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Regression Convolutional Neural Network for Energy Estimation in NOvA

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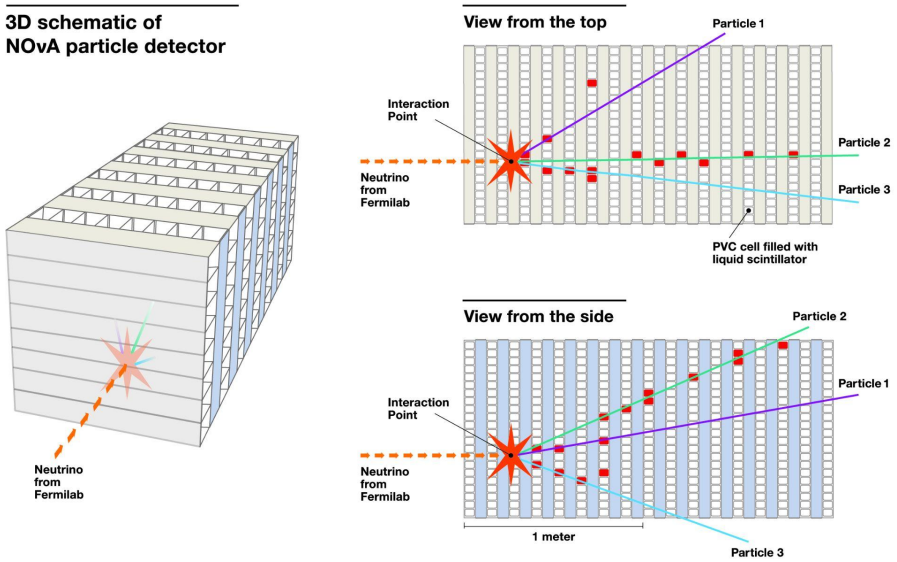
NOvA

NOvA Experiment Overview

- Long-baseline neutrino oscillation experiment
- NuMI beam at Fermilab produces muon (anti-)neutrinos
- Functionally equivalent near and far detectors
  - 810 km apart
- Observe ν_μ disappearance and ν_e appearance
- Measure $\Delta m^2_{32}, \theta_{23}, \delta_{CP}$

NOvA Detector

- Pixels: long 4 cm x 6 cm PVC cells
  - Filled with liquid scintillator
  - Wavelength shifting optical fiber
  - Avalanche photodiode for detection
- Alternate horizontal and vertical planes → 2 detector views



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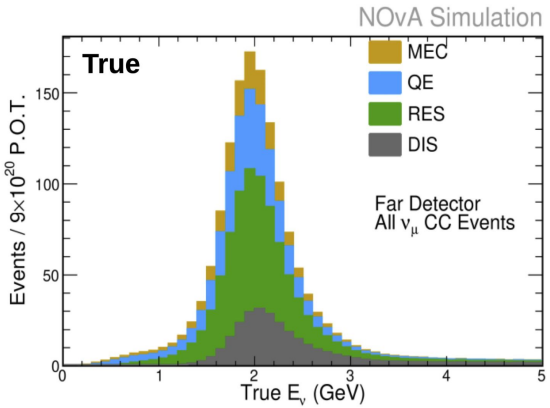
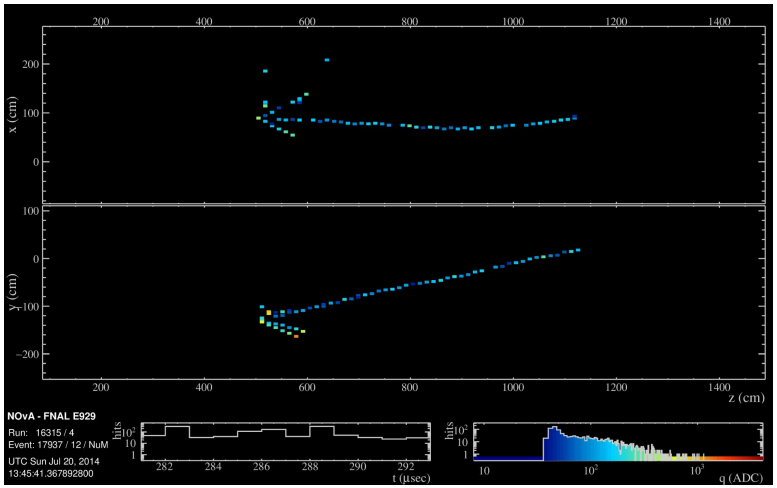
Energy Estimation

- High energy estimation fidelity required to measure oscillation parameters
  - Oscillation probability is a function of neutrino energy

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$ (Simplified 2-Flavour Case)

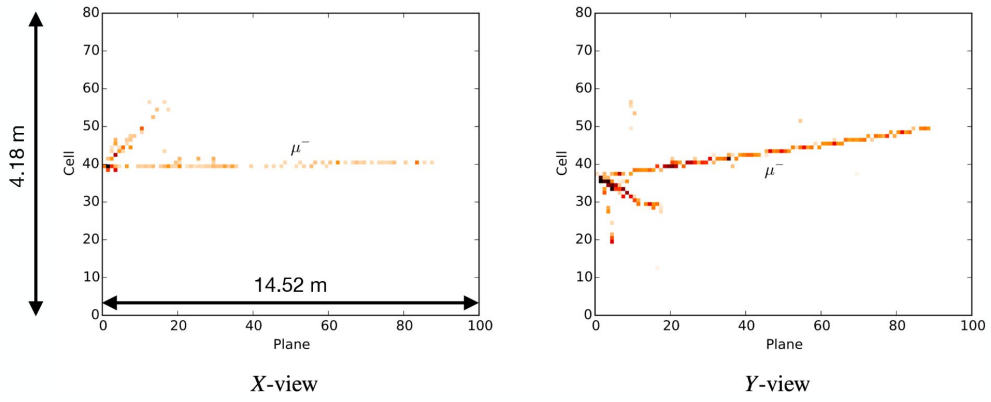
  - Improve energy resolution → improve oscillation parameter sensitivity
- Model must perform for many interaction modes and event topologies in NOvA





