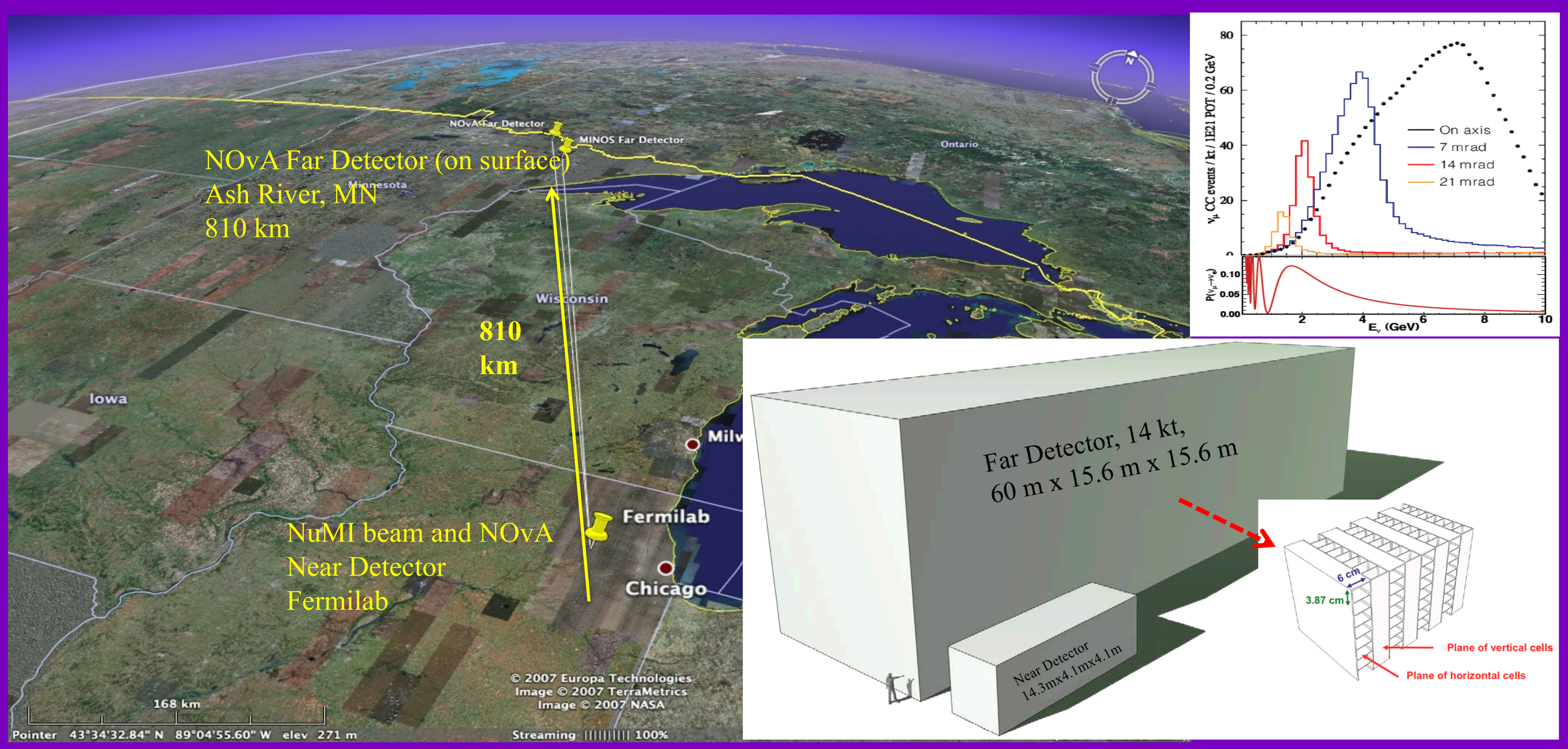
Energy Reconstruction in NOvA with Regression Convolutional Neural Networks

Pierre Baldi, Jianming Bian, Lars Hertel, Lingge Li
University of California, Irvine

