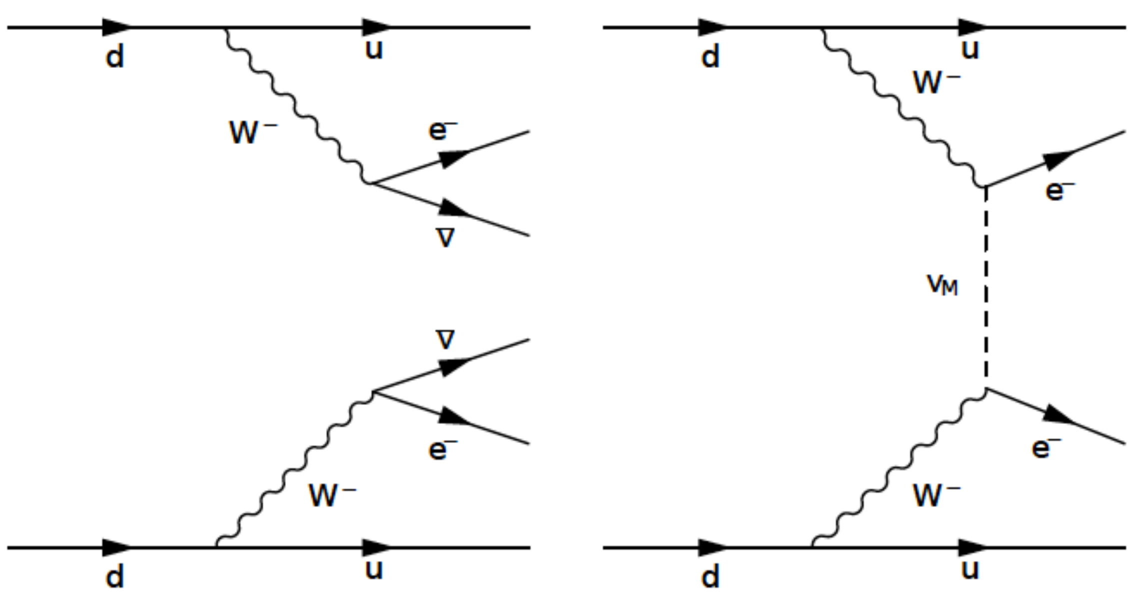
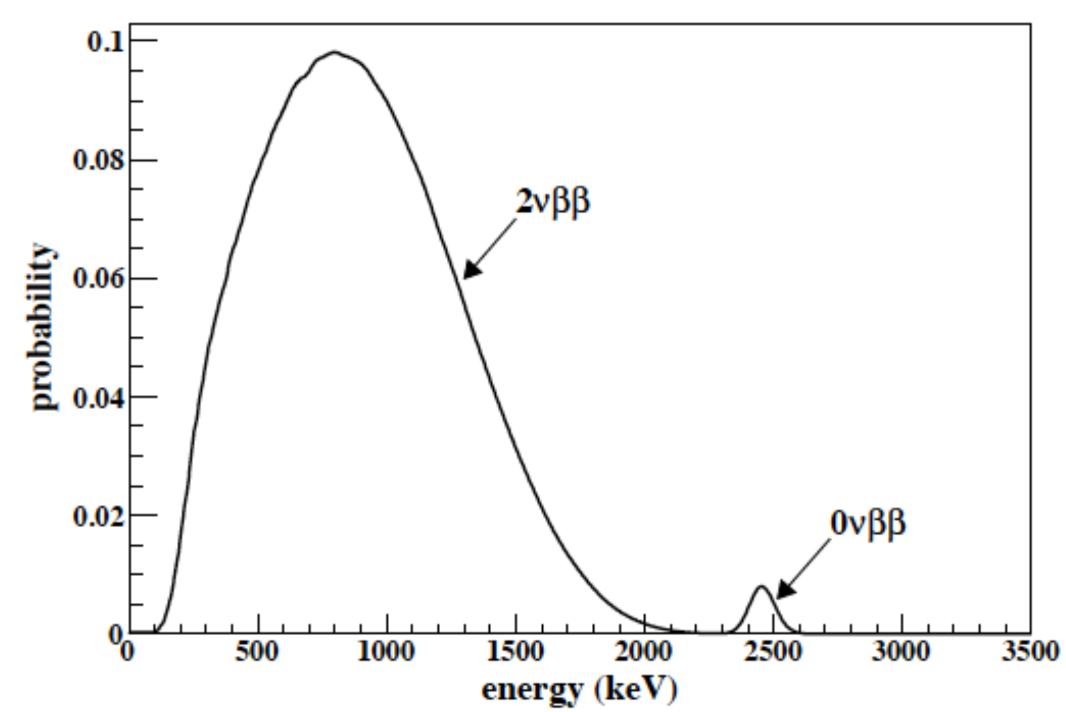
The EXO-200 experiment is designated for the search of double beta decay, in particular the neutrinoless mode



Two neutrino mode is a rare but allowed Standard Model process

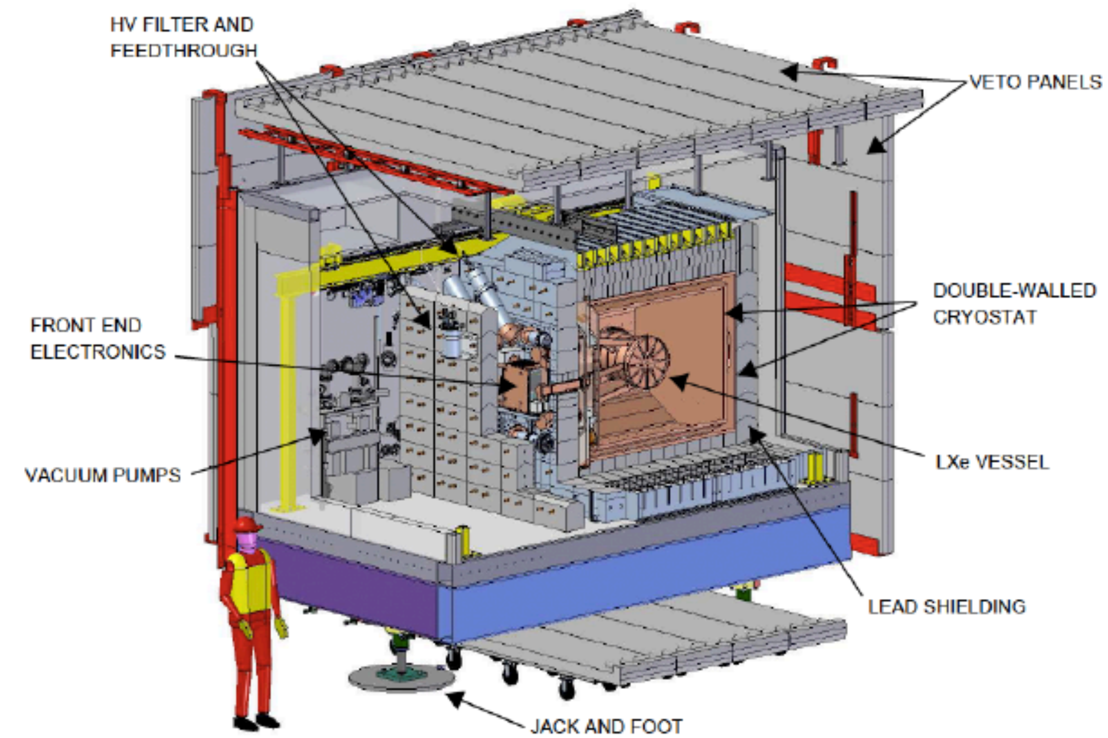
Neutrinoless mode can only happen if neutrinos are massive Majorana particles. The observation of this decay allows to determine absolute mass scale



Double Beta Decay and the EXO-200 Experiment

Located at the Waste Isolation Pilot Plant, Carlsbad NM

- 1585 m.w.e. overburden
- Muon rate at this depth measured to be ~$3 \cdot 10^{-7}$ $s^{-1}cm^{-2}sr^{-1}$
- Low levels of U/Th (compared to rock) and Rn

