OAK RIDGE National Laboratory

Machine learning application to event reconstruction from single-ended PMT readout

Xiaobin Lu

On behalf of the PROSPECT Collaboration

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

Session EG: Reactor and Short Baseline Neutrino Experiments:
EG.00001: PROSPECT's latest results for Sterile Neutrino Oscillation search
EG.00002: The PROSPECT ^{235}U Antineutrino Spectrum Measurement and its Nuclear Physics Impact
EG.00003: Joint Isotope-Dependent Analysis of the Daya Bay, PROSPECT, and STEREO Reactor Antineutrino Spectra
EG.00004: Improving PROSPECT Oscillation and Spectrum Measurements with Single End Event Reconstruction
EG.00005: PROSPECT-II: Extending Scientific Reach through Upgraded Performance and Multisite Operation
EG.00007: Machine Learning Applications for Reactor Antineutrino Detection at PROSPECT
EG.00009: Background Characterization at HFIR for Reactor Antineutrino Measurements
LK.00006 Machine learning applications for Ortho-Positronium tagging in liquid scintillator for the PROSPECT experiment

U.S. DEPARTMENT OF ENERGY

DNP2020
Fall Meeting of the Division of Nuclear Physics of the American Physical Society
Oct. 29 – Nov. 1, 2020 *Now Virtual Meeting!*
~~Hyatt Regency Hotel, New Orleans, LA~~
APS physics

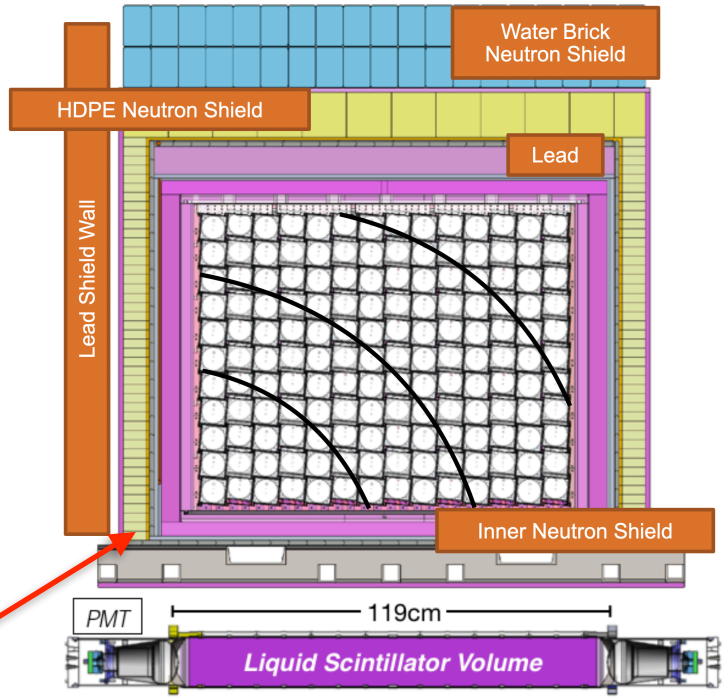
Outline

- PROSPECT experiment
- Machine learning
- Applications to single-ended event reconstruction
- Summary

Precision Reactor Oscillation and SPECTrum experiment

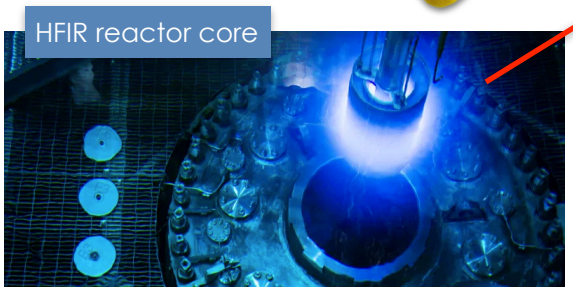
Experiment Description: NIM. A922 (2019) 287-309

- Short baseline neutrino experiment
- Located at High Flux Isotope Reactor at Oak Ridge National Lab(85MW, research reactor)
- ~10m from reactor core with high flux
- ~4 ton ^{6}Li dopped liquid scintillator
- Optical segmentation 14 by 11
- Double PMT readout in each cell
- On surface detector with Little overburden