Regression CNN (RegCNN)

- Model Inputs:
  - Muon track length
  - “Pixelmap” - detector event readout in 2 views
    - 2 Standard 100 x 80 images
    - Cropped around neutrino interaction
    - Train with random calibration scaling of pixelmap values
- Simultaneous prediction of total muon neutrino energy and muon energy



Model Training

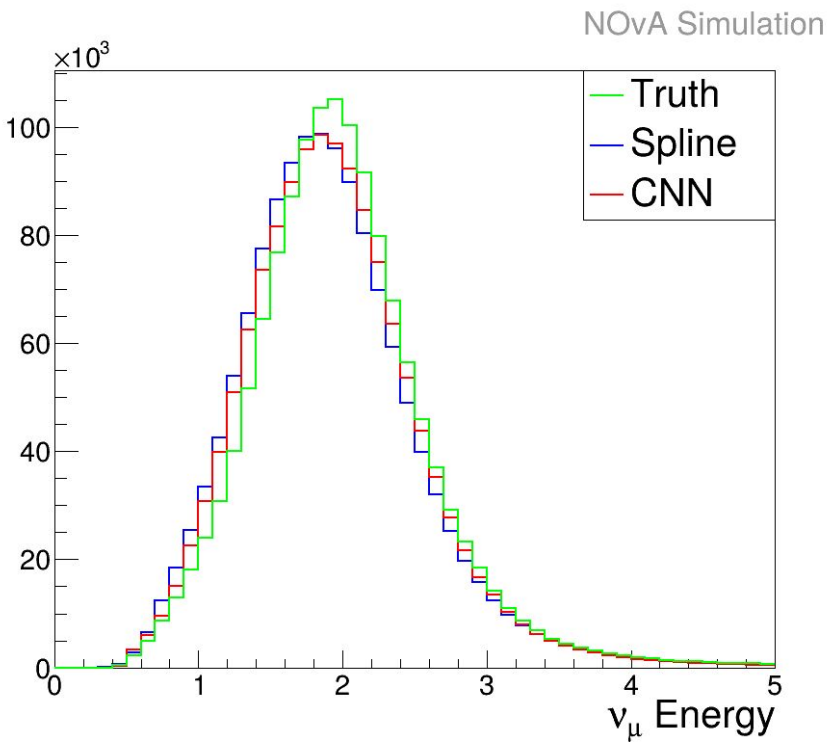
- Reweight true neutrino energy spectrum in training data
  - Flatten peak region, increase representation of tail regions
- Train separate models for each neutrino flavor, detector, beam configuration
- For ν_μ and ν_e:
  - Far Detector (FD)
  - Near Detector (ND)
  - ν_μ Beam Configuration
  - $\bar{\nu}_\mu$ Beam Configuration
- Present validation studies on ν_μ ND sample in this talk

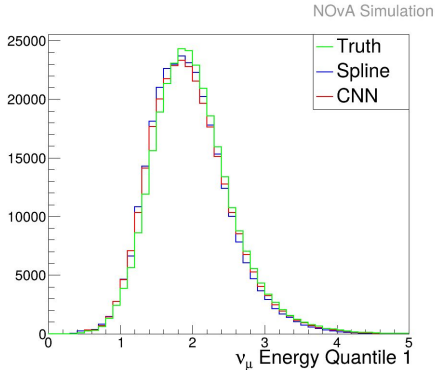
Model Validation

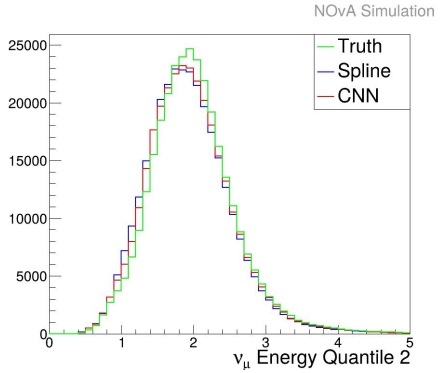
- Compare RegCNN performance to Spline energy estimator
  - Spline fit for NOvA's 10-year dataset analysis
- Primary benchmarks:
  - Energy spectrum
  - Energy spectrum "quartiles"
    - Calculate ratio of hadronic energy to total energy
    - Split dataset into 4 subsets based on this ratio
  - Resolution: Standard Deviation[(Reconstruct-True)/True]
  - Bias: Mean[(Reconstruct-True)/True]

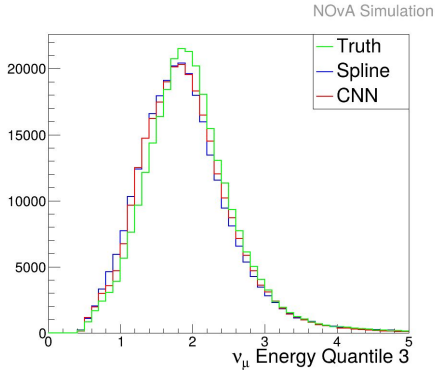
3rd Energy Estimation Method: Transformer ν_μ Energy Estimator developed by University of Minnesota.
See Neutrino 2026 Poster by Leon Tong for Transformer performance