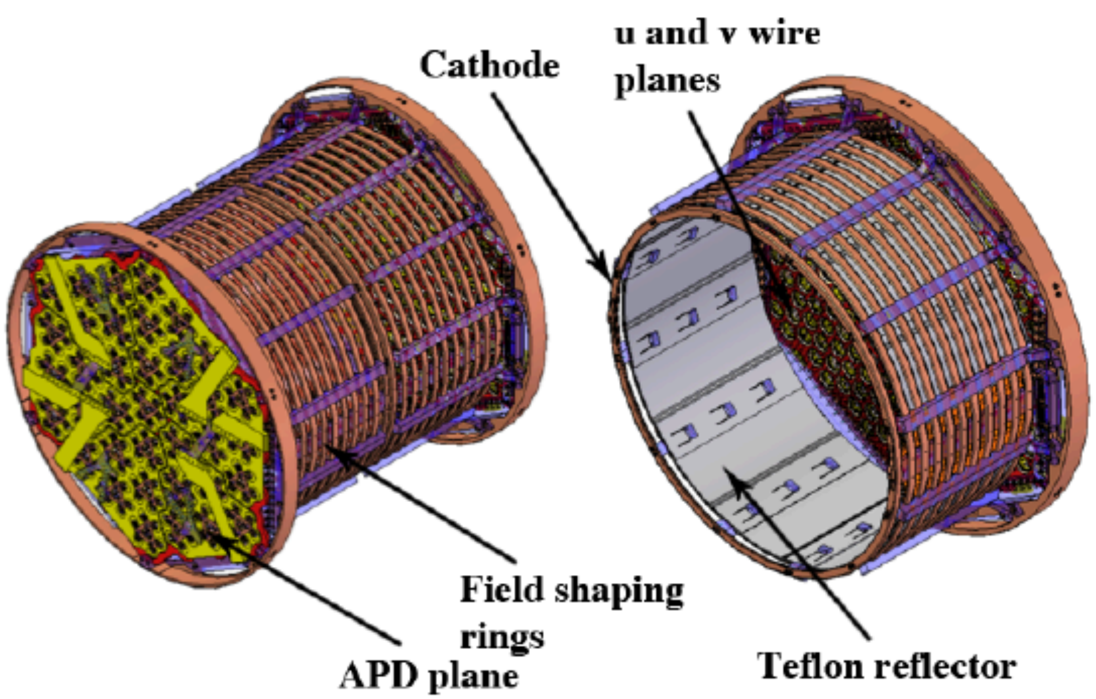


200 kg of Xenon enriched to 80.6% in Xe-136

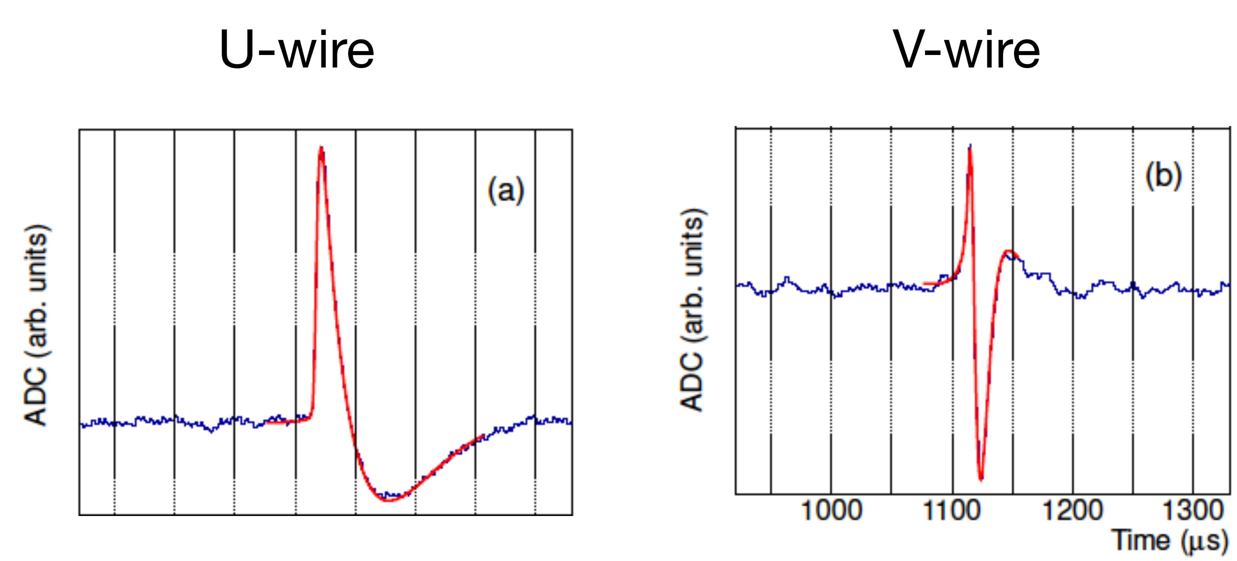
- High Q-value above most γ backgrounds
- Provides self shielding
- Currently using ~100 kg as fiducial volume

Time Projection Chamber inside Cu cryostat

- Split in two equal halves with common cathode
- U- and V-wires for charge collection and APDs for light collection
- All materials have been screen for radio-purity



Ionization and scintillation signals measured simultaneously



Most recent $2\nu\beta\beta$ and $0\nu\beta\beta$ measurements

Most recent $2\nu\beta\beta$ and $0\nu\beta\beta$ measurements

Data taking is split into 2 phases

Phase I: Sept 2011 - Feb 2014

Phase II: Jan 2016 - (2018)

- Electronics upgrade to lower APD noise
- Installation of de-radonator
- Increase drift field from 380 V/cm to 567 kV/cm

Analysis upgrades

Cosmogenics background reduction by 23% by introducing 19.1 min muon veto cut

Incorporation of transverse electron diffusion in simulation

Multivariate β - γ discriminator combining topological variables in a BDT

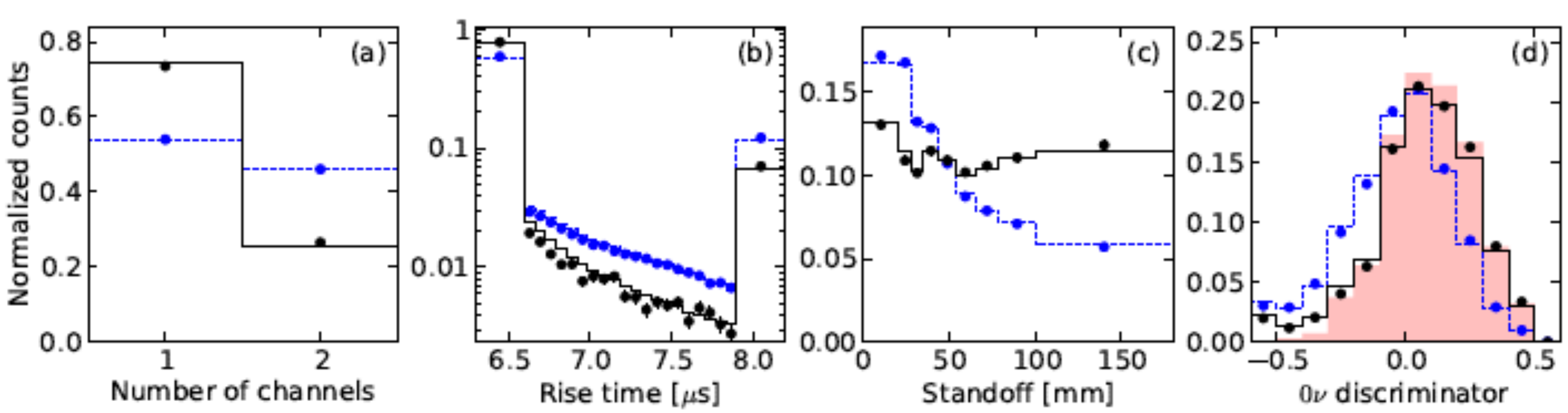
Combine Phase I and Phase II for a total exposure of 177.6 kg y

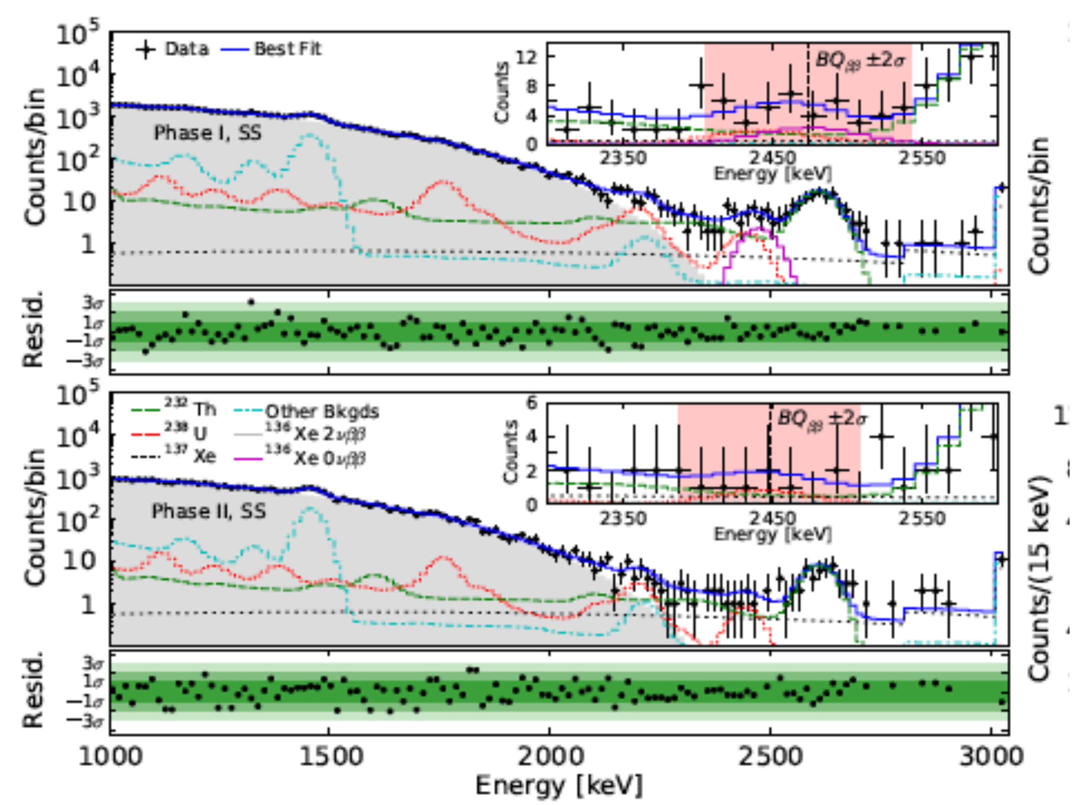
Simultaneous Maximum Likelihood fit in Energy_{SS} + Energy_{MS} + BDT_{SS}

No statistically significant $0\nu\beta\beta$ signal

$T_{1/2} > 1.8 \cdot 10^{25}$ yr ($\langle m_{\beta\beta}\rangle$ < (147- 398) mev)

Median sensitivity $3.7 \cdot 10^{25}$ yr (improved by 15% including the BDT variable)