Electron antineutrino $\bar{\nu}_e$

~7-9m



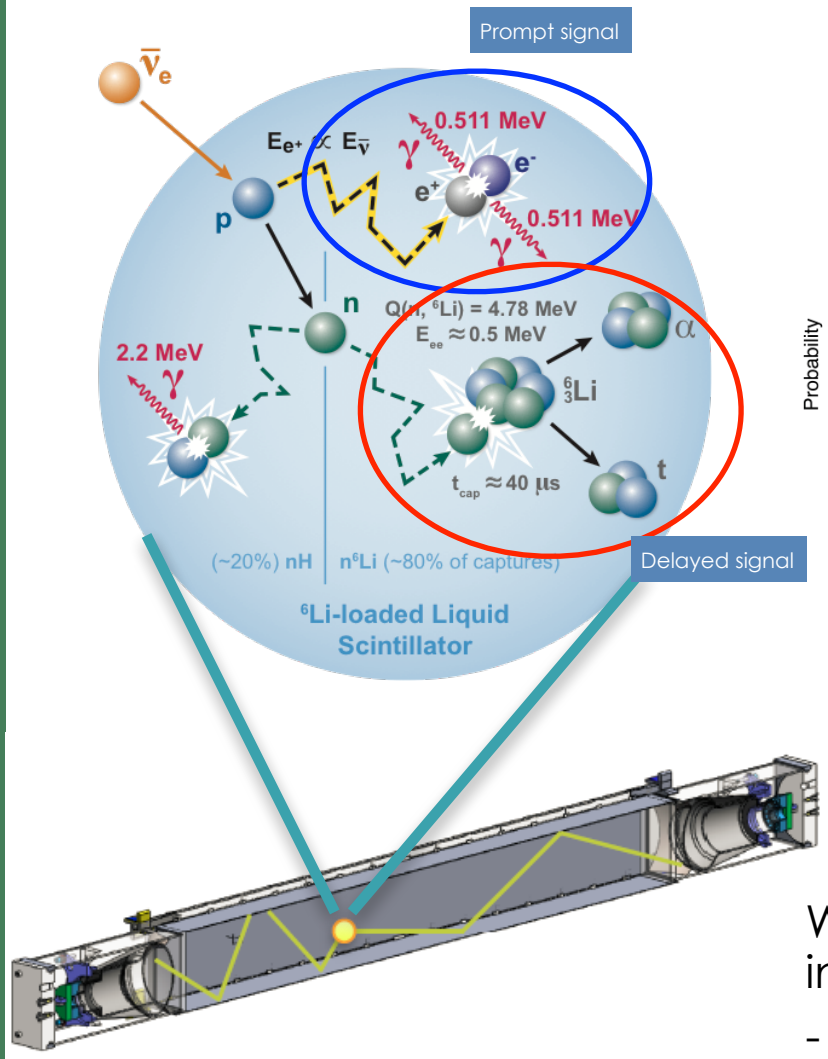
Phys. Rev. Lett. **121**, 251802(2018)
Phys. Rev. Lett. **122**, 251801(2019)

Physics Result:

- Less than one year data-taking
- 50k neutrino interaction candidates
- High precision ^{235}U antineutrino spectrum, x6 times higher stats than ILL experiment
- Sterile neutrino oscillation search disfavored at 2.5σ
- More