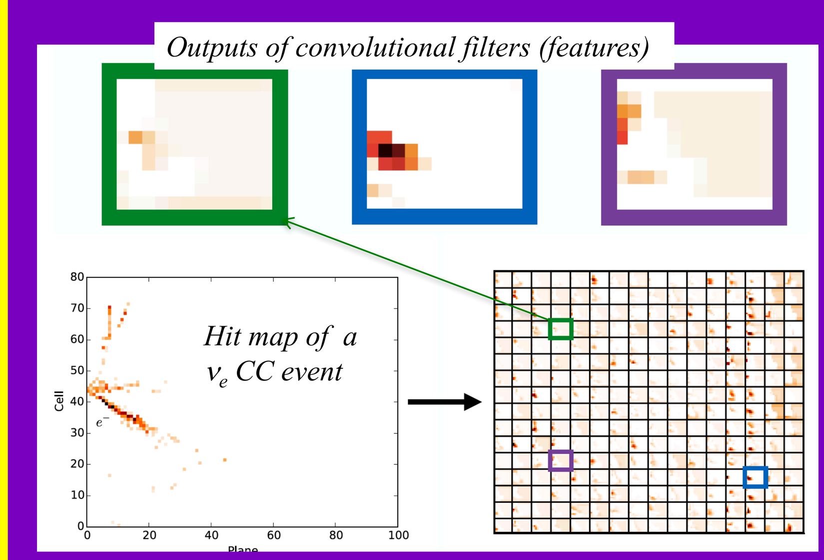
NuMI Off-Axis ν_e Appearance Experiment



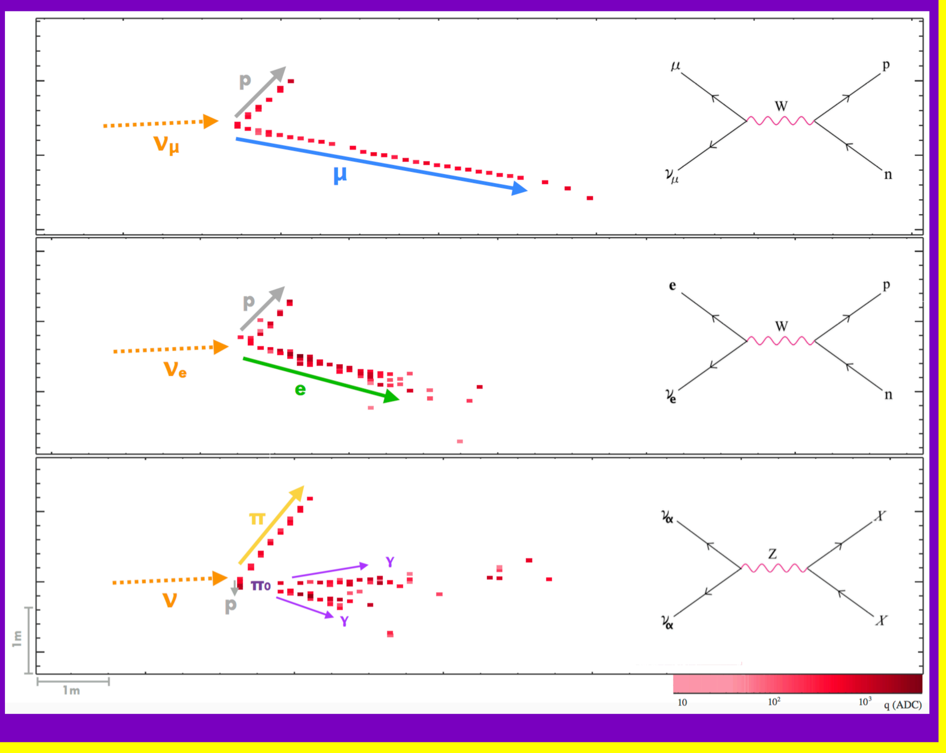
- Upgraded NuMI muon neutrino beam at Fermilab (700 kW design)
- Longest baseline in operation (810 km), large matter effect (±30%), sensitive to mass hierarchy
- Far/Near detector sited 14 mrad off-axis, narrow-band beam around oscillation maximum, small wrong sign components