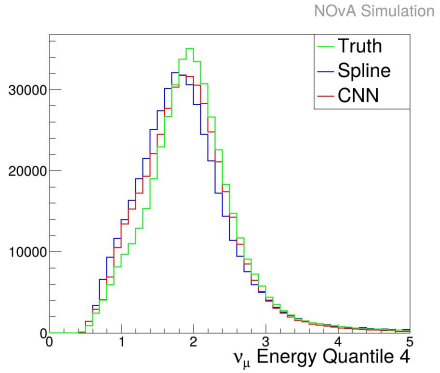
Neutrino Energy











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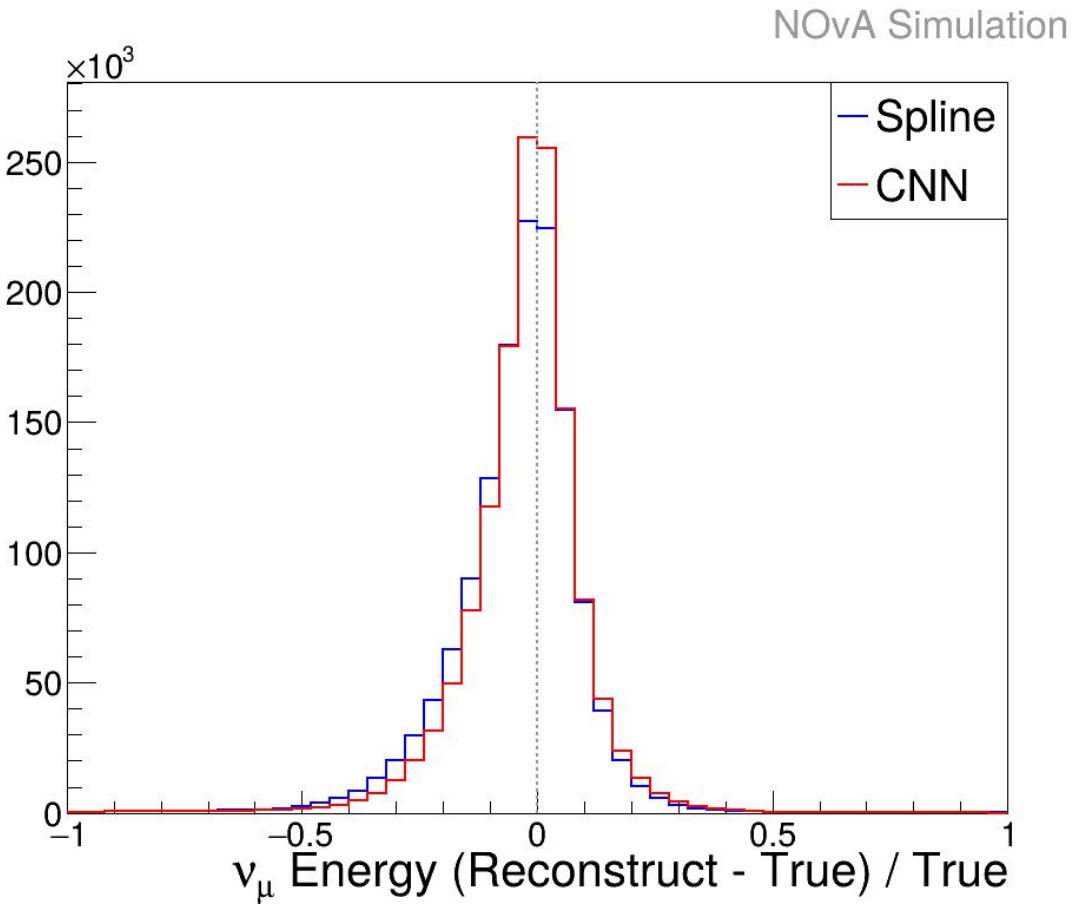
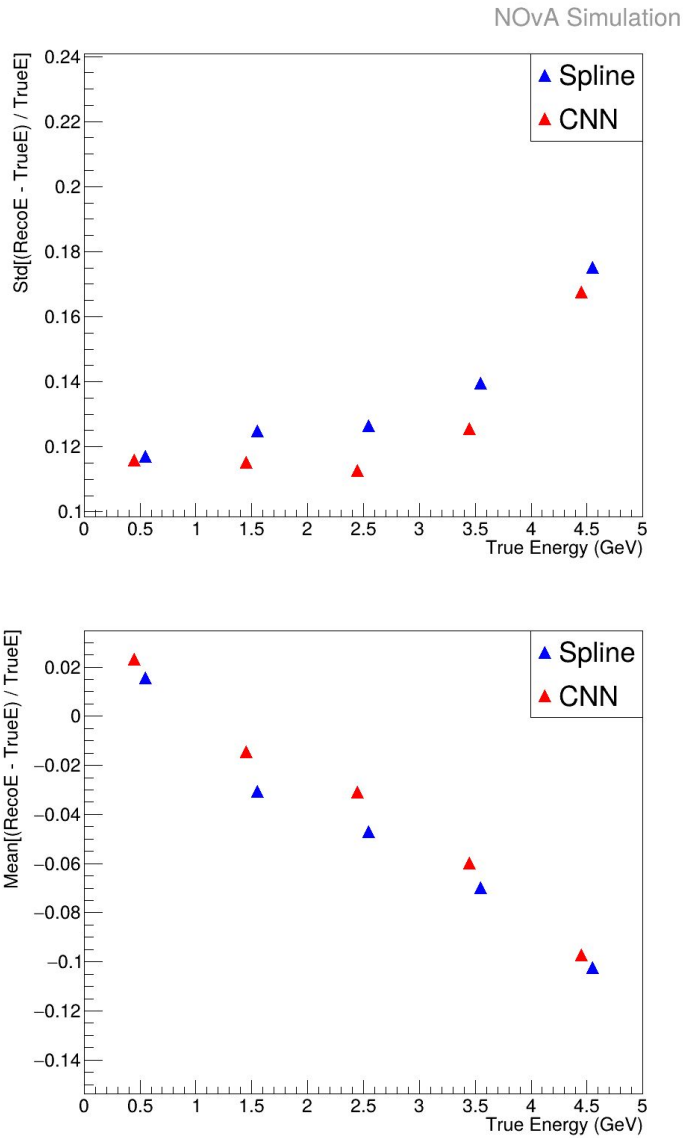
Neutrino Energy