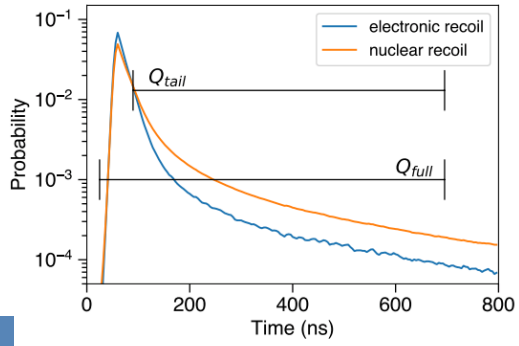
OAK RIDGE National Laboratory

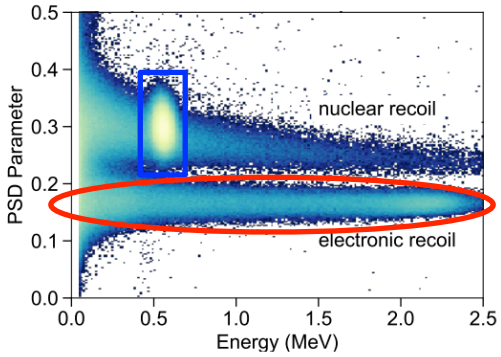
Neutrino detection via Inverse beta decay (IBD)



$$\bar{\nu}_e + p^+ \rightarrow n + e^+$$

Waveform





- Pulse Shape Discrimination (PSD)
- ⁶Li-doped EJ-309 liquid scintillator gives excellent PSD performance
- IBD pair event identification and background suppression

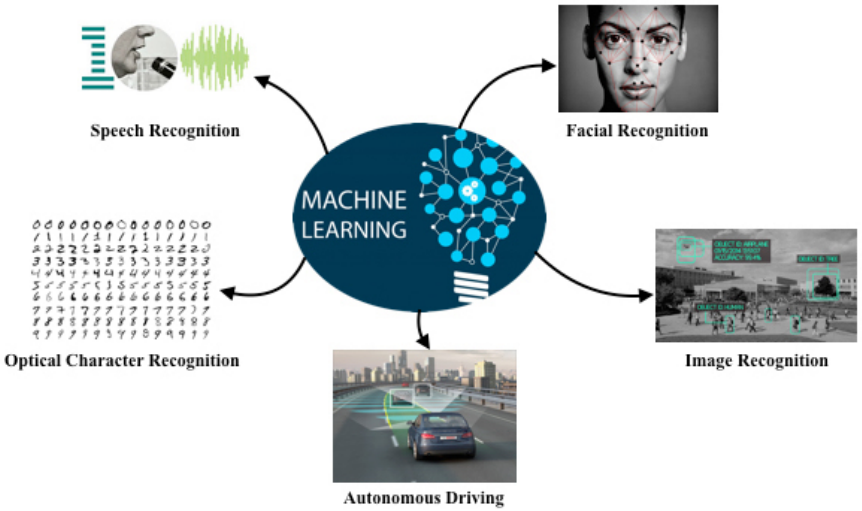
We can reconstruct interaction event by information from both PMTs readout:

- Photoelectrons, light arrival timing difference, pulse PSD, etc.

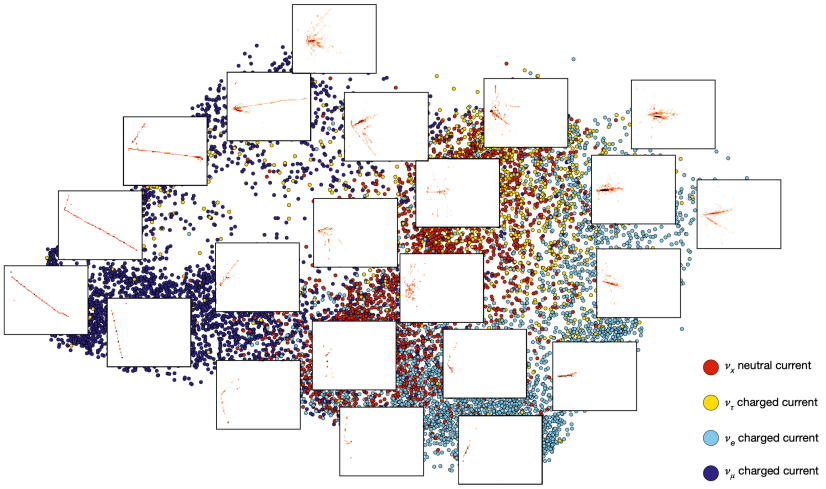
→ Particle type, energy, position, etc.