NOvA Event Topologies and Convolutional Neural Networks

Convolutional Neural Networks (CNNs) have demonstrated success in **classification** problems such as event identification. We propose a **regression** CNN based method to reconstruct electron neutrino energy and electron energy at NOvA. This method can also be extended to solve other regression problems in HEP, taking over kinematics-based reconstruction tasks

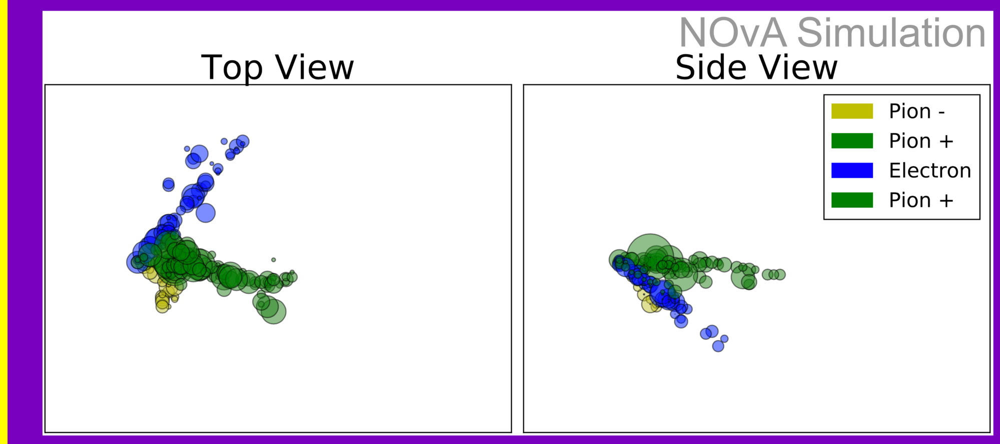


- NOvA pioneered application of CNNs in flavor tagging problems (CVN)
- ν_e , ν_μ and NC analyses at NOvA all use CVN as event selector

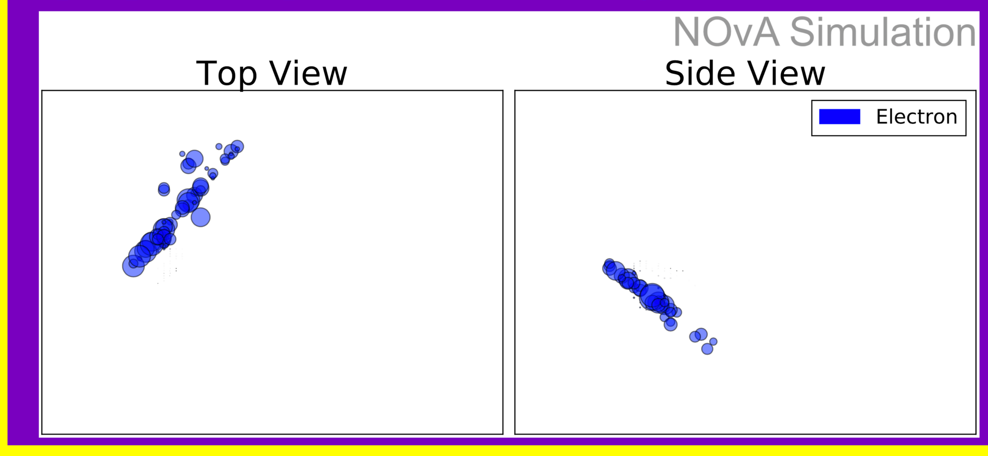


Regression Convolutional Neural Network for ν_e CC and Electron Energy

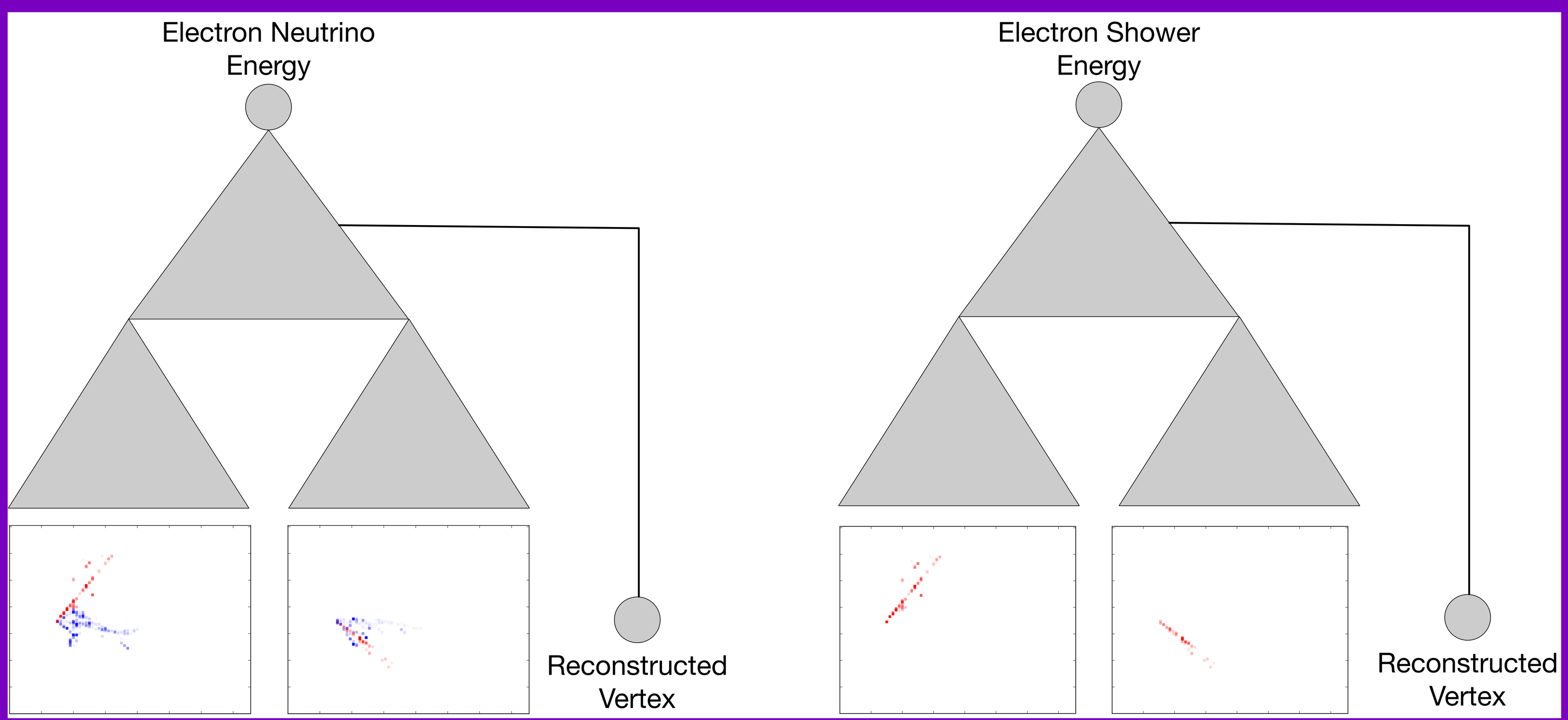
Input pixel maps for neutrino energy – full event



Input pixel maps for electron energy – electron shower



CNN Architecture



- Siamese architecture
- Reconstructed vertex inputs for location dependency

- Uses Inception modules
- Linear output for continuous variables
- No regularization

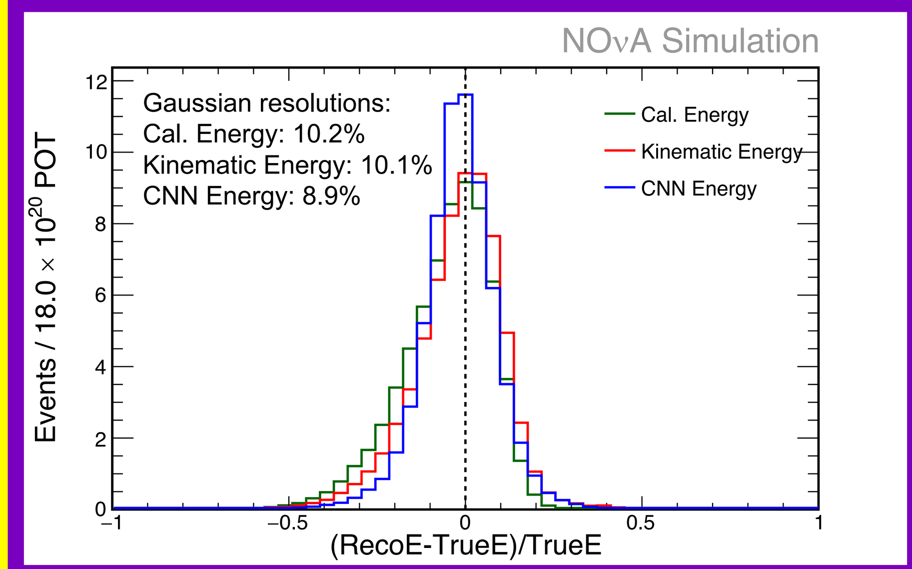
Loss function

$$L(\mathbf{W},\{\mathbf{x}_i,y_i\}_{i=1}^n)=\frac{1}{n}\sum_{i=1}^{n}\left|\frac{f_{\mathbf{W}}(\mathbf{x}_i)-y_i}{y_i}\right|$$

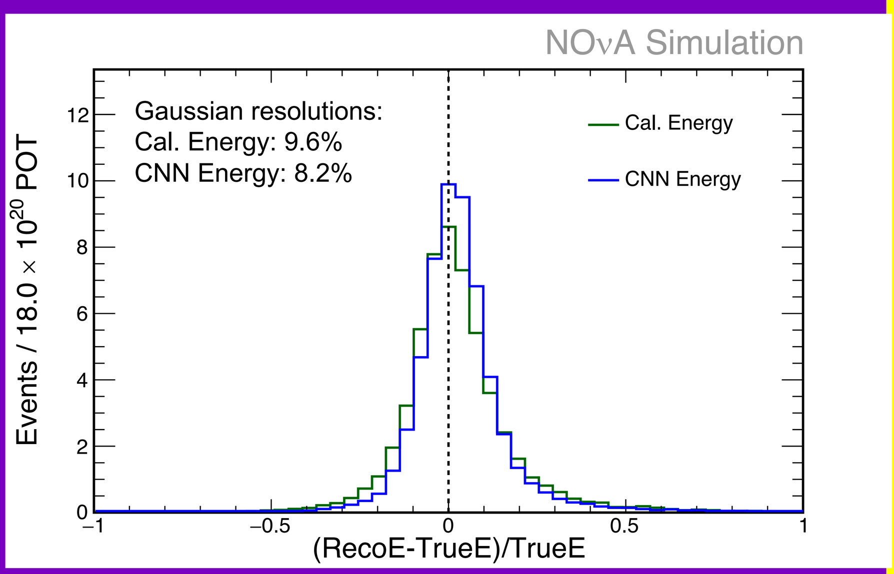
- Provides appropriate surrogate to optimize energy resolution $E_{reco}-E_{true}/E_{true}$
- Use absolute error instead of mean squared error to prevent large impacts from outliers
- CVN/GoogleNet are designed and trained for classification tasks, optimized training hyperparameters for regression task
- Hyperparameter optimization software SHERPA used

Results

Neutrino Energy

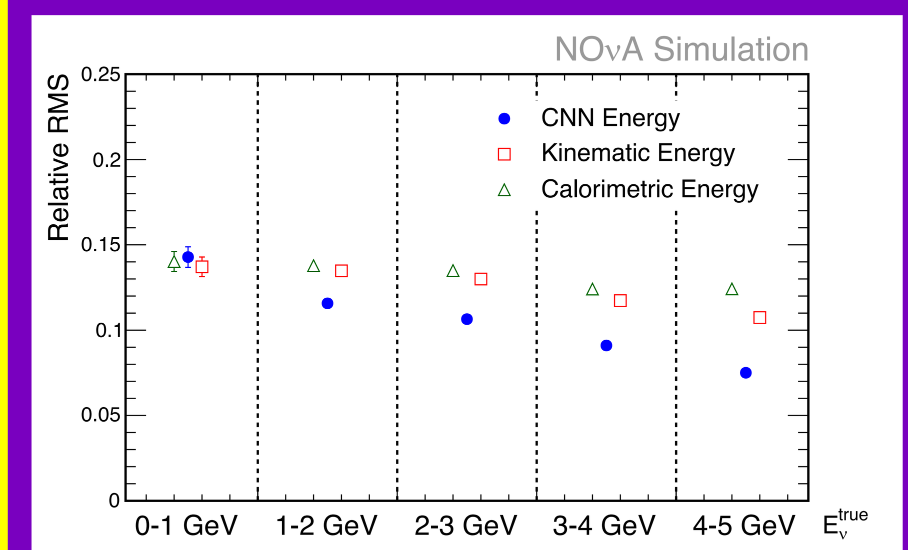


Electron Energy

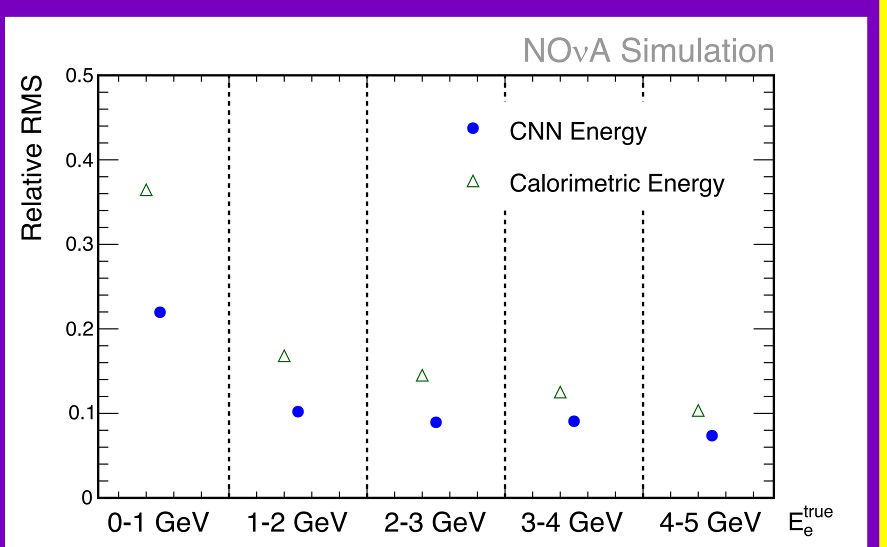


- Calorimetric energy - sum of calibrated calorimetric energy with a scale factor
- Kinematic energy - based on the method used in NOvA's ν_e analysis in 2017:
  $E(\nu_e) = A*E_{EM} + B*E_{HAD} + C*E_{EM}^{\ 2} + D*E_{HAD}^{\ 2}$
- CNN Energy - proposed regression CNN energy estimator

Reco. $E_{\nu e}$ Resolution vs. True $E_{\nu e}$



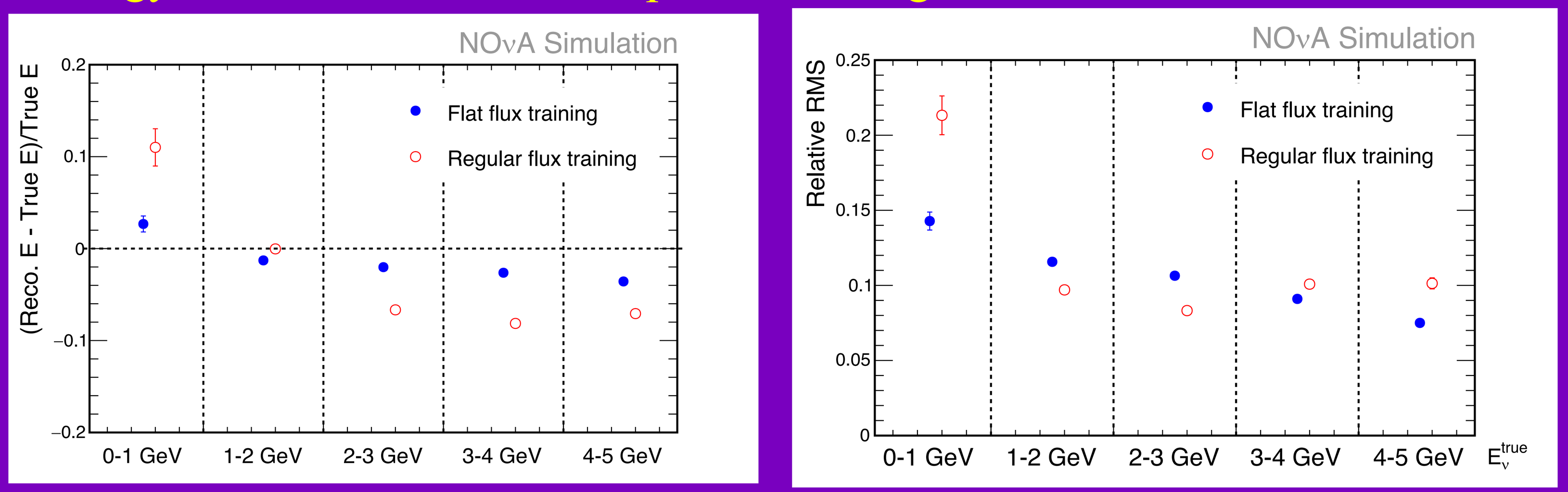
Reco. E_e Resolution vs. True E_e



- Energy scale of the three estimators shows no significant biases with respect to the true neutrino energy, and the regression CNN has better energy resolutions

Flat flux vs. Regular Flux Training

To minimize dependence of estimated neutrino energy on true neutrino energy, a flat neutrino flux shape is used to generate Far Detector MC

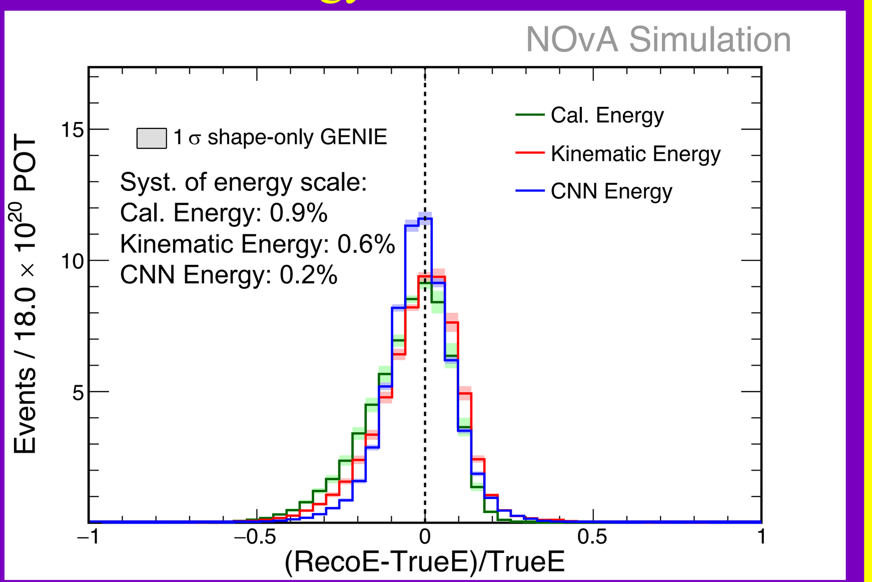


Energy scale from the flat flux training has less biases vs. true neutrino energy.

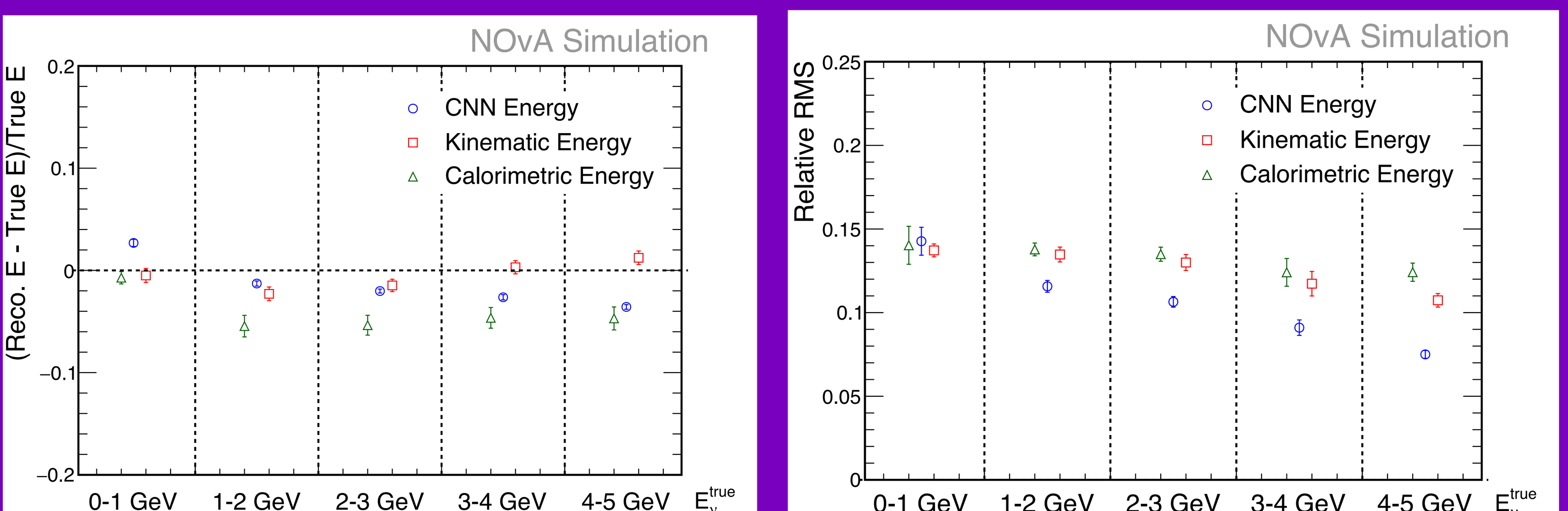
Systematic Uncertainties

- Systematic uncertainties in the energy reconstruction from the simulation of neutrino interactions are evaluated by using the reweighing knobs built into GENIE
- The regression CNN shows smallest systematic uncertainties from the simulation of neutrino interactions

Neutrino Energy



Reco. $E_{\nu e}$ Energy Scale vs. True $E_{\nu e}$ / Reco. $E_{\nu e}$ Resolution vs. True $E_{\nu e}$



Error bars represent systematic uncertainties evaluated by GENIE reweighing

http://novaexperiment.fnal.gov/

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Contact: Jianming Bian, bianjm@uci.edu
Lars Hertel, lhertel@uci.edu
Lingge Li, linggel@uci.edu