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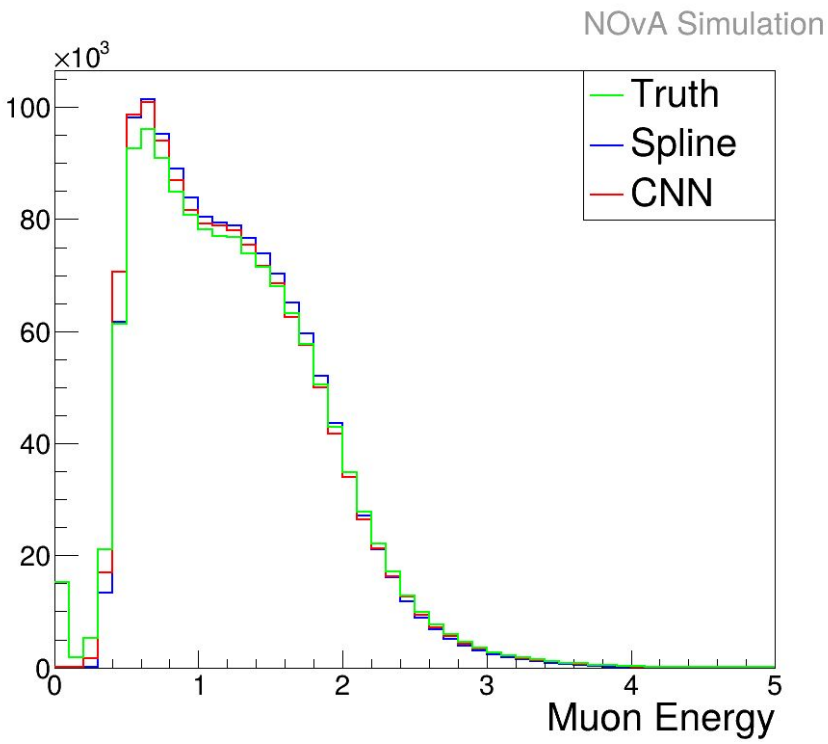
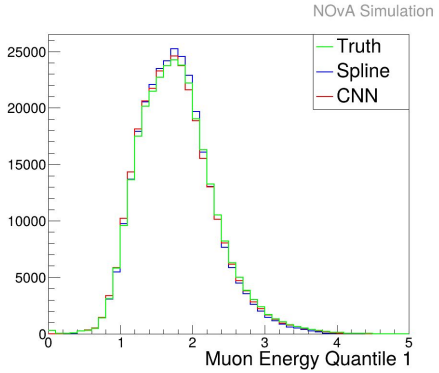
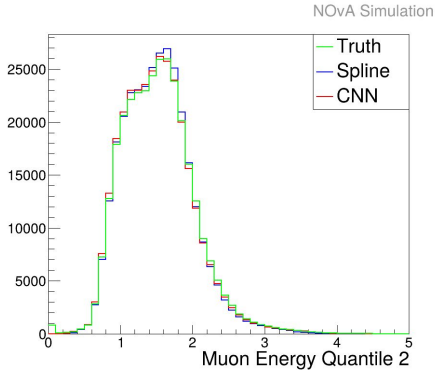
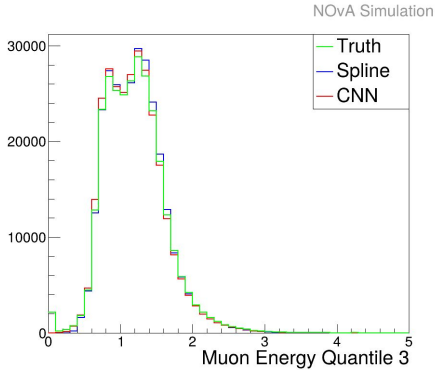
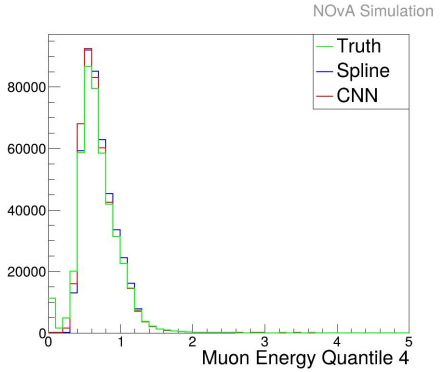
Muon Energy











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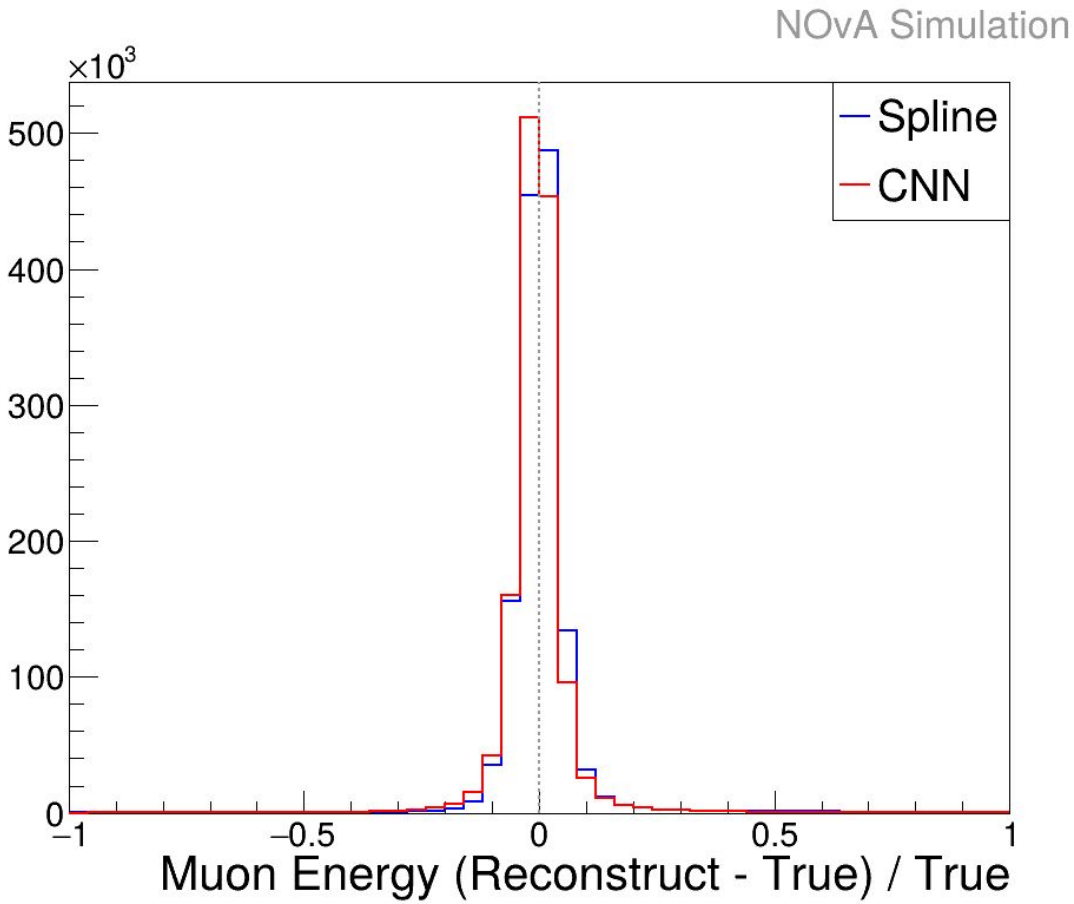
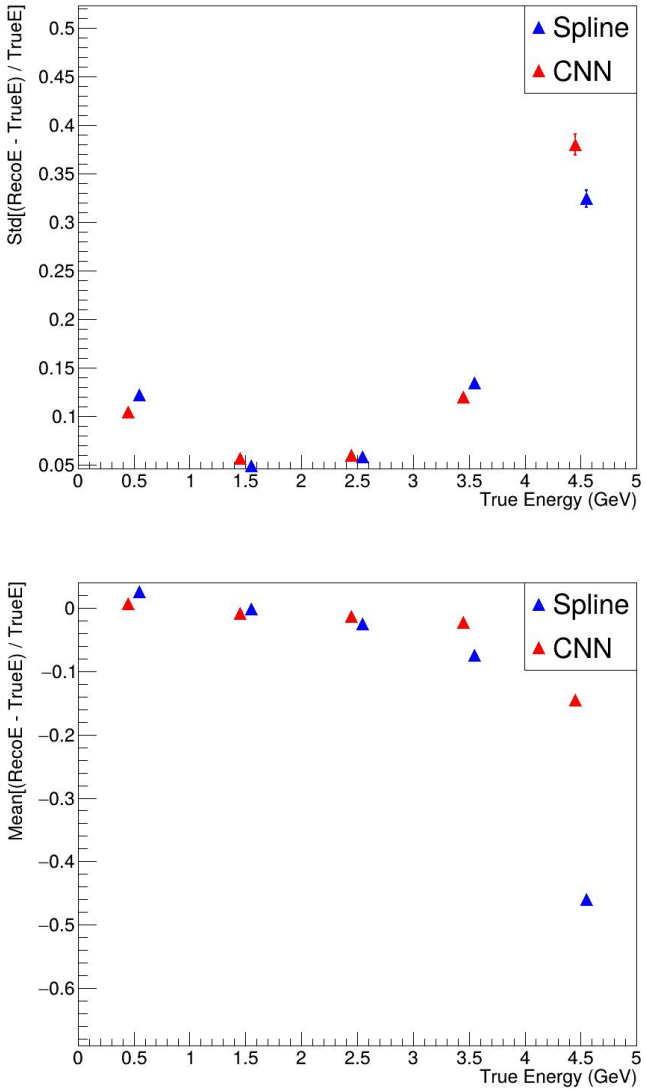
Muon Energy





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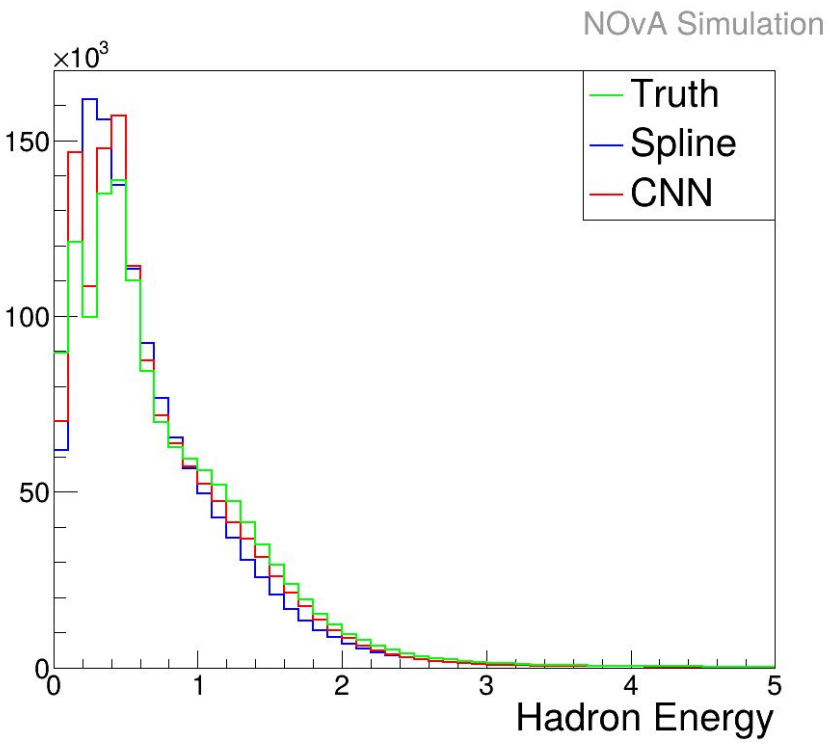
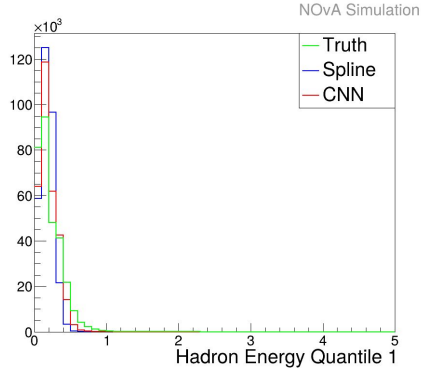
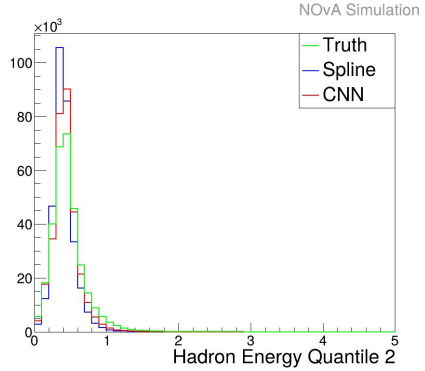
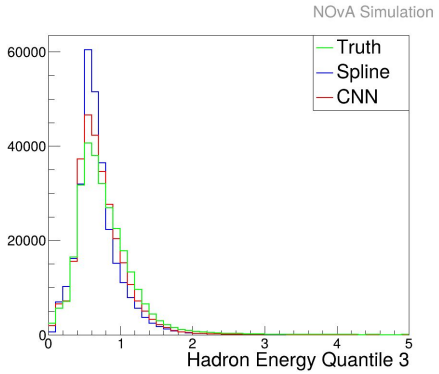
Hadronic Energy

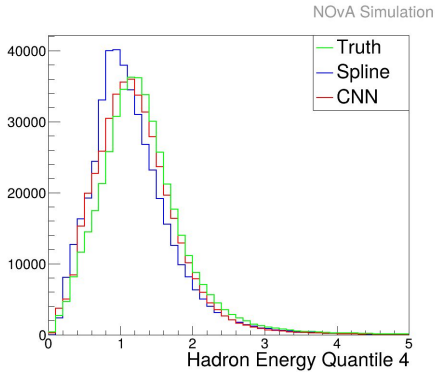
- Double peak structure in simulated hadron energy spectrum
  - Spline fails to reconstruct double peak without piecewise fit segments
  - RegCNN reconstructs double peak



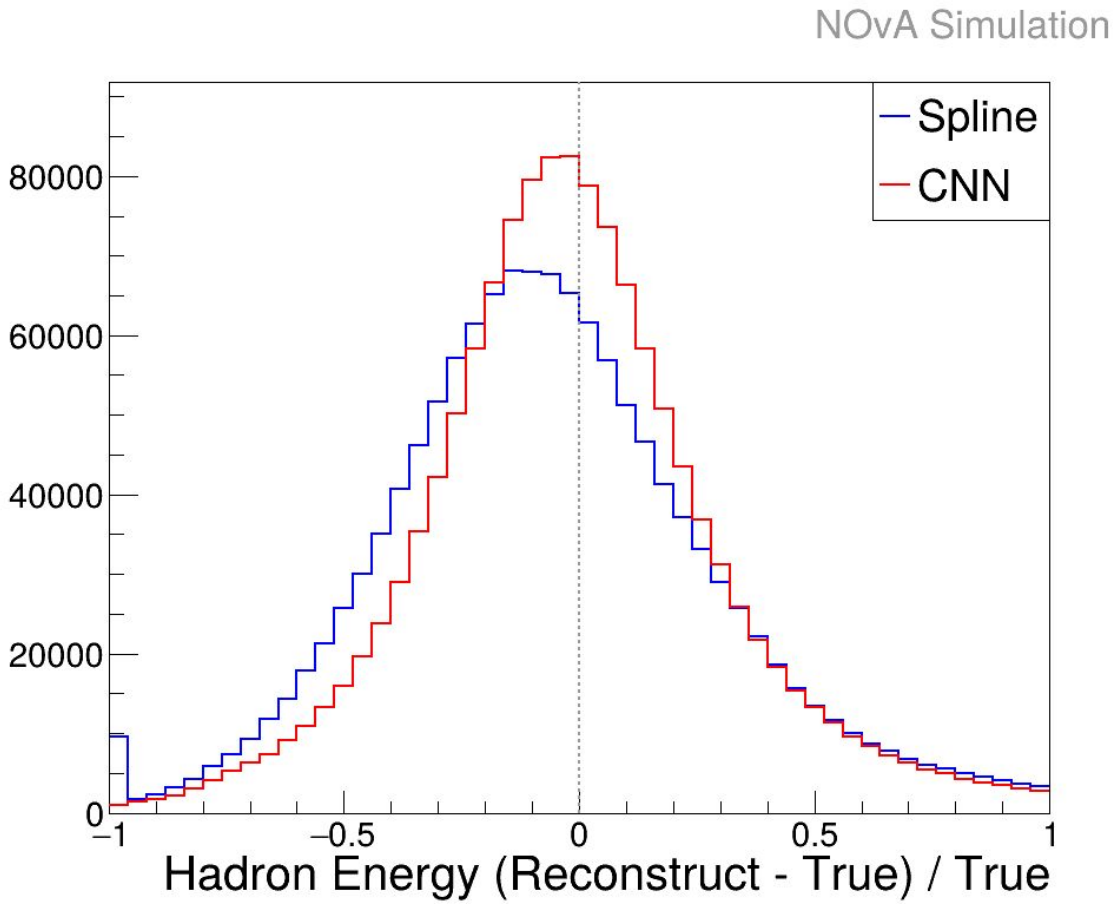


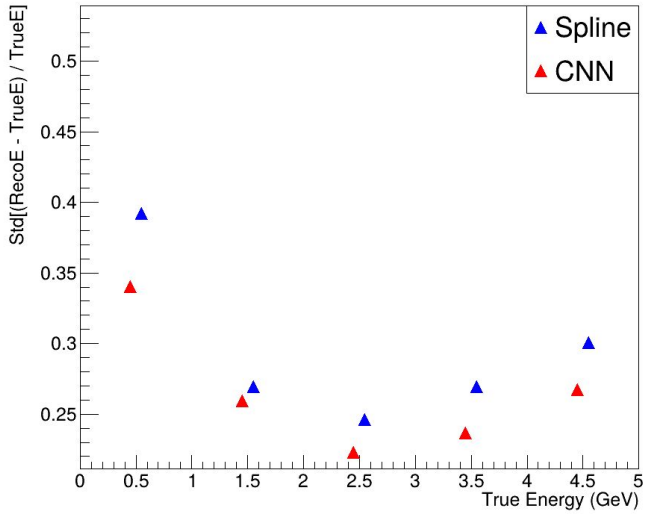


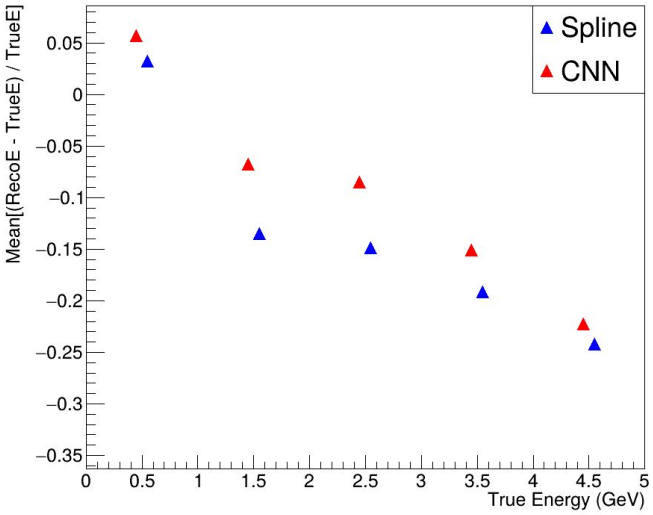




Hadronic Energy







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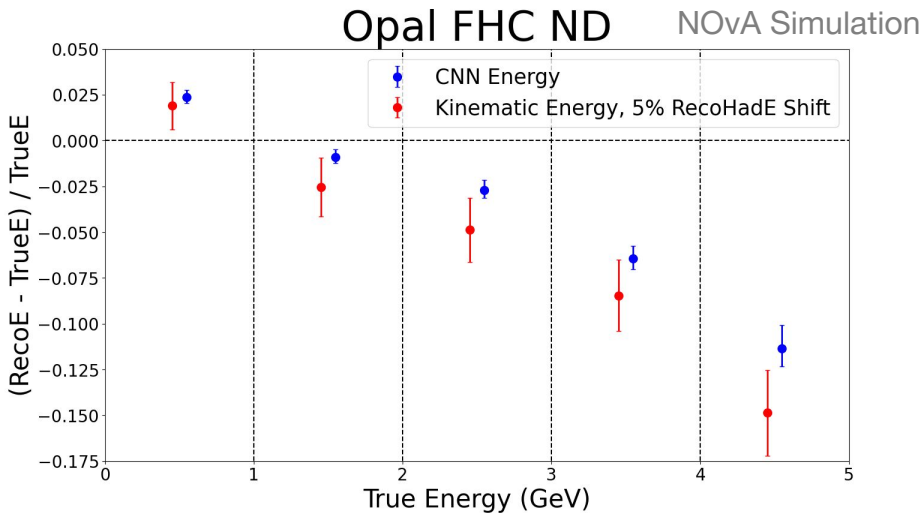
Calibration Robustness

- Train with calibration shift on input pixelmap
  - Scale by factor from Gaussian distribution (mean=1, std=0.1)
- Evaluate energy estimators on 5% calibration shift samples
  - Spline (Kinematic) method has 5% shift in energy
  - RegCNN demonstrates significant robustness to calibration shifts (~0.5% shift in energy)



(Bars in plot show effect of up/down shift)

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Calibration Systematic in NOvA

- Calibration is largest source of systematic error for NOvA's Δm^2_{32}, $\sin^2\theta_{23}$ measurements
  - NOvA set current world-leading Δm^2_{32} limit

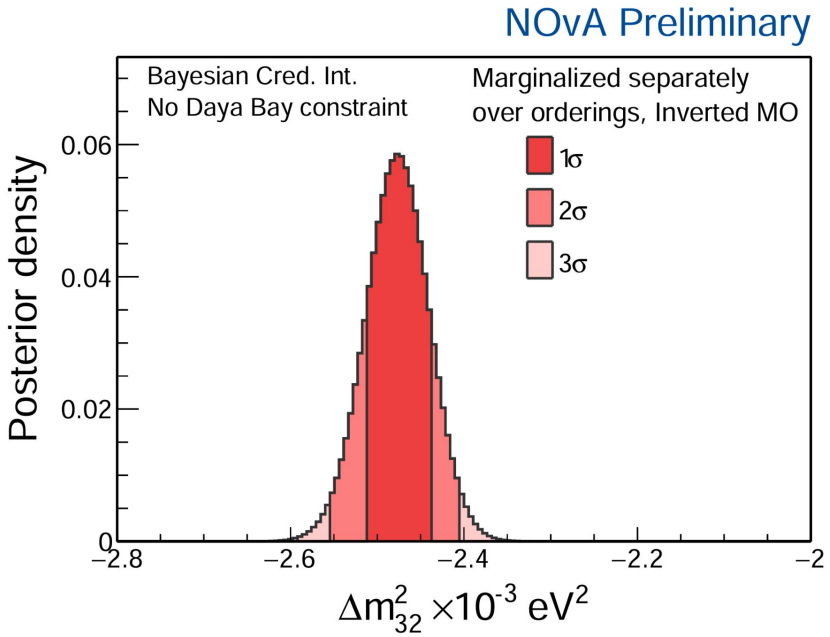
"Precision measurement of neutrino oscillation parameters with 10 years of data from the NOvA experiment" (DOI:10.1103/x53y-2b86)

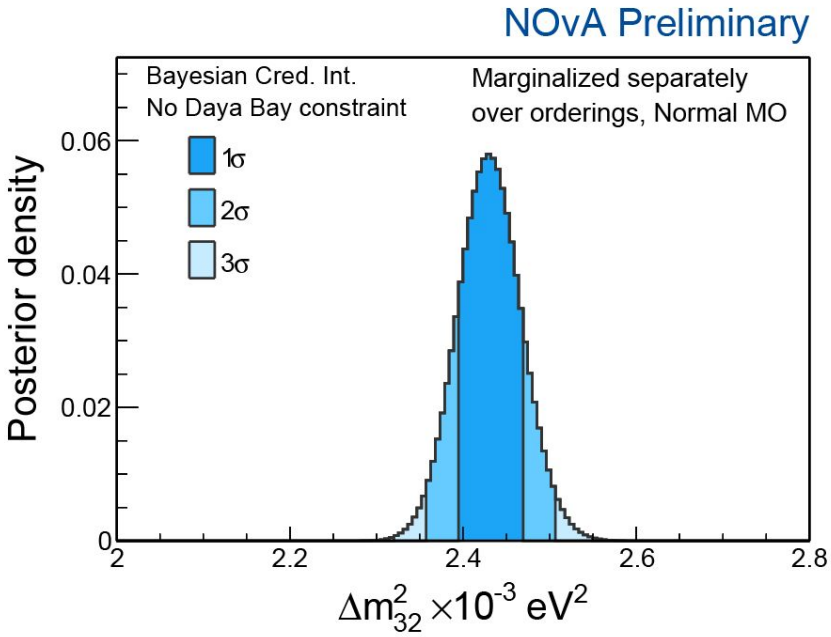
Source	$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-5}$ eV^2)	$\sin^2\theta_{23}$ ($\times 10^{-3}$)	δ_{CP} ($\times 10^{-2}$ π)
Beam flux	+0.06/-0.12	+0.40/-0.75	+0.16/-1.00
Calibration	+1.40/-1.80	+3.20/-16.0	+1.70/-17.0
Detector model	+0.17/-0.27	+0.36/-3.90	+0.37/-3.30
Lepton Reco.	+0.90/-1.40	+2.70/-4.50	+0.61/-2.90
ND – FD Uncor.	+0.25/-0.34	+2.40/-2.50	+0.79/-4.00
Cross Sections	+0.65/-1.10	+3.10/-5.10	+2.00/-9.70
Neutron model	+0.25/-0.39	+2.70/-0.49	+0.43/-1.30
Systematic Unc.	+1.70/-2.30	+6.60/-18.0	+2.90/-21.0
Statistical Unc.	+3.20/-4.40	+22.0/-85.0	+6.60/-74.0

Current Oscillation Analyses

(DOI:10.1103/x53y-2b86): “Precision measurement of neutrino oscillation parameters with 10 years of data from the NOvA experiment”

- Neutrino 2026:
  - Zoya Vallari: “Probing the 3-Flavor paradigm with NOvA”
  - Artur Sztuc (Poster): “Prospects for Mass Ordering Measurements with NOvA”
  - Larry Zhao (Poster): “Bayesian Fit to NOvA Data Subsamples for Three Flavor Oscillation Analysis”





Summary

- Developed simultaneous prediction of neutrino energy and lepton energy in RegCNN
- RegCNN improved energy reconstruction performance compared to Spline used in previous NOvA analyses
- Input pixelmap shifted for robustness to calibration uncertainties
  - RegCVN more robust to calibration shifts than traditional non-ML method
  - Significant reduction of calibration uncertainty in physics analyses

Thank you!