Machine learning in life and science

- Tremendous success and wide applications in real world
  - Voice/image recognition
  - Automatic driving
  - AlphaGO



Projected CNN features extracted from NOvA's event selection



t-distributed stochastic neighbor embedding (t-SNE)

Nature Phys. 560, 41(2018)

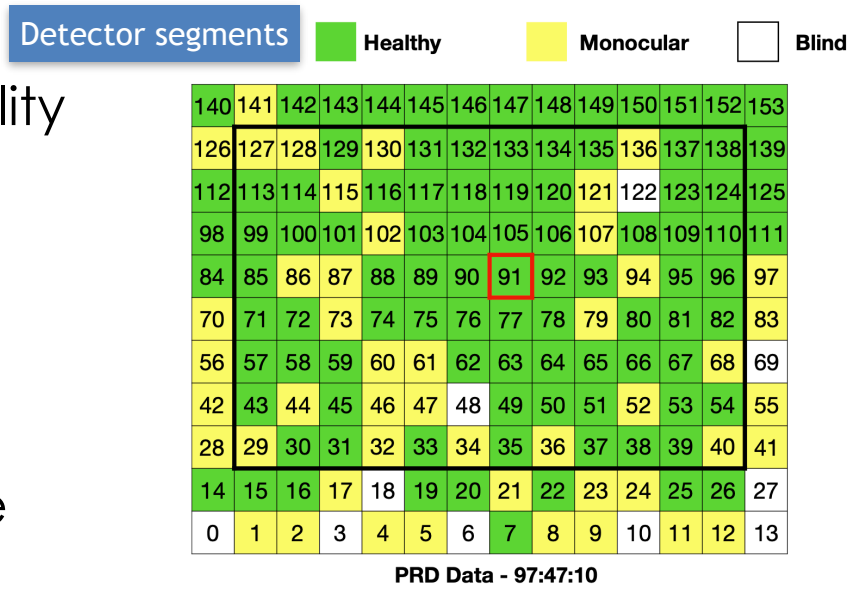
- It has gained popularity in HEP
  - Event selection/reconstruction
  - Track classification
  - Discovery of the Higgs boson

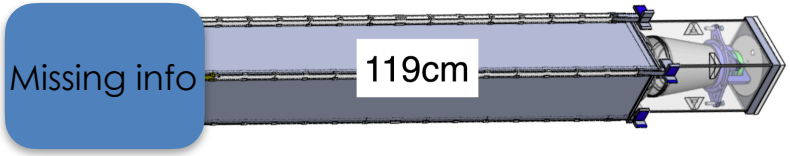
The features extracted from event selections are well separated for various event types, even in projected two-dimensional space.

Application in singled-ended PMT segments

PROSPECT arXiv:2006.11210

- Over the course of the operation, certain PMTs showed current instability and had to be turned off.
- ~30% of cells either
  - one disabled PMT(yellow)
  - two disabled(white)
- For uniformity reasons, these single-ended information is not used in the analysis.
- These events in single-ended cells can be used to veto background(particle ID) or recover IBD events(energy/ position) .





An upgraded design is also under way to ensure minimum contact between PMTs and liquid scintillator.

Model

- Tensorflow packages to implement machine learning
- The model consists of several hidden layers of neurons
- The model training isn't computational heavy ~ 5min on modern personal laptop, depending on the size of training data

Typical model

```
_________________________________________________________________
Layer (type)                 Output Shape              Param #
=================================================================
dense_50 (Dense)             (None, 128)               1280
_________________________________________________________________
dense_51 (Dense)             (None, 128)               16512
_________________________________________________________________
dense_52 (Dense)             (None, 1)                 129
=================================================================
Total params: 17,921
Trainable params: 17,921
Non-trainable params: 0
```

Data format:

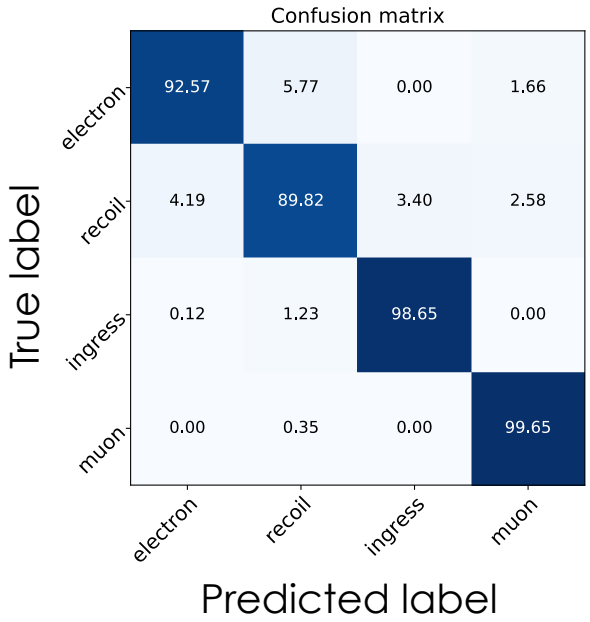
	p0h	p0a	p0rise	p0PSD	p1h	p1a	p1rise	p1PSD	E
0	52.349998	306.500000	11.233334	0.025412	127.275002	785.571411	6.150480	0.095454	0.141742

PMT0 PMT1 Calibrated quantities

PID Performance

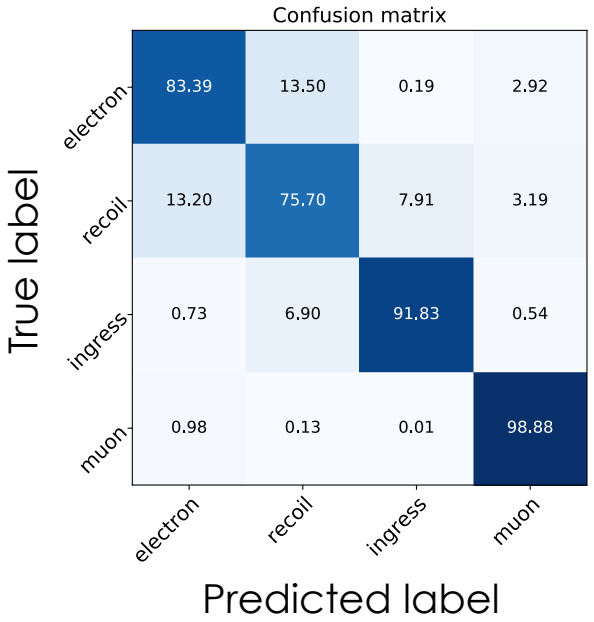
- Double PMTs PID reconstruction as a benchmark
- Particle identification capability still retain to certain degrees with the loss of 2nd PMT readout