EXO-200 status

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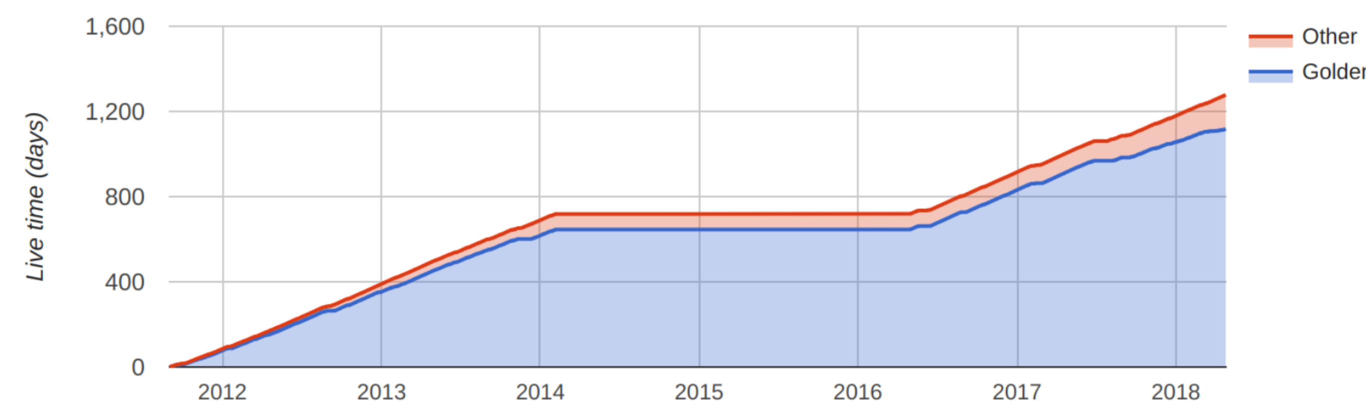
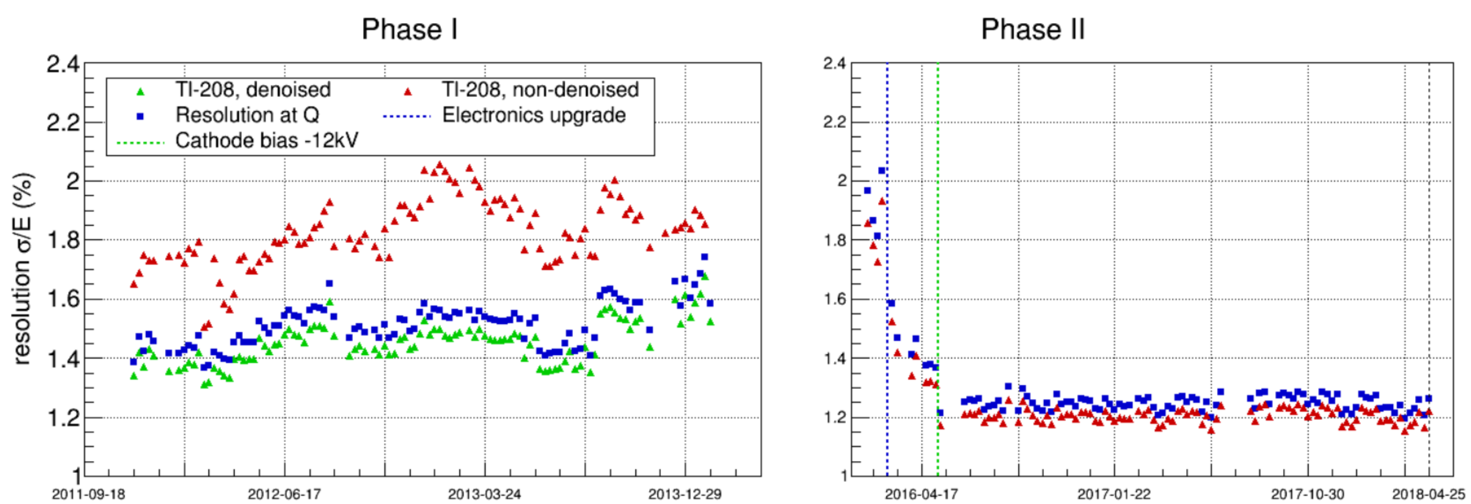
Data taking is ongoing

- We try to maximize up-time
- WIPP issues are mostly the limiting factor

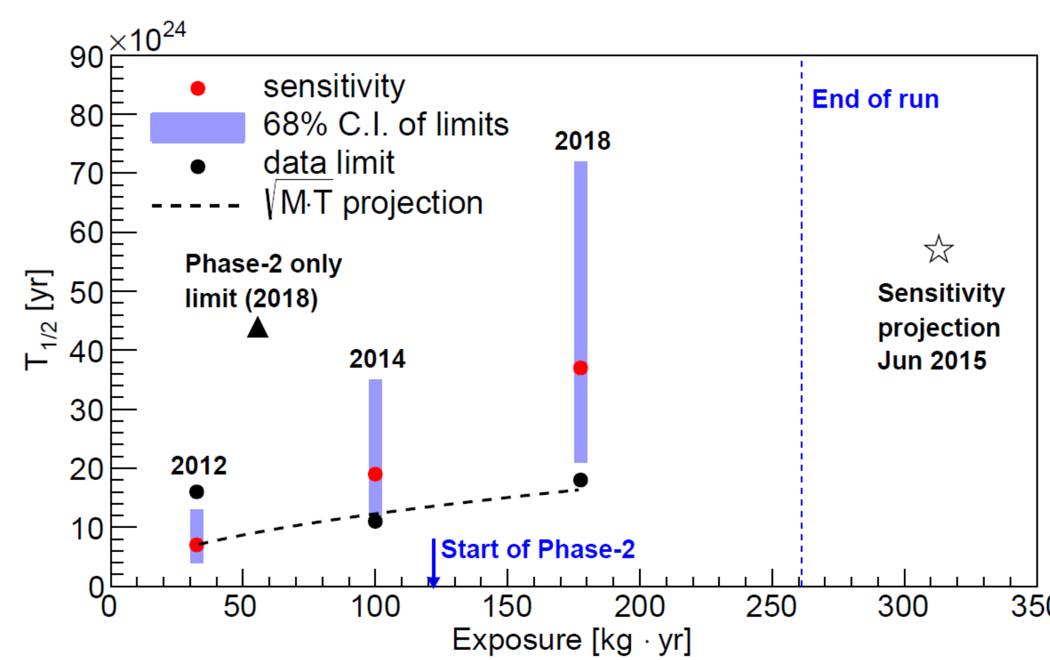




After electronics upgrade and increase in drift field, energy resolution is improved and stable

Projected sensitivity until the end of run

- Increases faster than simple sqrt(exposure) scaling due to analysis improvements
- Data limits are subject to background fluctuations
- End of run exposure smaller than originally projected due to less data taking

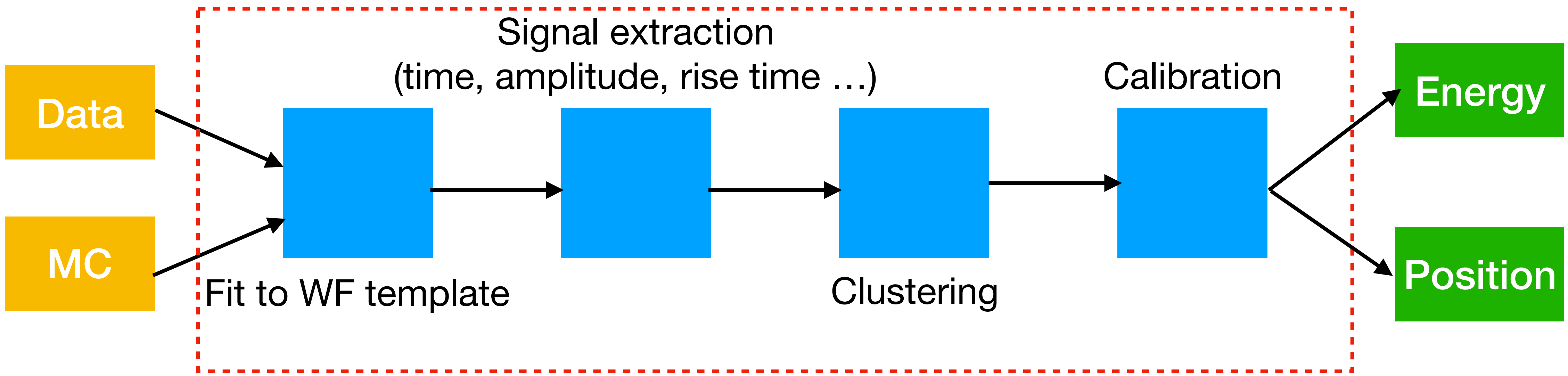


EXO-200 data analysis with deep neural networks

EXO-200 data analysis with deep neural networks

The use of deep learning has impacted many areas and yielded remarkable results and it has found it’s way into fundamental science including particle physics

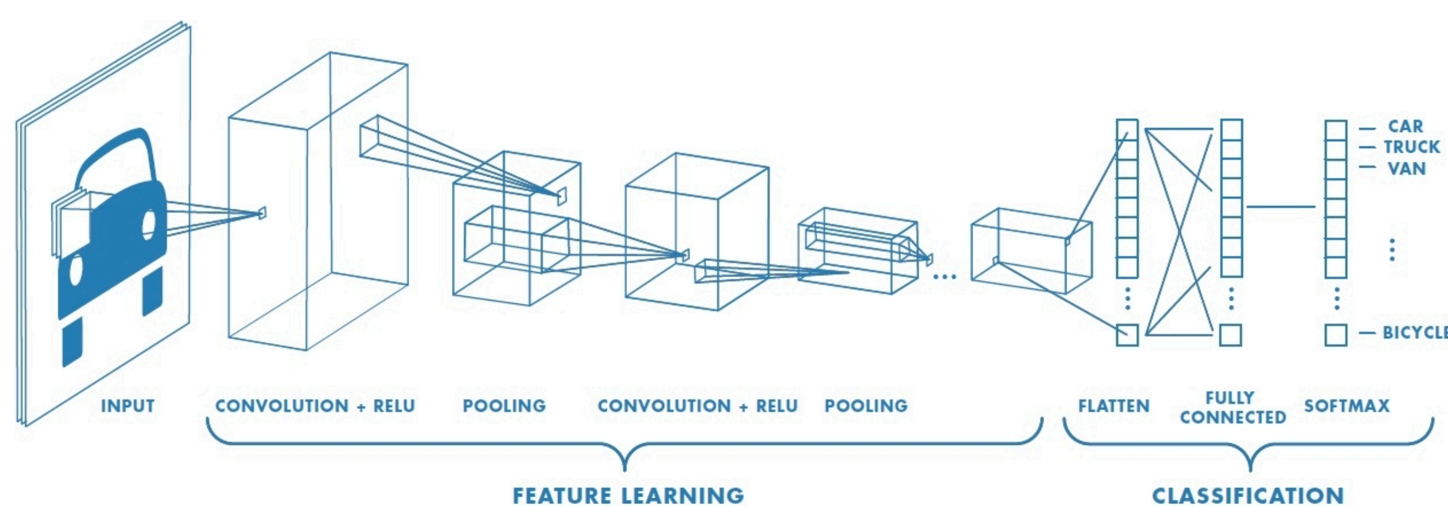
Main advantage over classical method: Usage of all available information in raw data without making any assumptions on how the signal should look like



Replace these modules by complex learnable model (neural network)

A neural network consists of many learnable parameters

Training done by minimizing discrepancy between truth information and predicted output by back propagation



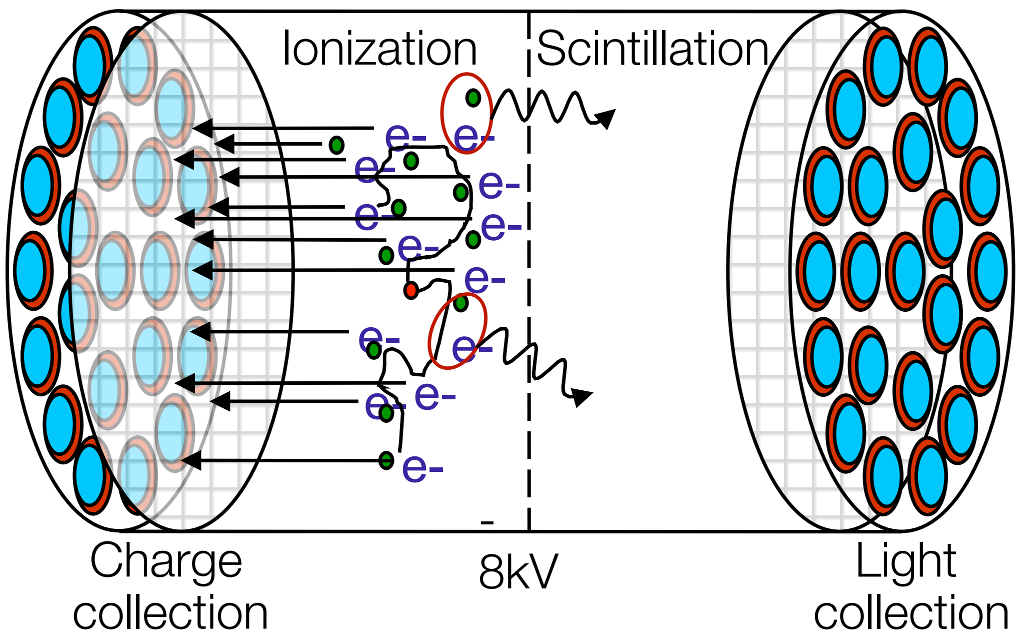
EXO-200 data analysis with deep neural networks

Charge-only energy reconstruction

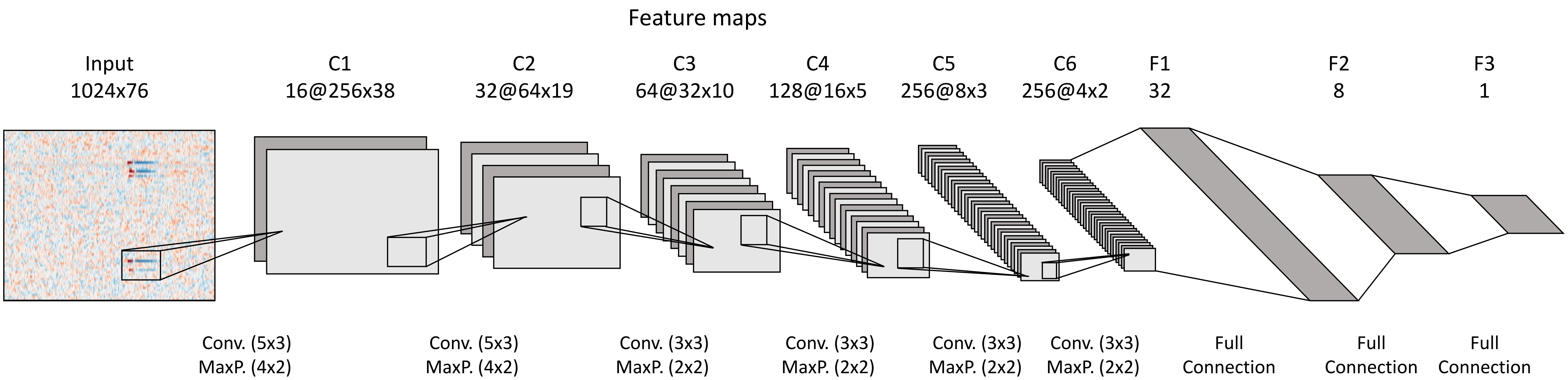
Energy reconstruction from raw charge waveforms of charge collection (U) wires

Training on Monte Carlo events

- 100 epochs with ~750,000 events
- Single and multiple scatters in LXe
- With real noise sampled from detector
- Uniform energy distribution



Event images are fed to deep convolutional neural network

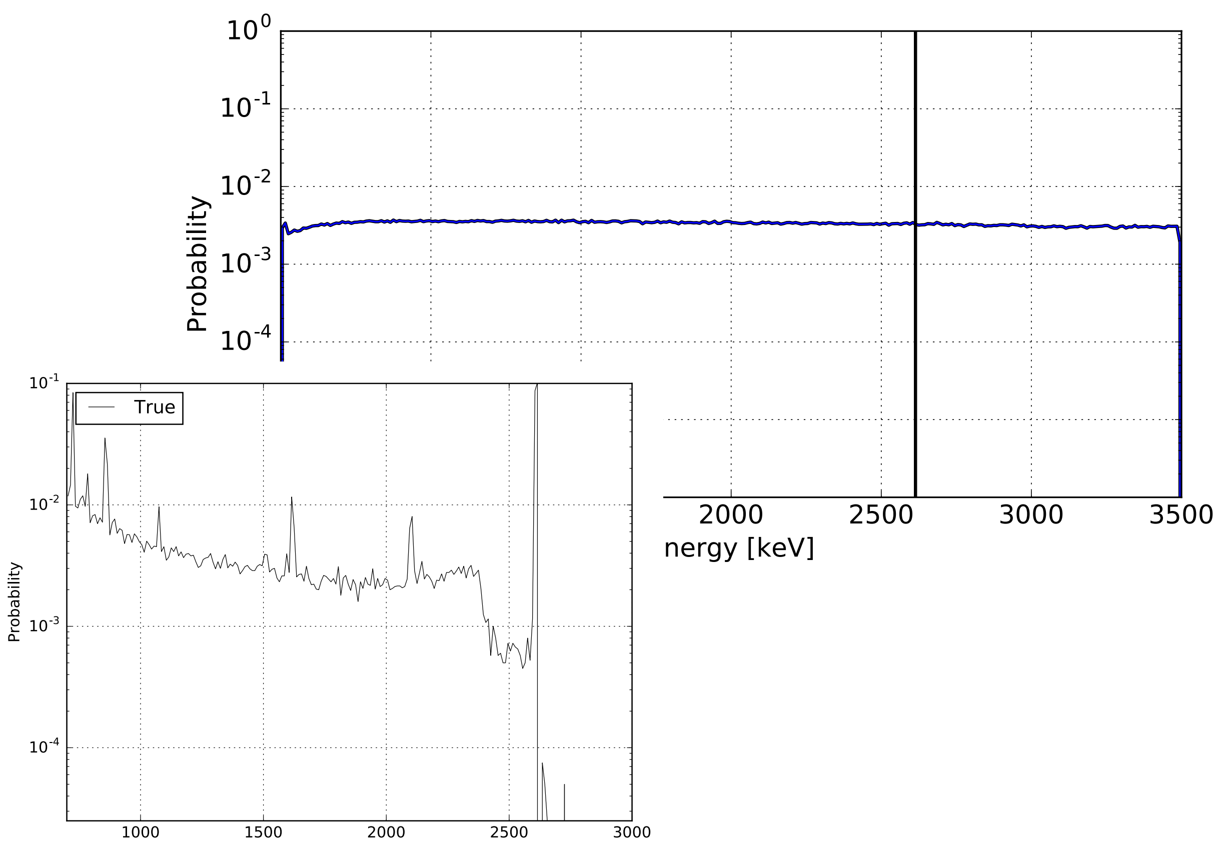


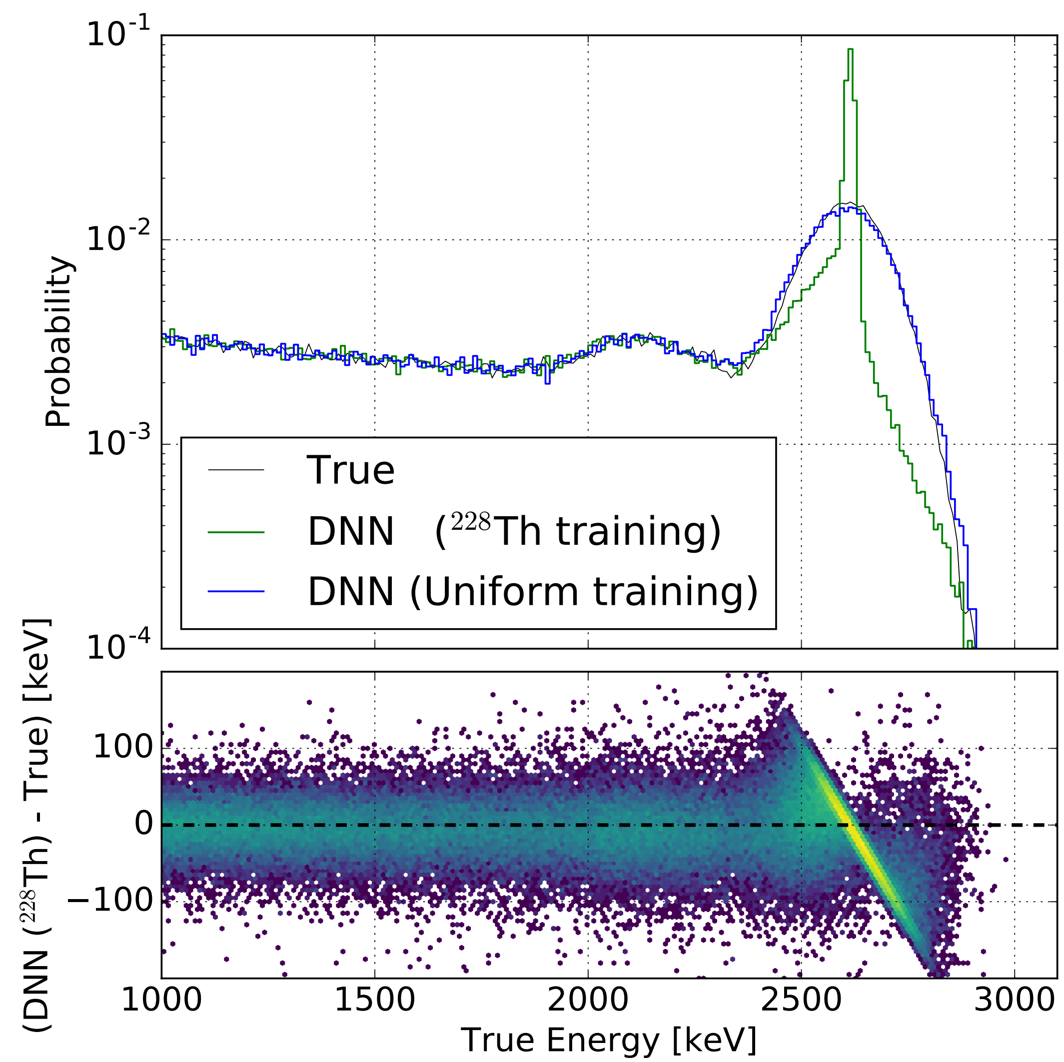
EXO-200 data analysis with deep neural networks

Charge-only energy reconstruction

The importance of training on uniform data distribution

- Uniform energy spectrum proved crucial for training
- Otherwise overtraining on sharp MC training peaks
- Shuffles independent validation events towards sharp peaks from training





EXO-200 data analysis with deep neural networks

Charge-only energy reconstruction

Reconstruction works over the energy range under study

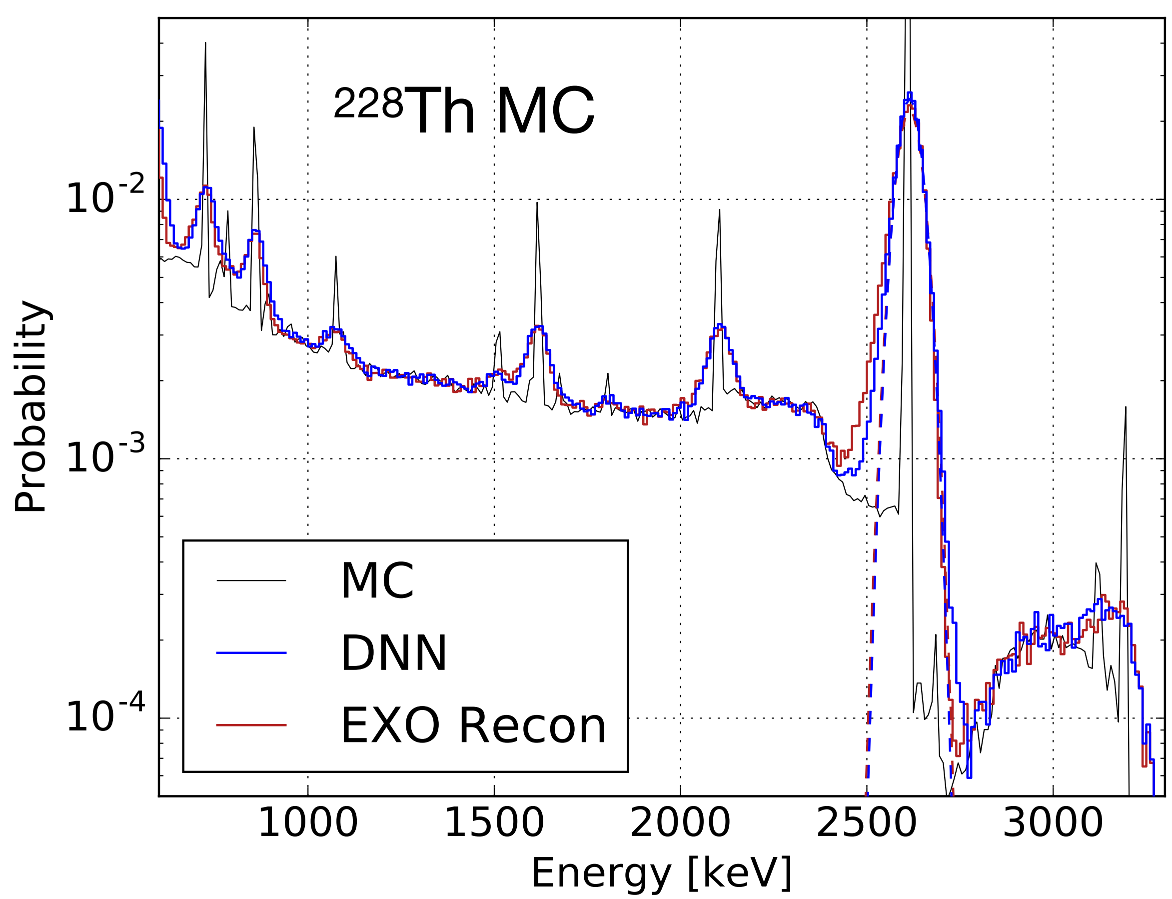
Residuals w/o energy dependent features

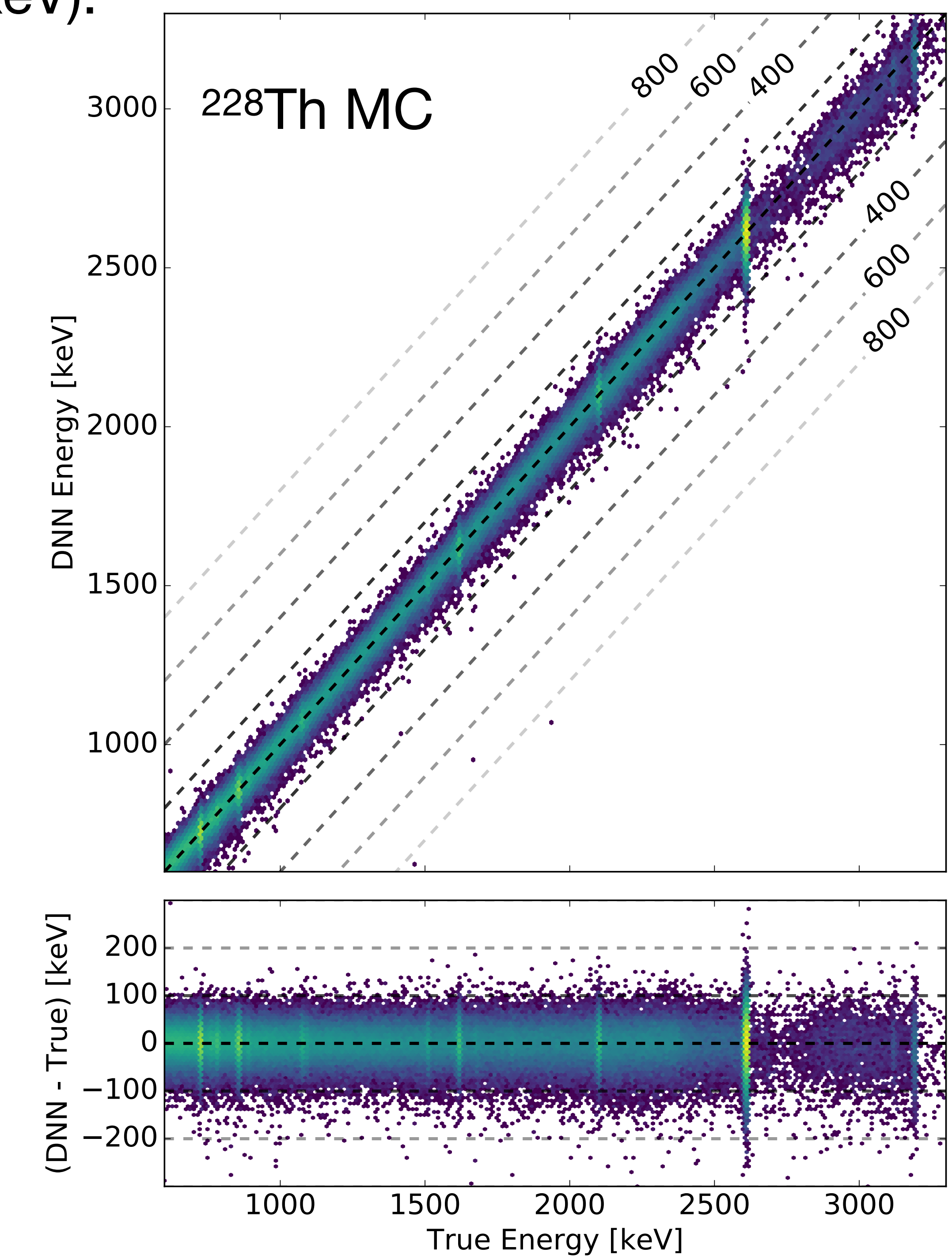
Resolution (σ) at the ^{208}Tl full absorption peak (2615 keV):

DNN: 1.22% (SS: 0.94%)

EXO-200 Recon: 1.29% (SS: 1.15%)

Network outperforms in disentangling mixed induction and collection signals (see valley before ^{208}Tl peak)





EXO-200 data analysis with deep neural networks

Charge-only energy reconstruction

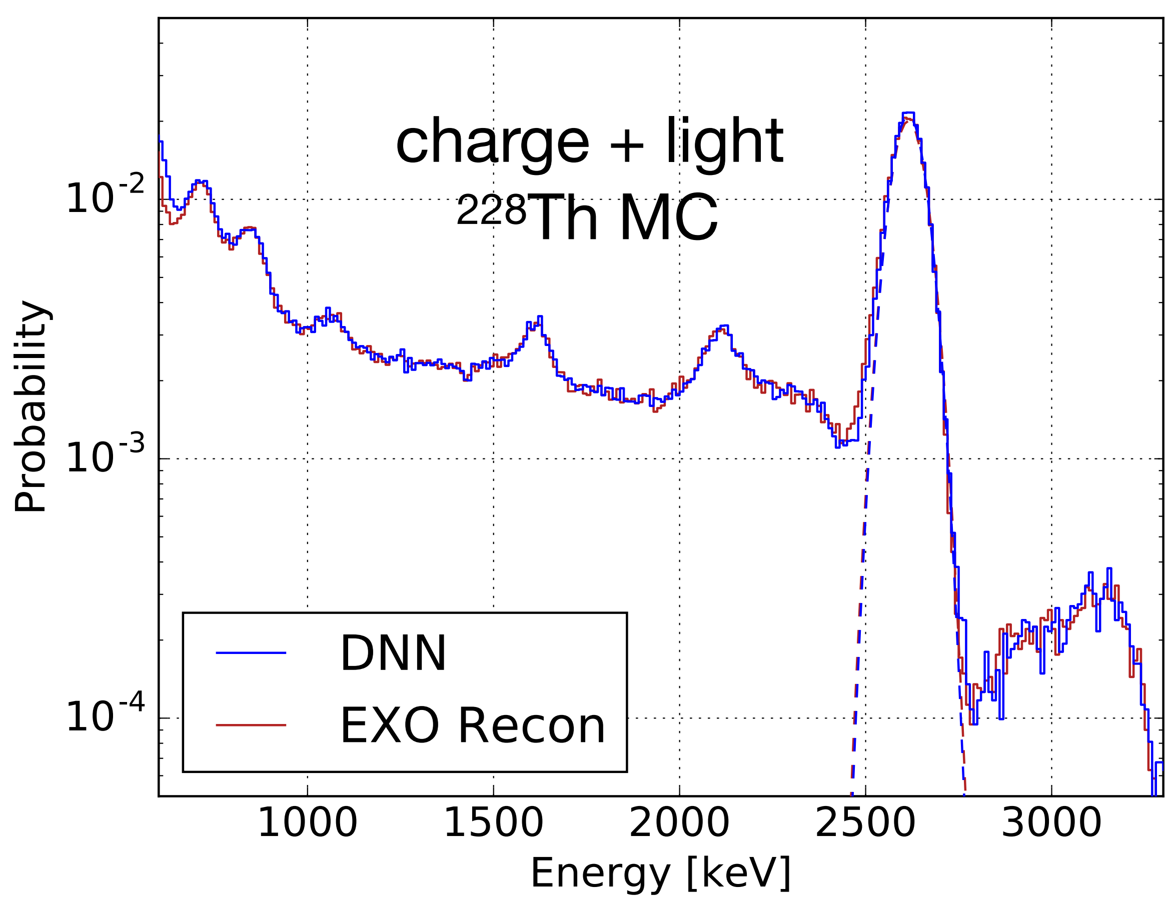
Works on real calibration events over the energy range under study

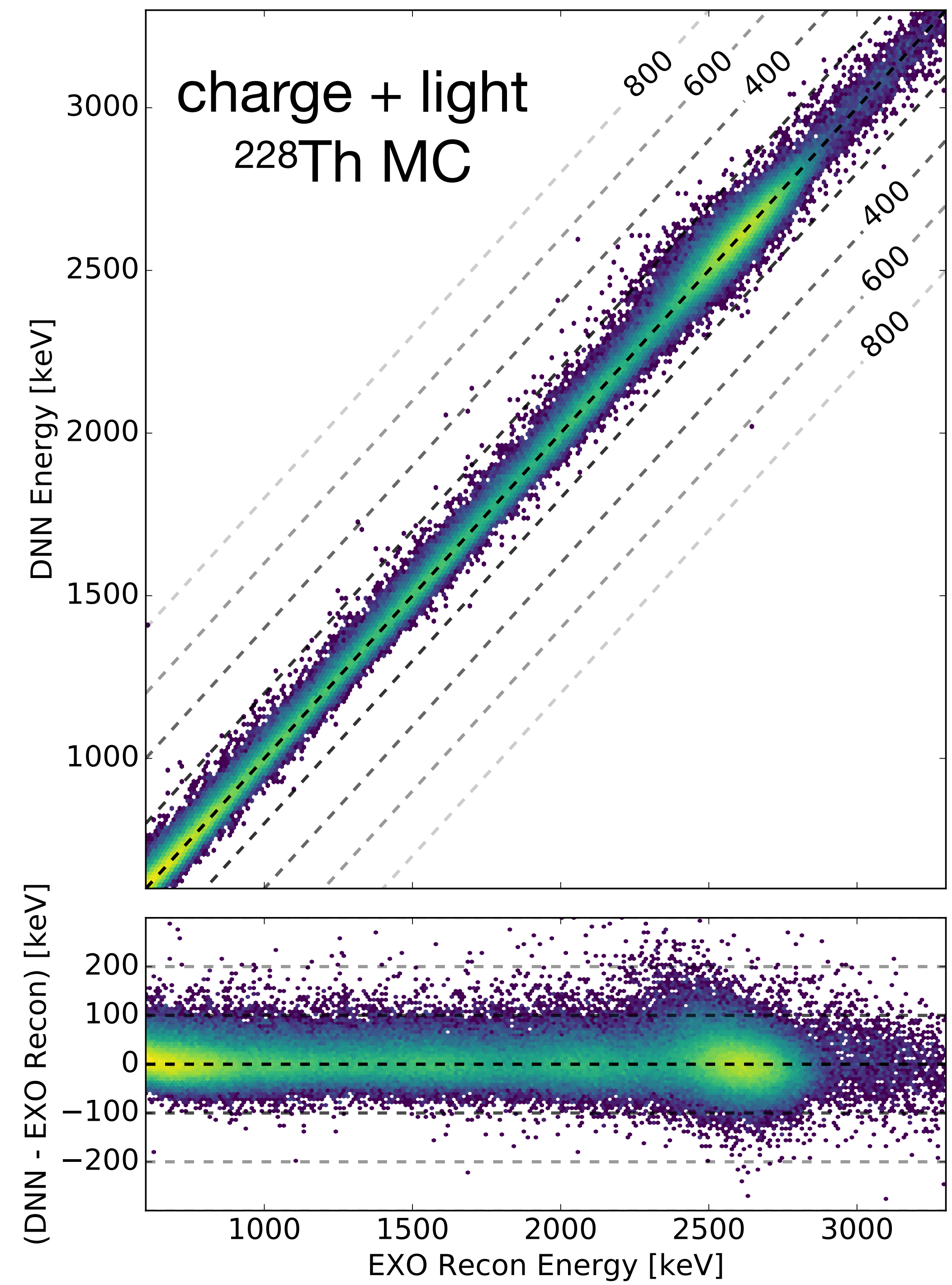
Residuals w/o energy dependent features

Resolution (σ) at the ^{208}Tl full absorption peak when combining with light channel from EXO-200 reconstruction:

DNN: 1.65% (SS: 1.50%)

EXO-200 Recon: 1.70% (SS: 1.61%)





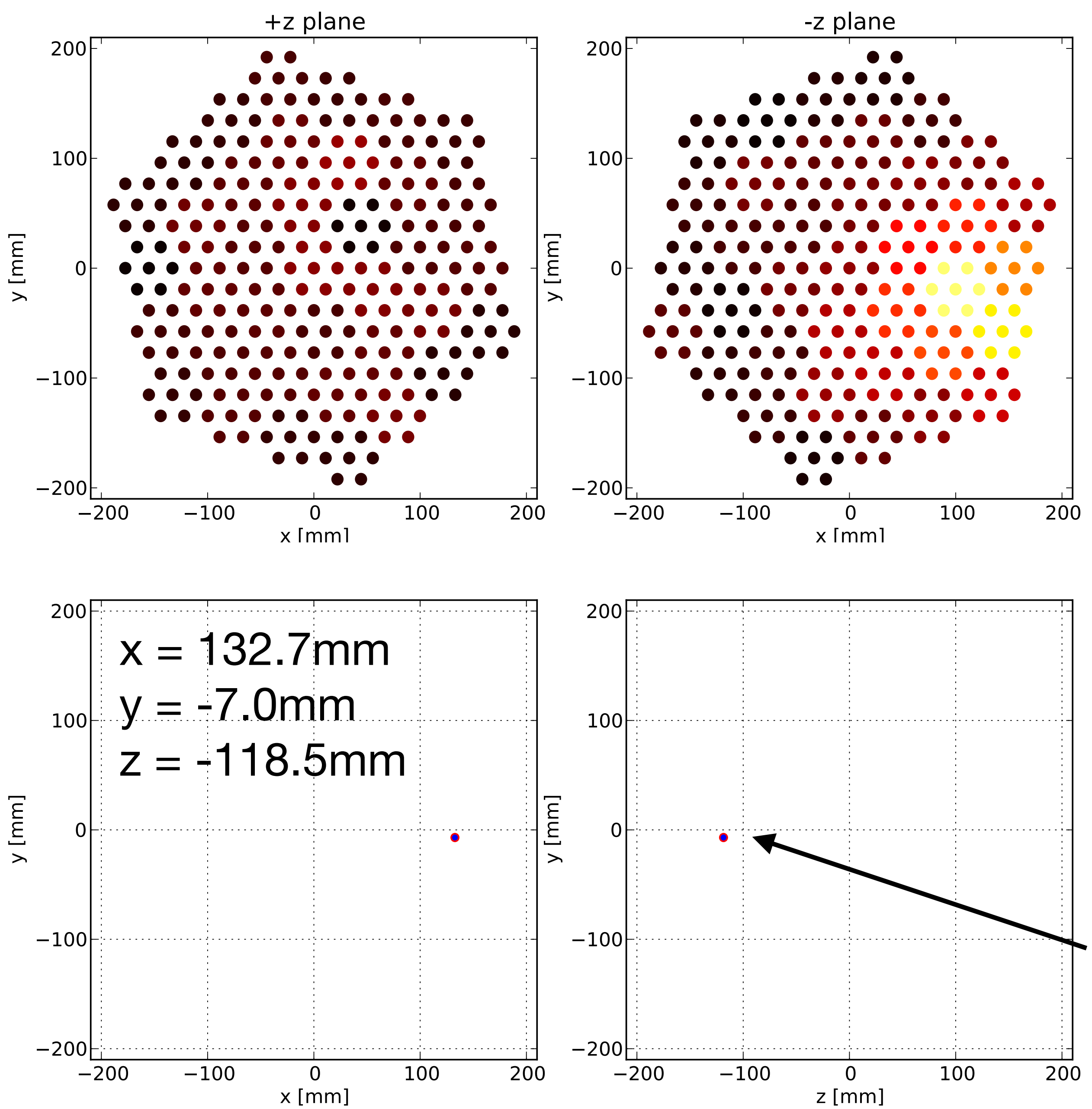
EXO-200 data analysis with deep neural networks

Position reconstruction from scintillation light

Event position reconstruction from scintillation light

Truth label provided by ionization information of real data

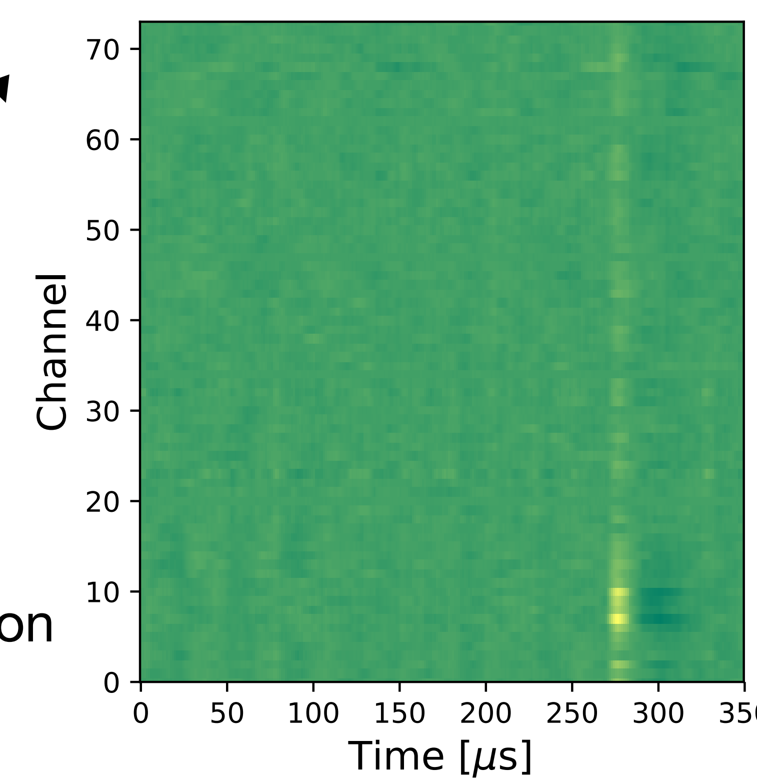
Input are all 74 raw APD waveforms cropped to 350µs



Event position is encoded in APD pattern

Truth information extracted from ionization signal

The time dimension adds information on waveform shape and noise



EXO-200 data analysis with deep neural networks

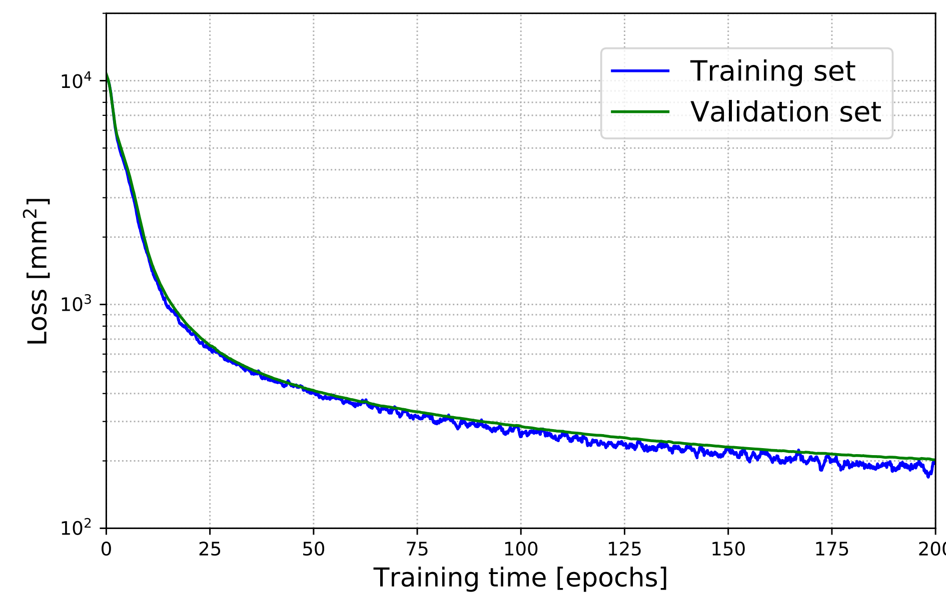
Position reconstruction from scintillation light

Waveform image is fed to convolution neural network (CNN) consisting of 4 convolutional layers and 3 fully connected layers

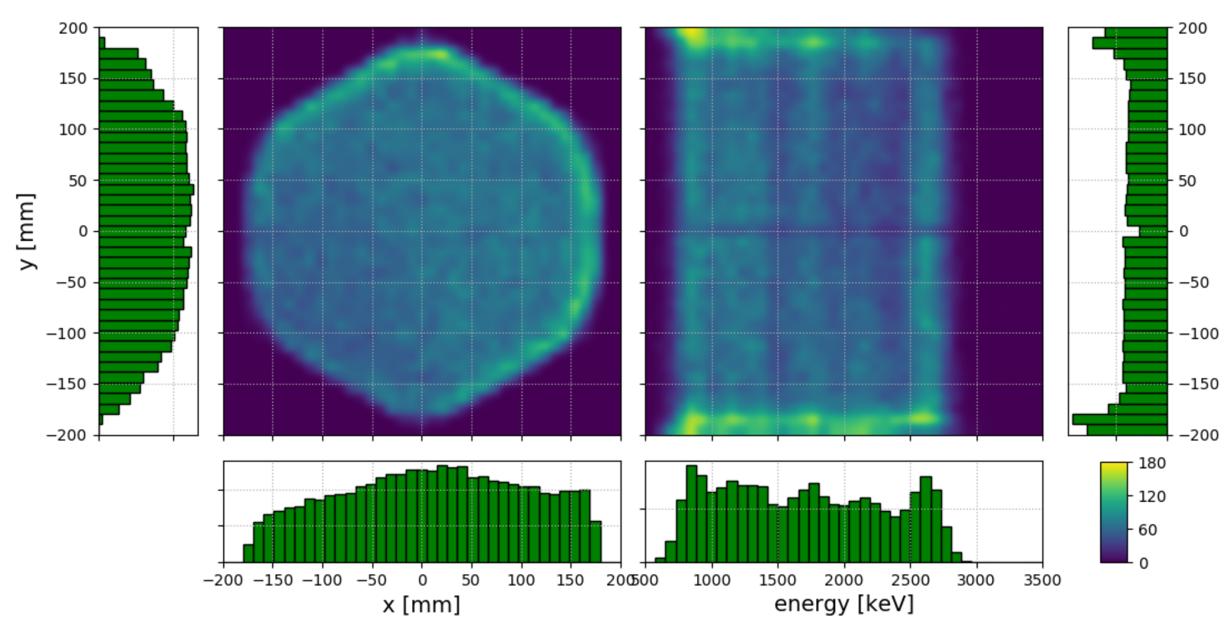
Output has three units corresponding to event position in x-, y-, z-coordinate

Loss function is Euclidean loss with L2 regularization

$$L = C + \lambda \cdot R \quad \text{where} \quad C = \frac{1}{3m}\sum_{t=1}^{m}\sum_{k=1}^{3}\left(y_t^k - \hat{y}_t^k\right)^2$$



Training is done on real calibration data with uniform distribution in both space and energy