Double PMTs Recon Benchmark



~10-15%

Single PMT Recon performance



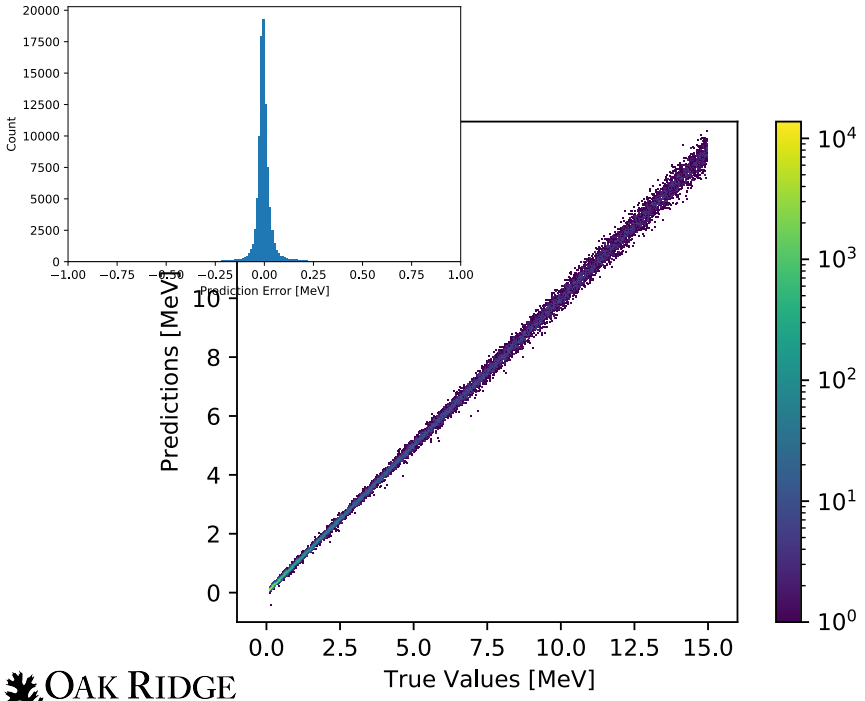
E Recon Performance

- Double PMTs E reconstruction as a benchmark
- Energy reconstruction is severely degraded without 2nd PMT readout