EXO-200 data analysis with deep neural networks

Position reconstruction from scintillation light

Loss function reaches 200mm^2 after training the DNN for 200 epochs

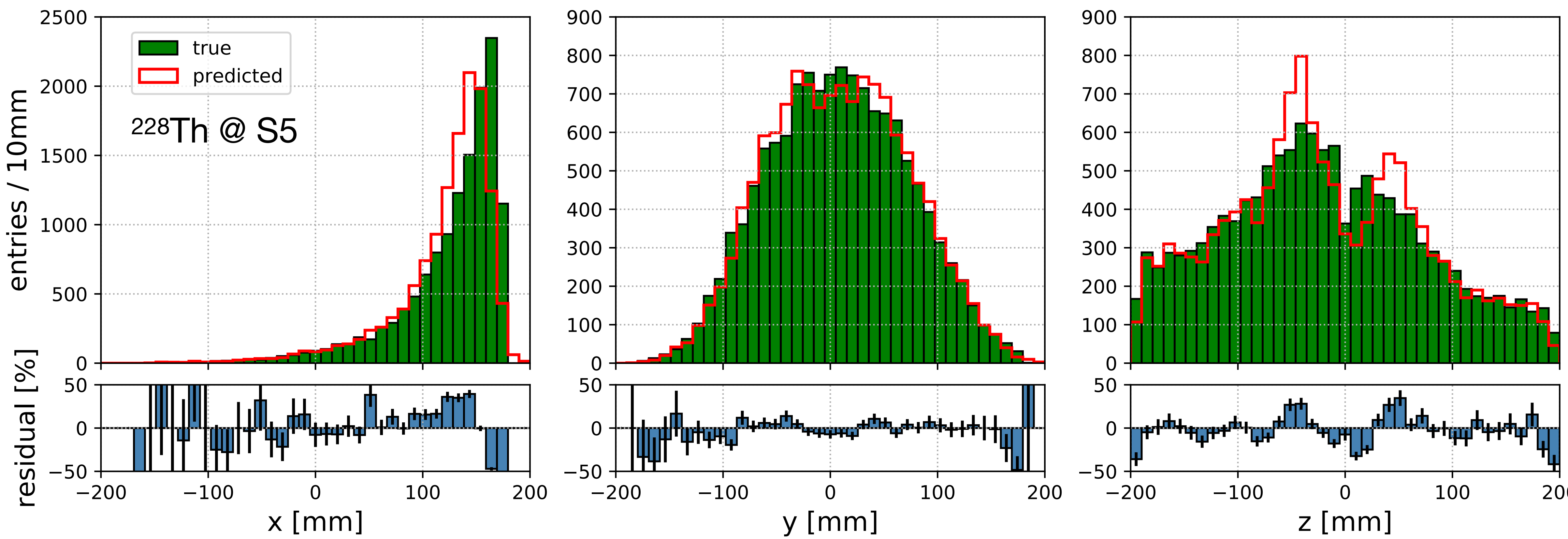
The corresponding resolution in 3D is 25mm

The model is tested on independent source data at different locations

Performance limit is given by deviation of truth labels (position from ionization) measured to be σ_{3D} = 3mm

Similar accuracies achieved for different source types and positions

Accuracy: 22.5mm (d_x = 13.6mm, d_y = 11.3mm, d_z = 8.1mm) corresponding to R^2 = 0.99



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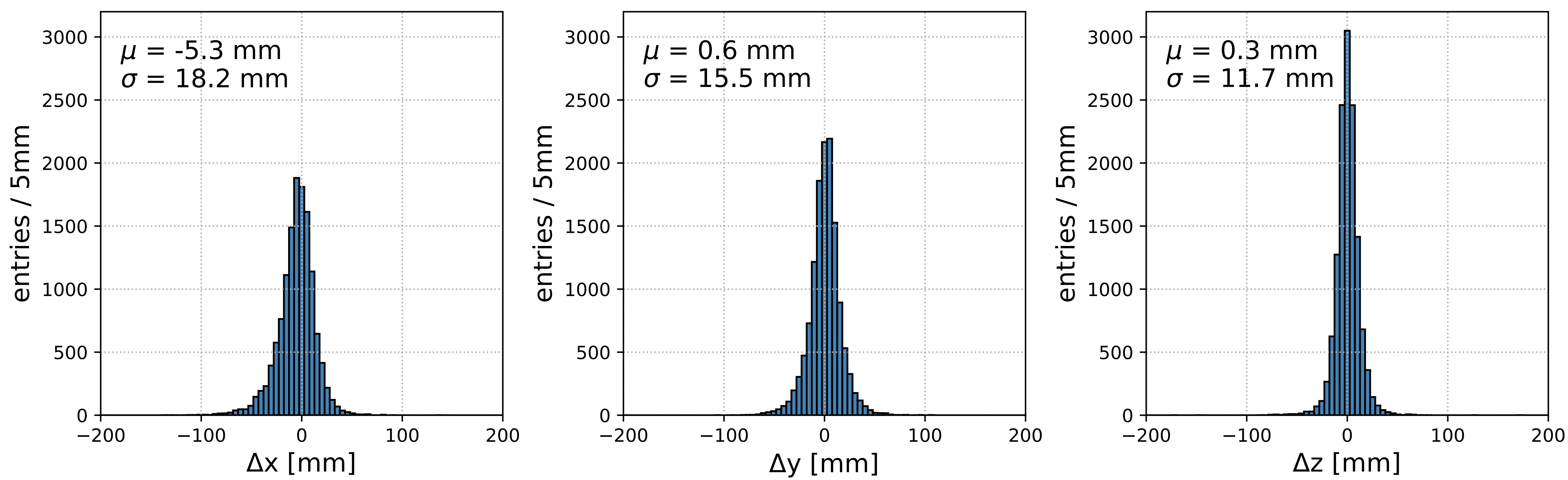
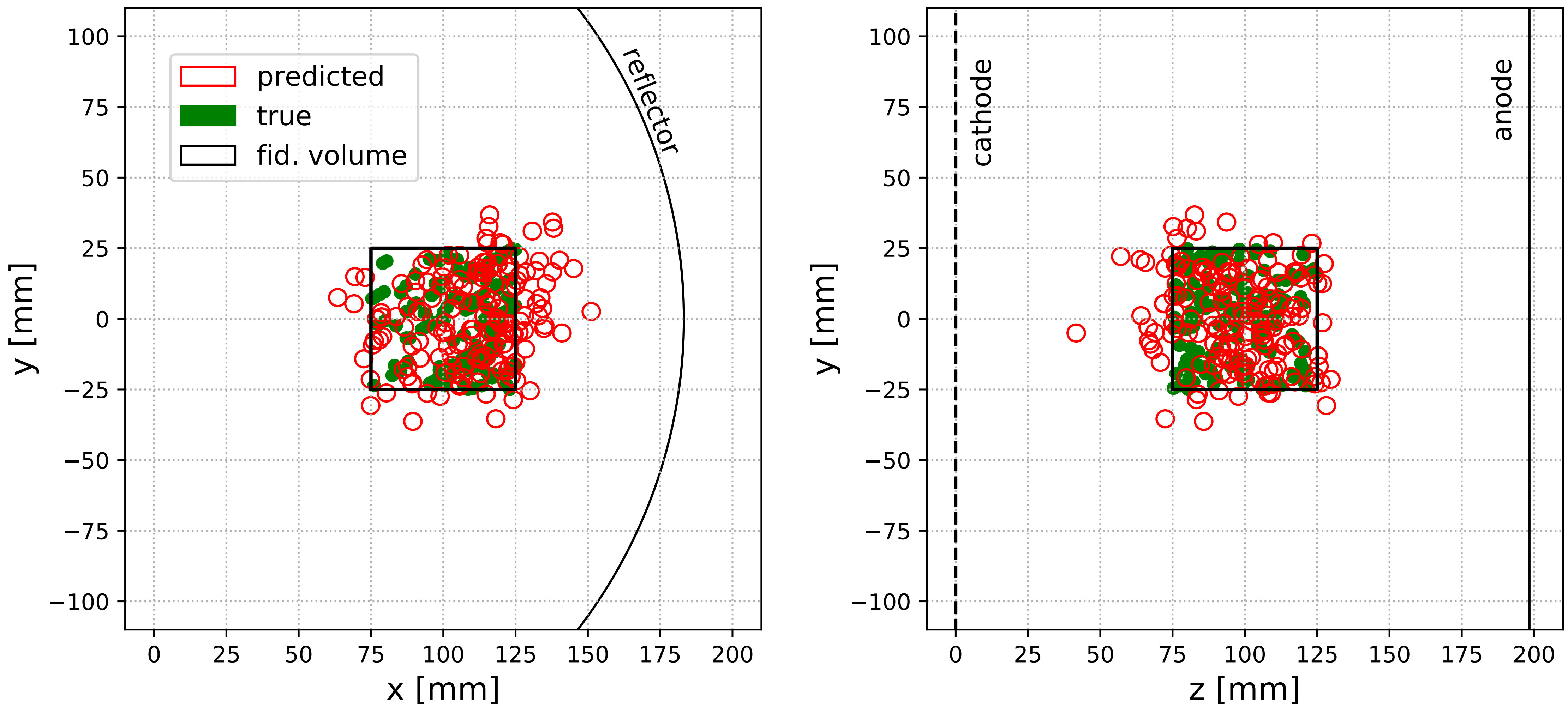


EXO-200 data analysis with deep neural networks

Position reconstruction from scintillation light

The model is also applied to a test set manually constructed by applying tight fiducial cut of 50mm x 50mm x 50mm at position x = 100mm, y = 0mm, z = 100mm

The accuracy reached is 13mm with d_x = 8.3mm, d_y = 4.8mm, d_z = 6.2mm



Summary

EXO-200 is in its final data taking period

The projected sensitivity is $5.2 \cdot 10^{25}$ yrs

Last Phase I + II analysis yields $0\nu\beta\beta$ half-live limit of $>1.8 \cdot 10^{25}$ yrs

EXO-200 has demonstrated the use of deep neural networks for the data analysis directly from raw data

Improved energy resolution compared to classical approach

DNNs are promising for direct event classification

Future experiments may benefit from such approaches in simplifying the processing of data and extraction of high level features