Energy resolution 5%@1MeV

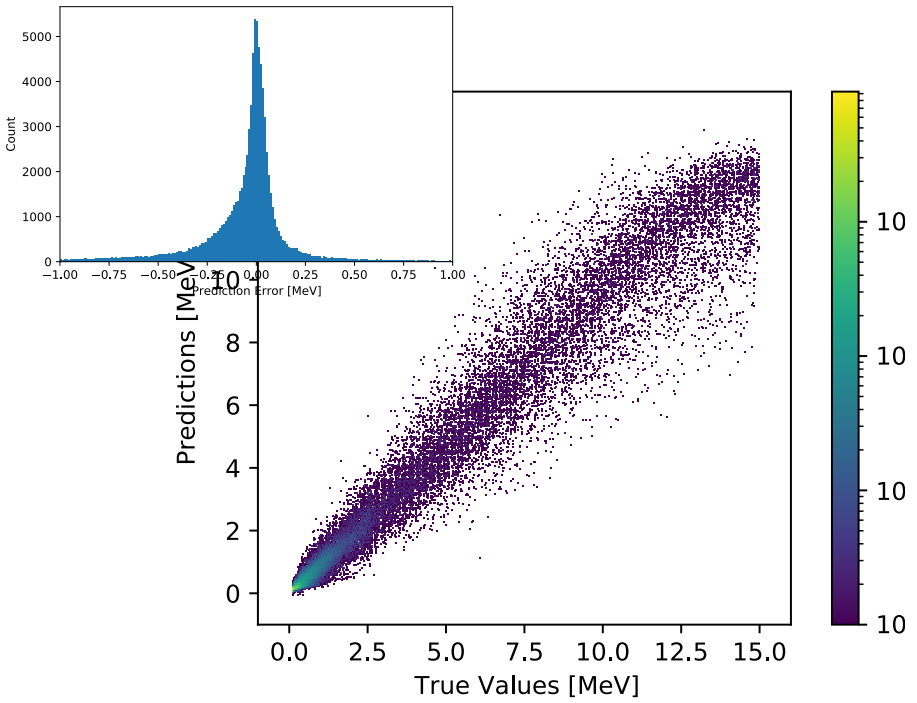
Double PMTs Recon Benchmark

Testing set Error: 0.03 MeV



Single PMT Recon performance

Testing set Error: 0.23 MeV

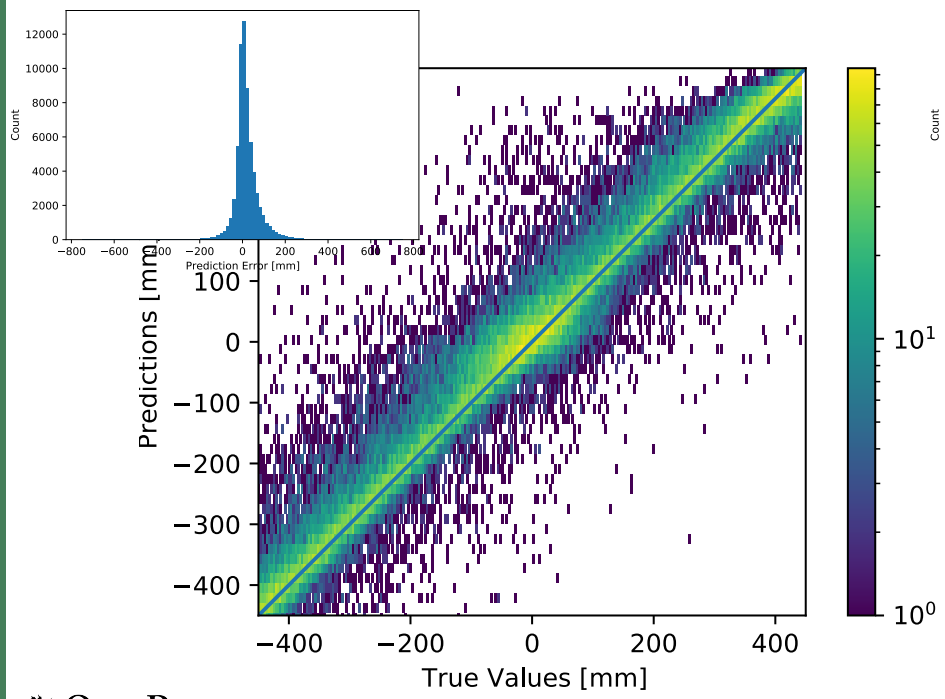


Z-pos Recon Performance

- Double PMTs Z-pos reconstruction as a benchmark
- Position reconstruction along the cell is severely disabled without 2nd PMT readout

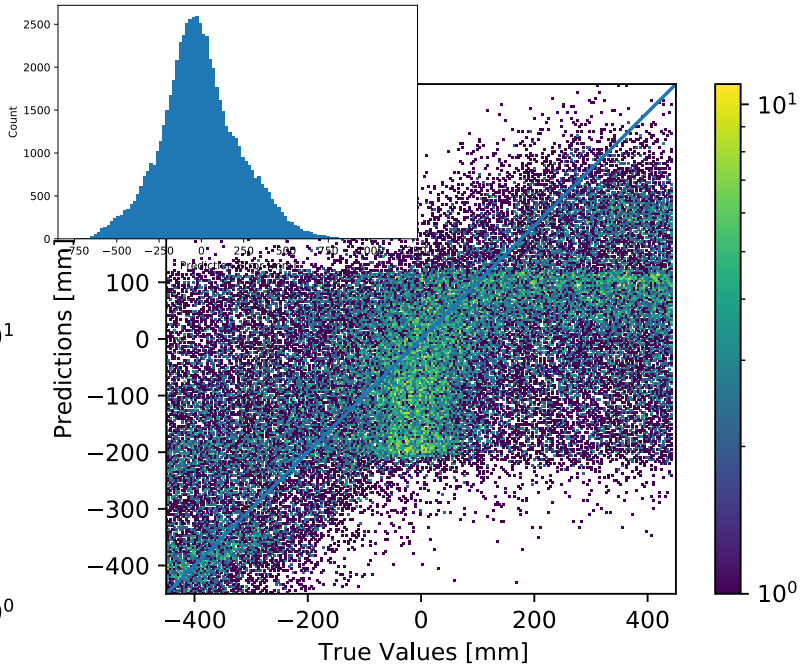
Double PMTs Recon Benchmark

```
Testing set Mean Abs Error:  40.2 mm
```



Single PMT Recon performance

```
Testing set Mean Abs Error:  180.5 mm
```



Summary

- PROSPECT is a successful short baseline reactor antineutrino experiment with ~50k IBD events measured
- Additional single PMT cell information will be utilized in future analysis to furthermore reduce background
- Machine learning application
  - Single-ended particle ID sees a ~ average10% degradation compared to full event reconstruction
  - In single-ended cells, energy/z-pos reconstruction is severely degraded, IBD reconstruction is less likely to achieve

Future work

- Possible improvement with simulated training data
- Apply CNN to actual waveforms
- IBD pattern recognition with CNN+RNN


Thank you
prospect.yale.edu
15 Institutions, 70 collaborators
HEISING-SIMONS FOUNDATION
U.S. DEPARTMENT OF ENERGY
GRFP
BROOKHAVEN NATIONAL LABORATORY
NIST
LE MOYNE COLLEGE
A.D. 1946
Drexel
UNIVERSITY OF WATERLOO
W&M
Yale
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory