New NuMu CC Energy Estimator based on a Recurrent Neural Network

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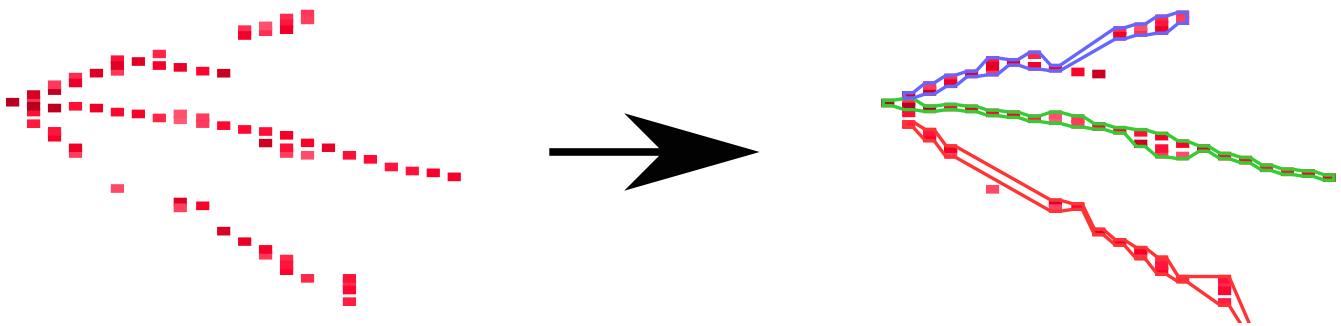
Introduction

- I have developed a new NuMu CC energy estimator based on a Recurrent Neural Network for NOvA:
  - RNN EE has 15% better energy reconstruction.
  - And it is 5 times less sensitive to the major systematic uncertainty.

  compared to the Standard NOvA energy estimator.

- I have ported this energy estimator to DUNE and will present initial performance results.

NOvA. RNN Energy Estimator.



NOvA's RNN NuMu CC ($\nu_\mu \rightarrow \mu + \text{Had}$) energy estimator:

- It looks at all reconstructed particles in each event.
- It reads their calorimetric energy, number of hits, direction, dimensions, PID, energy and momenta.
- And predicts the ν_μ and μ energies.

Porting NOvA RNN EE to DUNE

- I have tried to port NOvA's RNN energy estimator to DUNE.
- I have used information from particles found by Pandora in order to reconstruct ν_μ energy.
- From all PFParticle found by Pandora I have considered only the ones that have associated track or shower.
- I would like to thank Christopher Backhouse for helping me getting started with DUNE.

DUNE RNN EE. Inputs

Pandora PFParticle:

```
particle.is_shower
particle.length
particle.start.{x,y,z}
particle.dir.{x,y,z}
particle.energy
particle.calE
particle.charge
particle.nHit
```

Event vars:

```
addr.run
reco.event.calE
reco.event.charge
reco.event.nHits
```

DUNE RNN EE. Setup

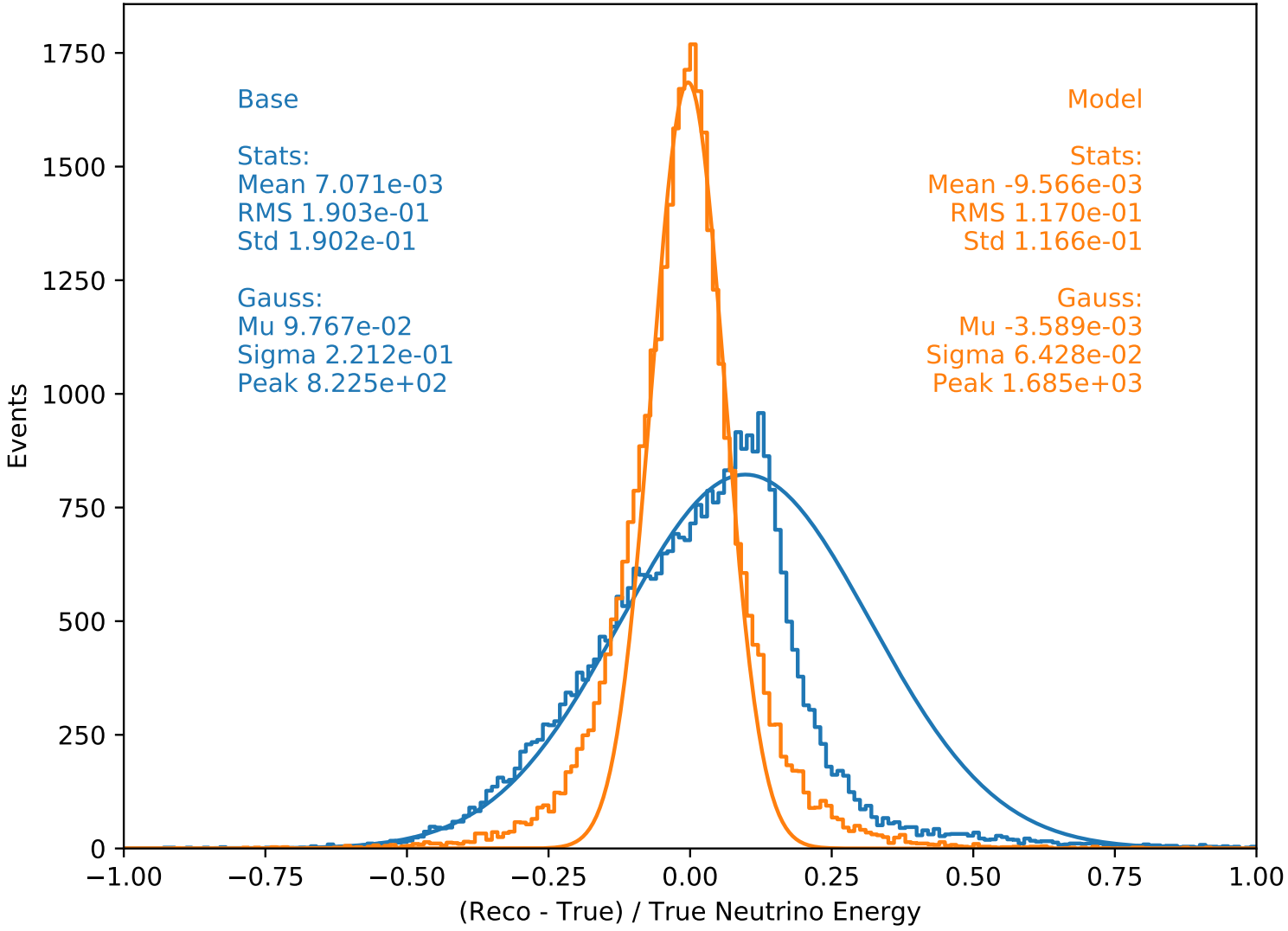
- Used MCC11 dataset:
  `prodgenie_nu_dune10kt_1x2x6_mcc11_lbl_reco`

- I have required the following preselection for Training Sample:
  - `mc.isCC && (abs(mc.pdg) == 14)`
  - `mc.nuE < 5.0`
  - `reco.numue.longestTrackContained`

- Additionally I have required that truth vertex is contained in the fiducial volume for the Evaluation Sample.

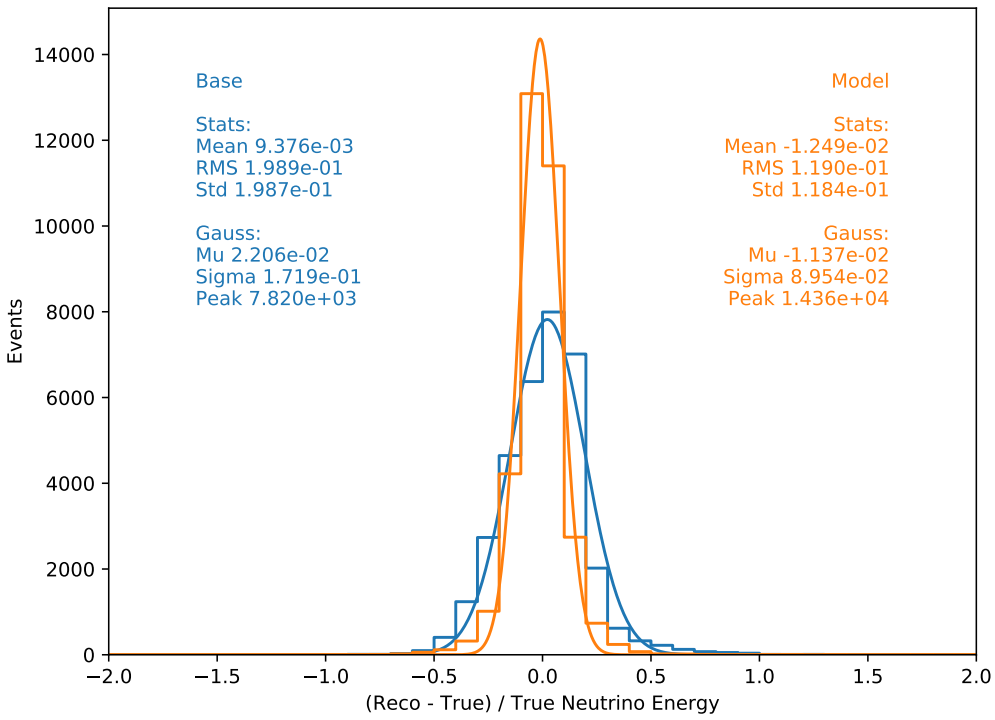
- Problem: entire MCC11 dataset has only 200k events – not sufficient for fully optimized training.

DUNE RNN EE. Neutrino Energy Resolution

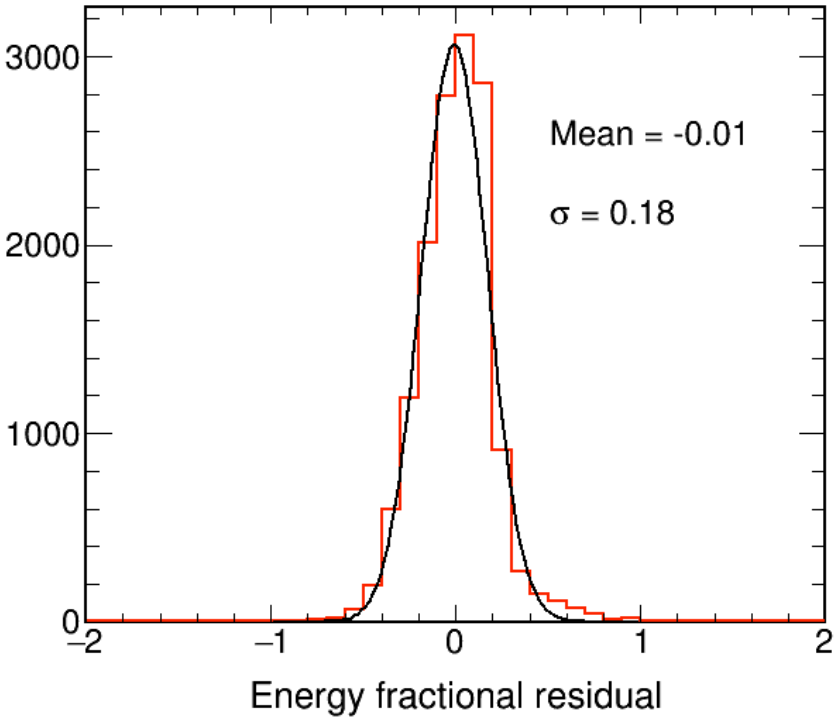


RNN EE (RMS 12%) has better energy resolution that the DUNE Kinematic EE (RMS 19%)

DUNE. RNN Coarse Binning vs Kinematic EE



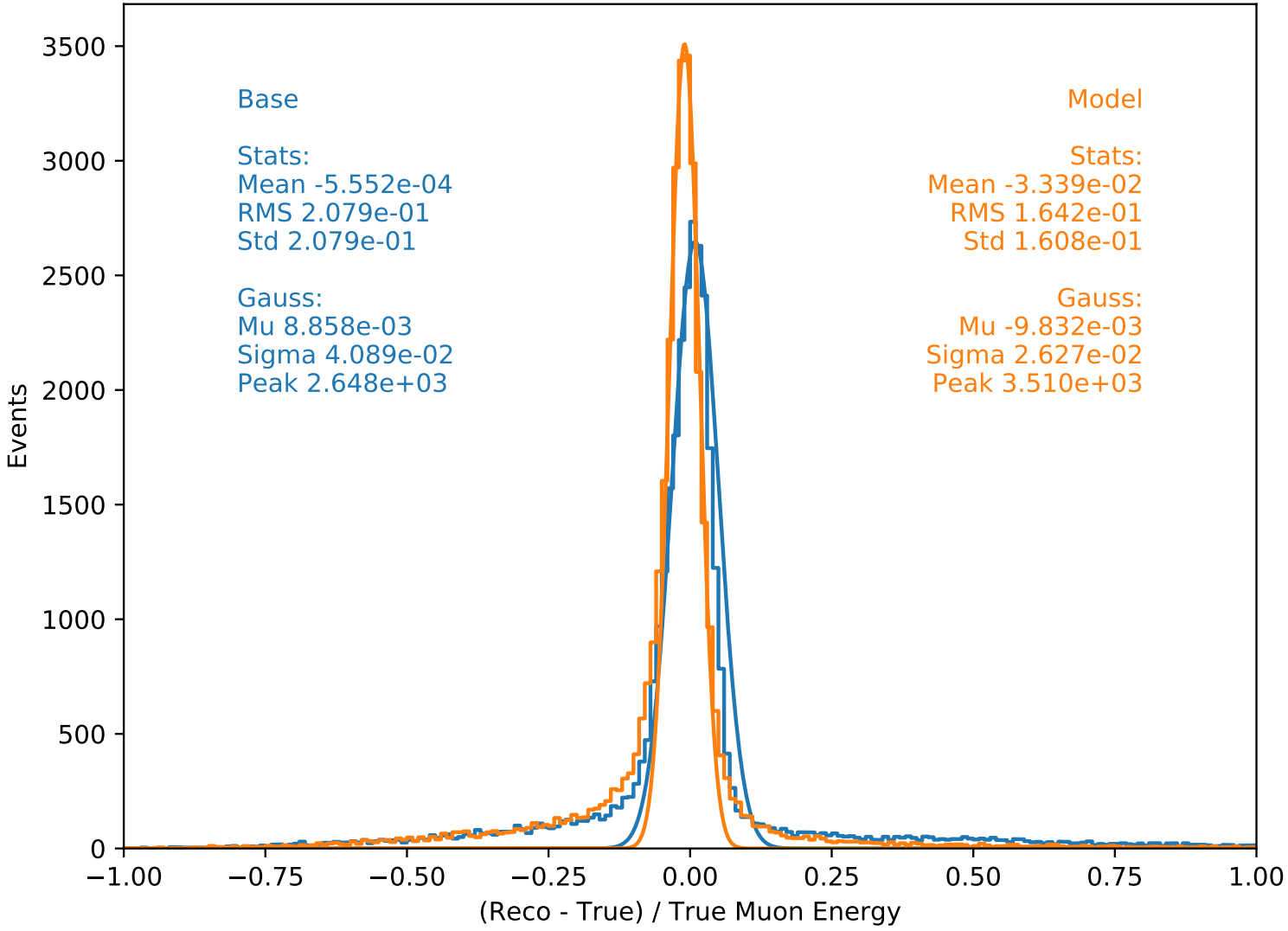
(a) Reproduction



(b) Official

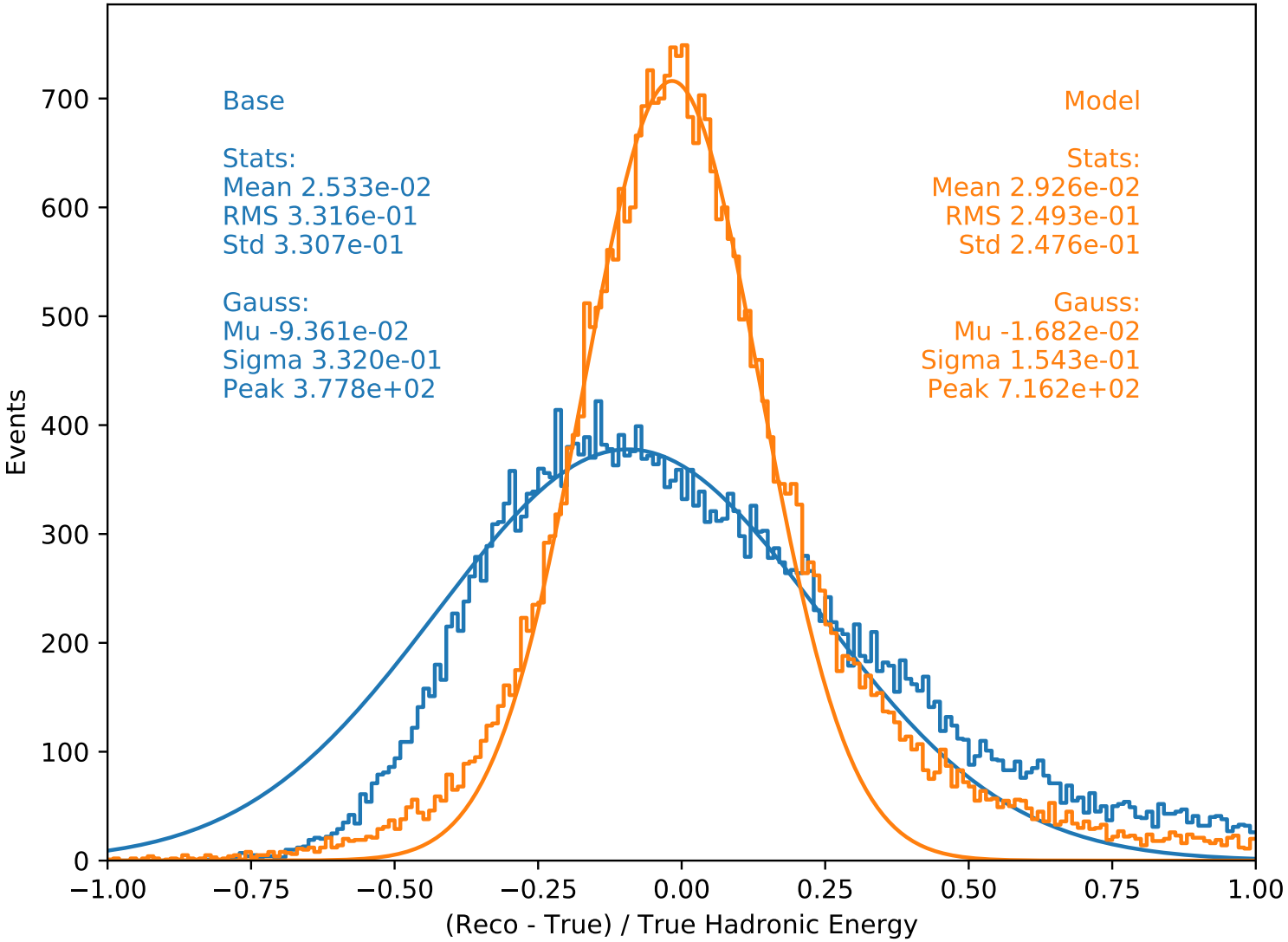
Good agreement between my reproduction of Kinematic energy resolution and results by Nick Grant (APS DPF 2017)

DUNE RNN EE. Muon Energy Resolution



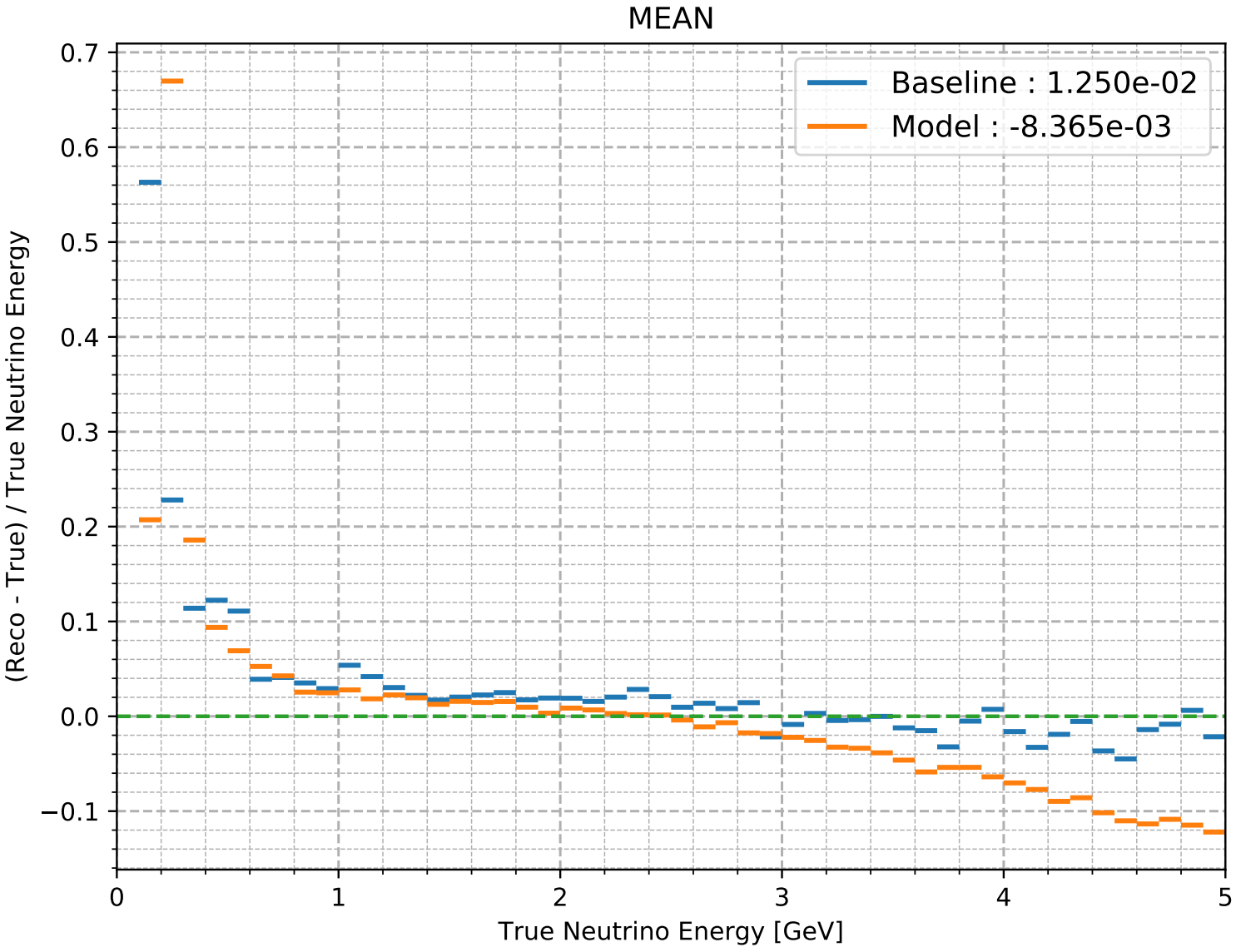
RNN EE (RMS 16%) has better energy resolution that the DUNE Kinematic EE (RMS 21%)

DUNE RNN EE. Hadronic Energy Resolution

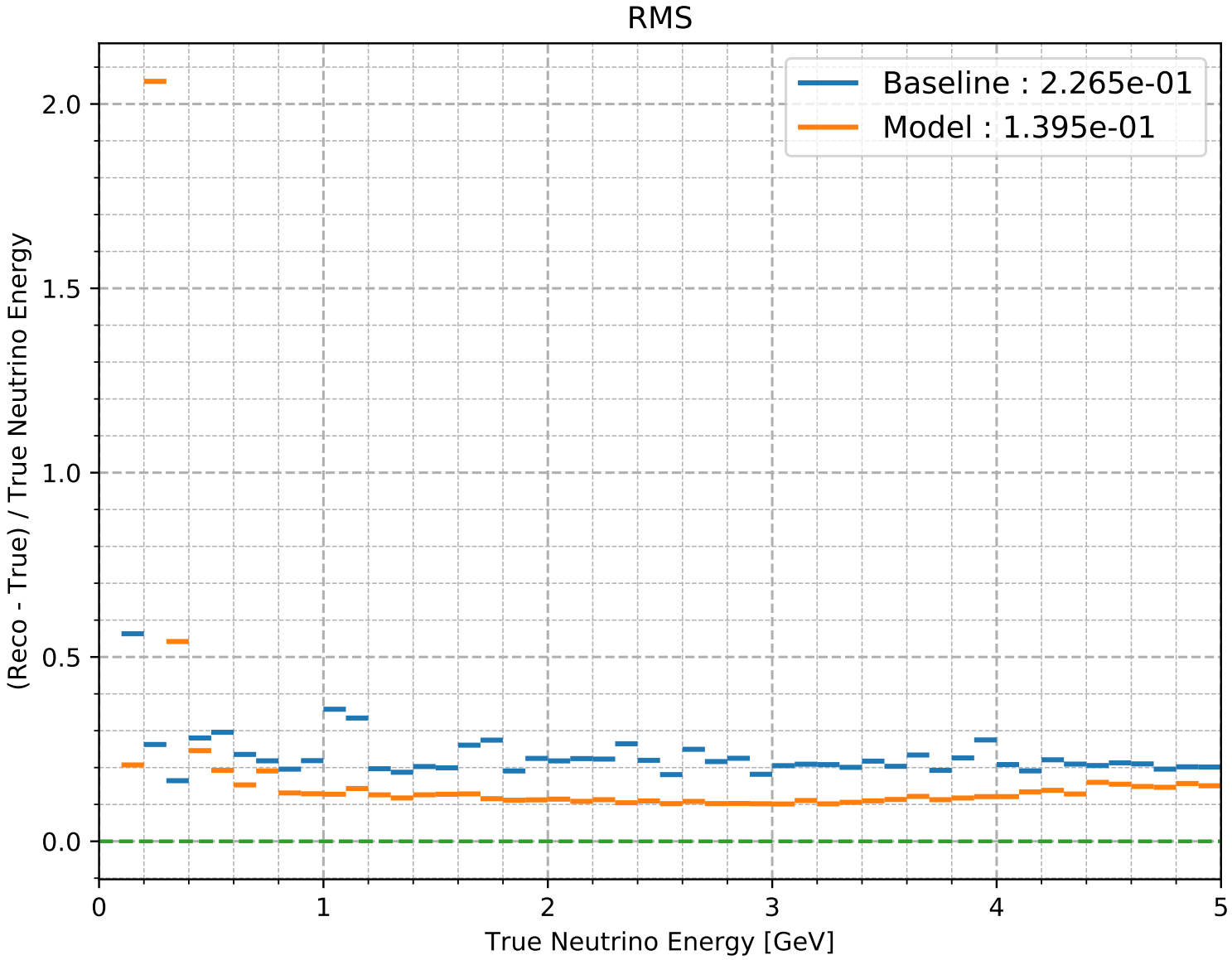


RNN EE (RMS 25%) has better energy resolution that the DUNE Kinematic EE (RMS 33%)

DUNE RNN EE. Means of Energy Resolution vs True Energy



DUNE RNN EE. RMS of Energy Resolution vs True Energy



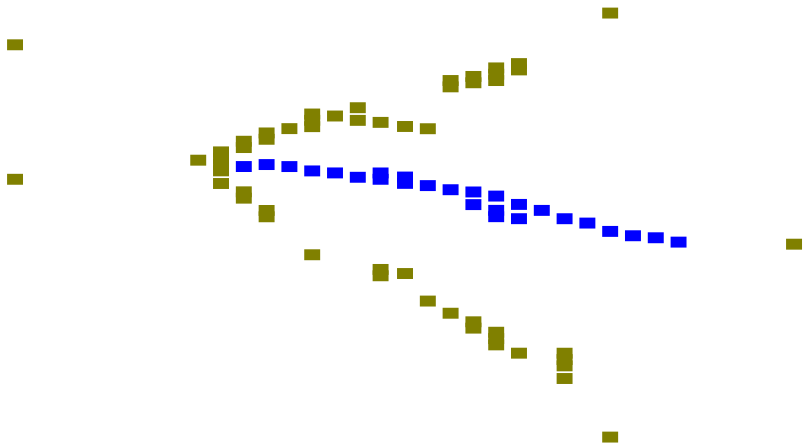
DUNE RNN EE. Conclusions

- RNN EE on DUNE achieves better energy reconstruction RMS 12% vs 19% for Kinematic EE.

- Future Steps:
  - I can finish *art* package to evaluate RNN EE for DUNE in a couple of weeks.
  - Need to refine choice of input variables.
  - Need more training events to fully optimize RNN EE.
  - Need to study RNN EE sensitivity to systematic uncertainties.
  - Can apply mitigation techniques to reduce impact of particular systematic uncertainties.

Backups

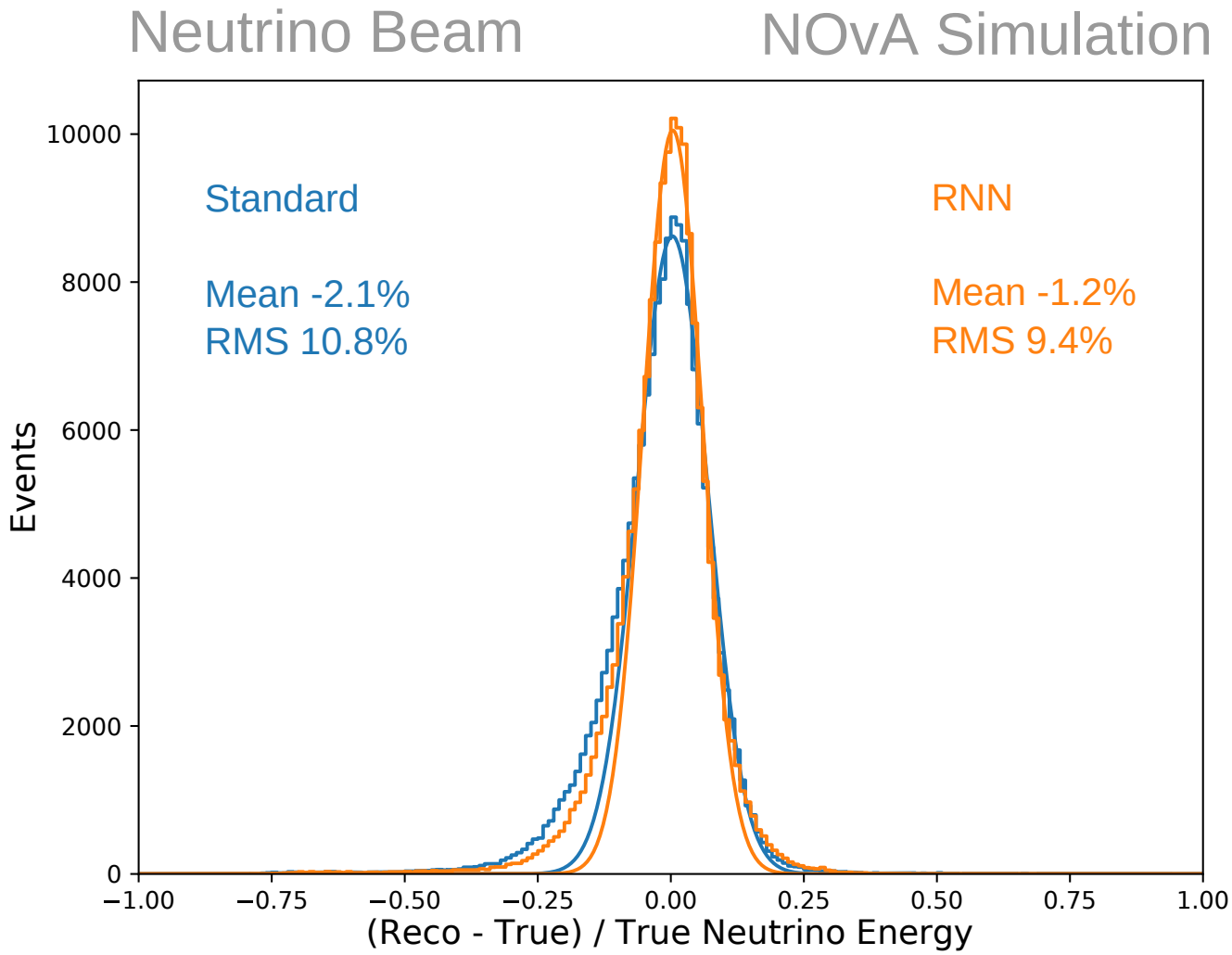
NOvA. Standard Energy Estimator.



NOvA's NuMu CC ($\nu_\mu \to \mu + \text{Had}$) energy estimator is similar to DUNE's NuMu CC energy estimator:

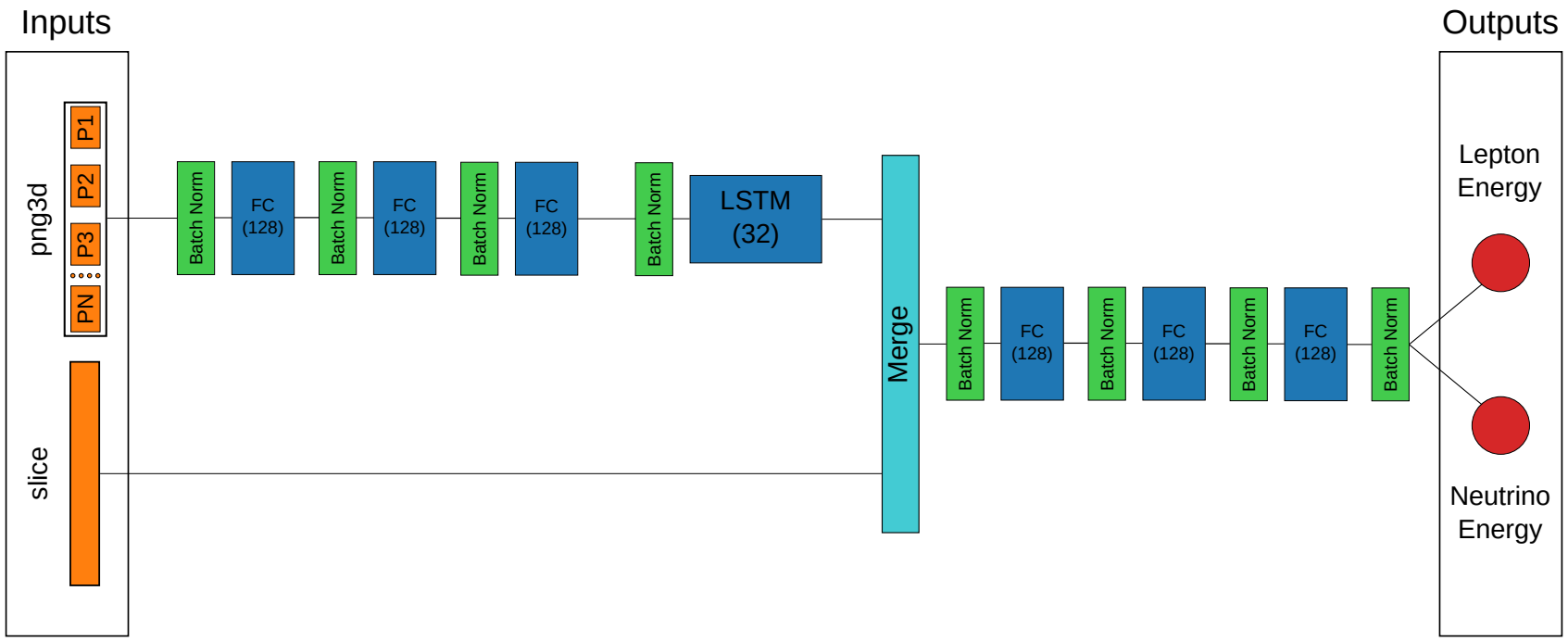
1. Find muon track (blue) and estimate E_μ from muon track length.
2. Estimate E_{Had} from calorimetric energy of hadronic hits (yellow).
3. $E_\nu = E_\mu + E_{\text{Had}}$.

NOvA. RNN Energy Estimator Performance



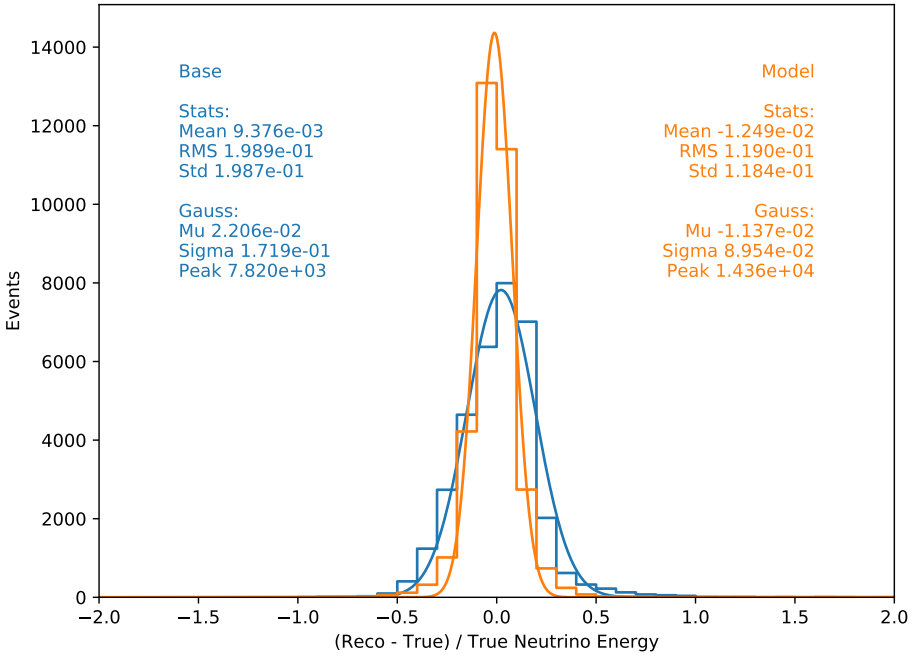
RNN energy estimator is better than the Standard in terms of RMS 9.4% vs 10.8%.

DUNE. RNN EE Architecture

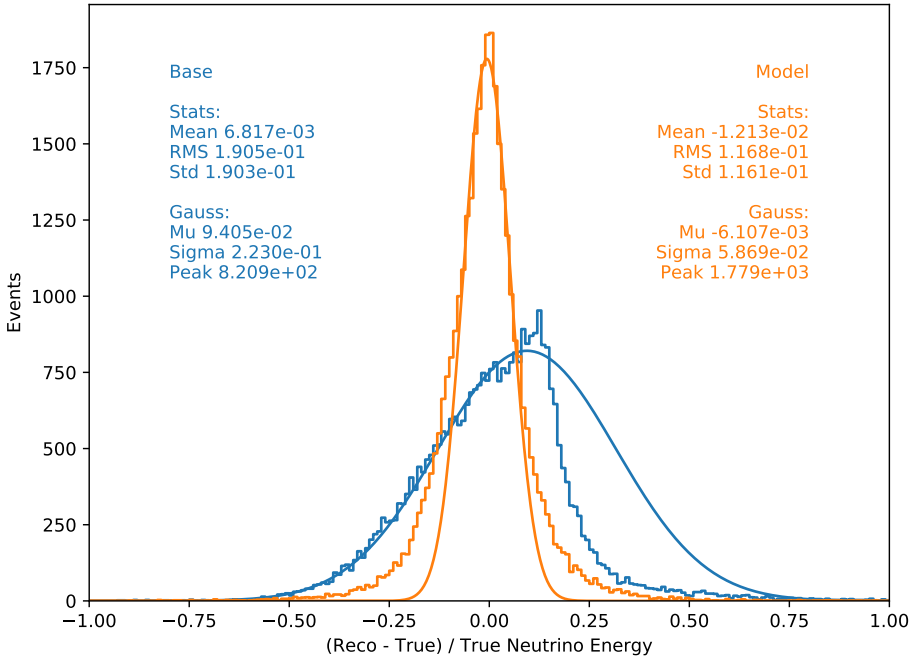


Architecture of the DUNE's RNN Energy Estimator

Coarse vs Fine Binning

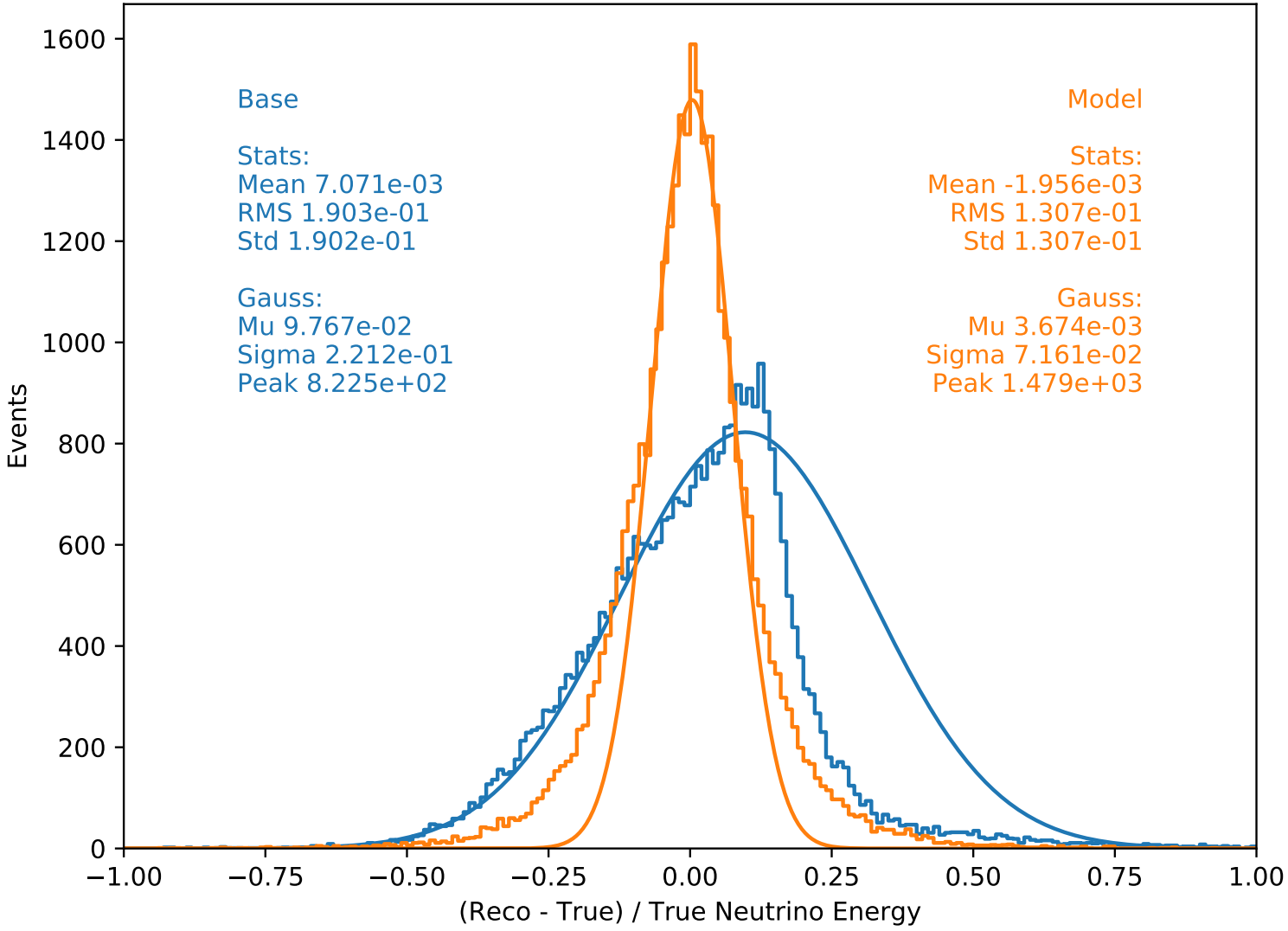


(a) Coarse Binning



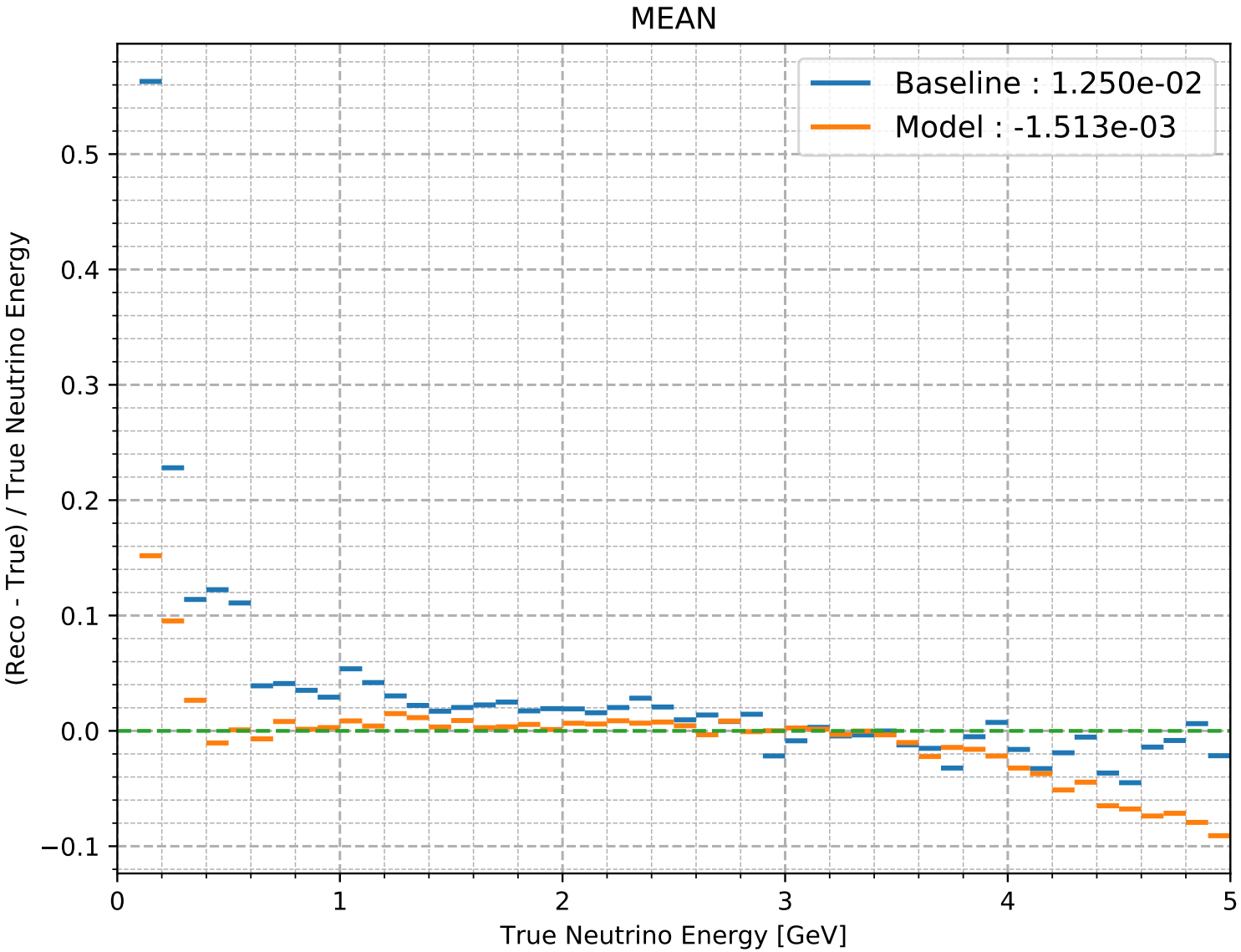
(b) Fine Binning

DUNE Flat RNN EE. Neutrino Energy Resolution

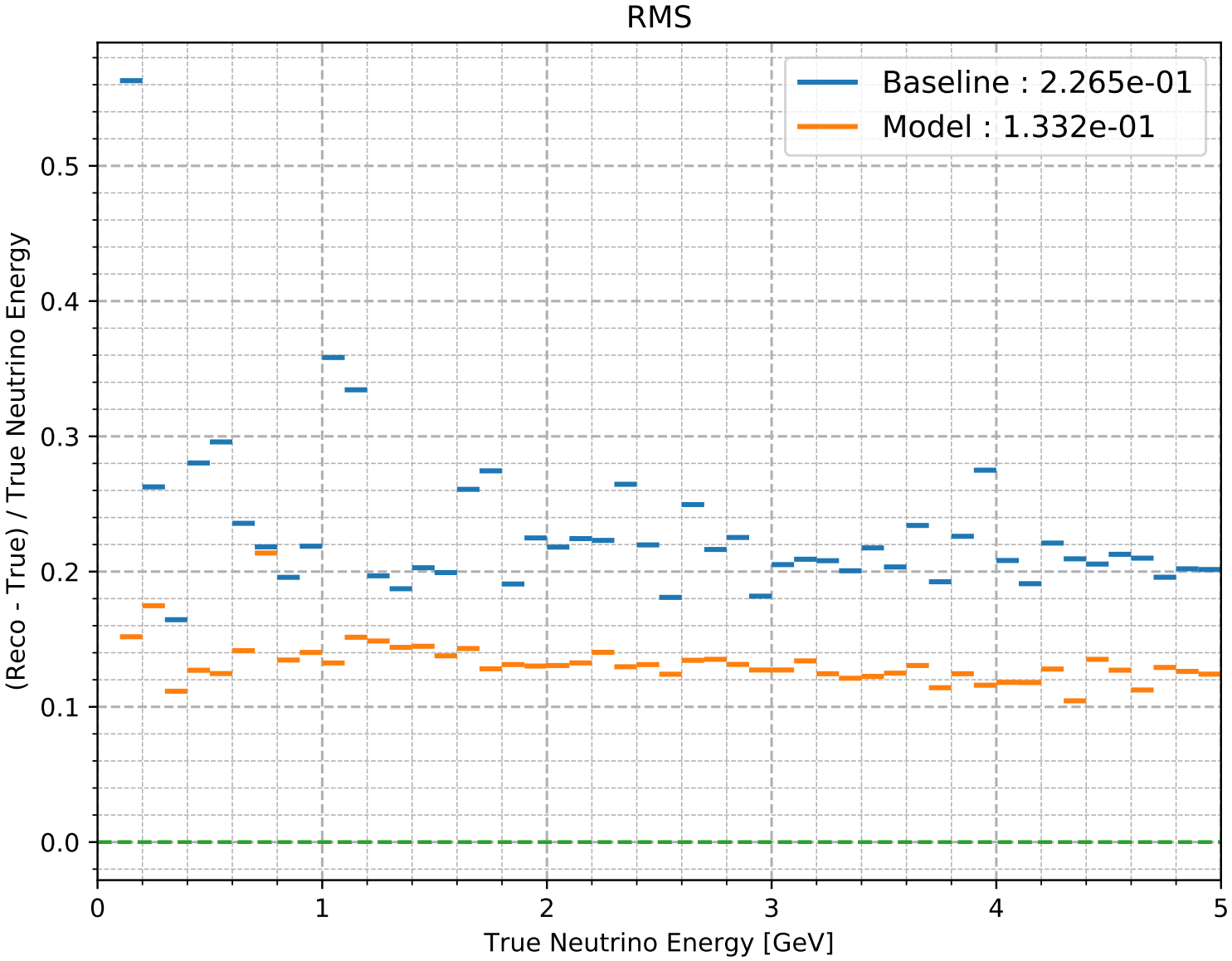


RNN EE (RMS 13%) has better energy resolution that the DUNE Kinematic EE (RMS 19%)

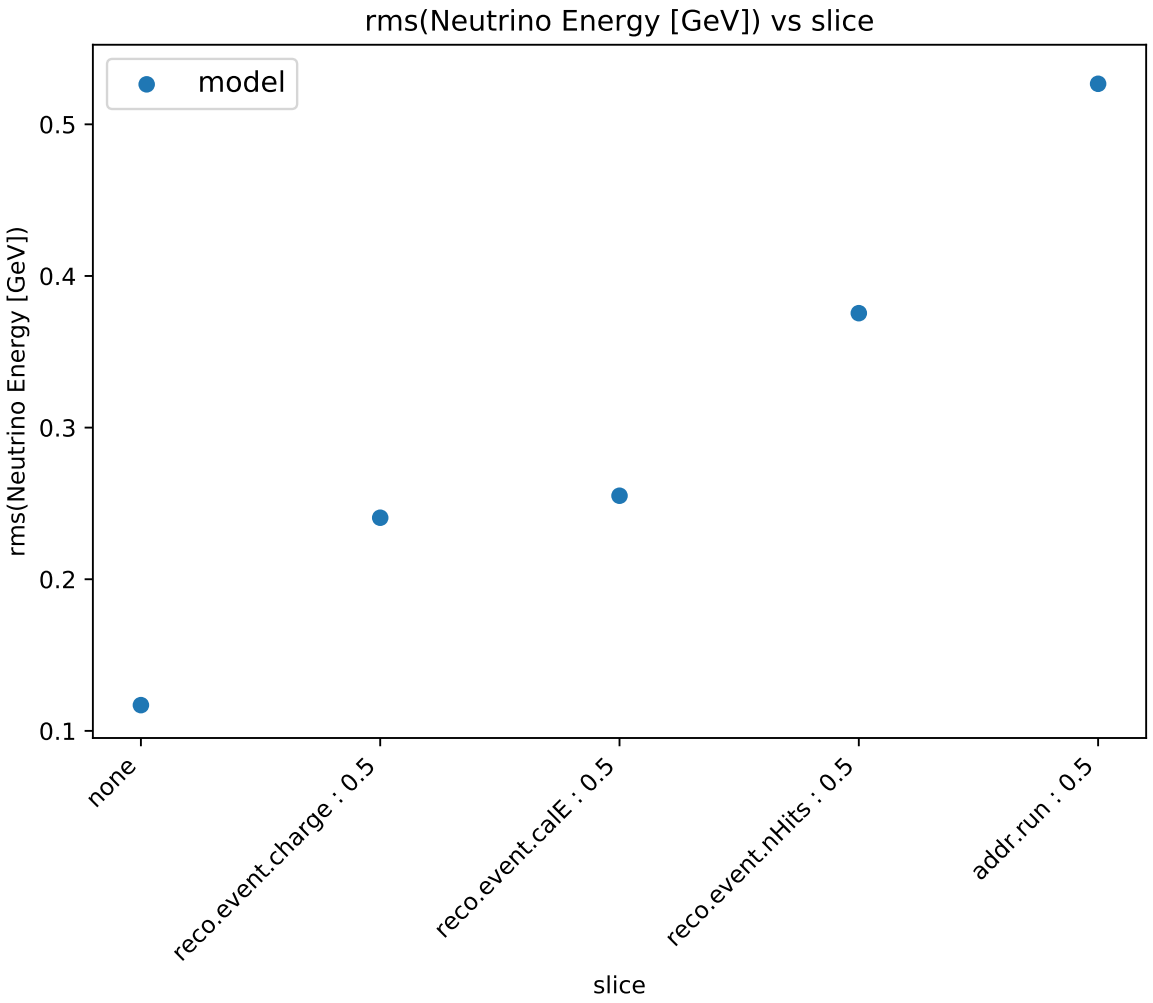
DUNE Flat RNN EE. Means of Resolution vs True Energy

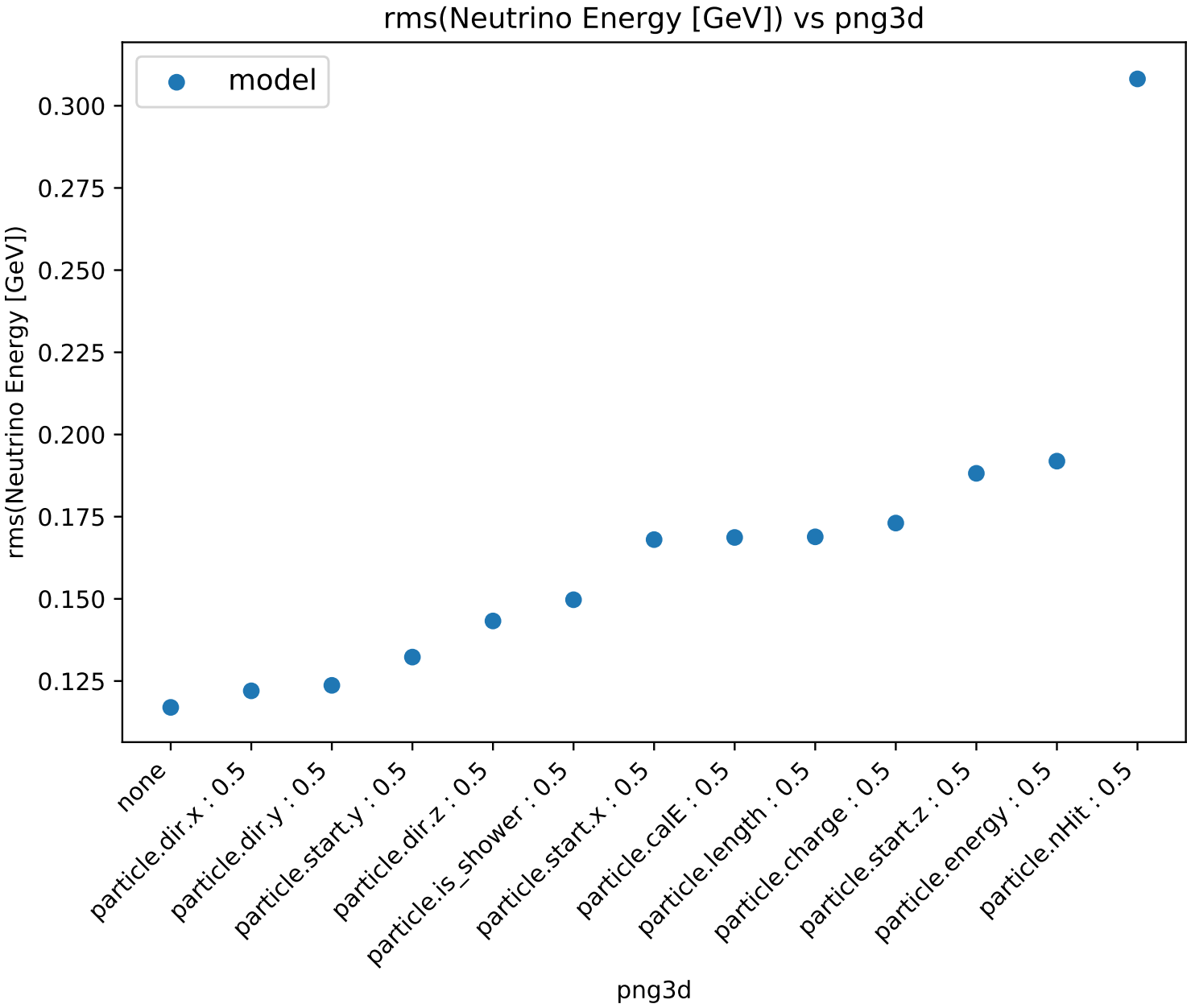


DUNE Flat RNN EE. RMS of Resolution vs True Energy



DUNE RNN EE. Variable Importance. Event Level



Higher value == more importance.
High `addr.run` is an artifact, its importance is zero.

DUNE RNN EE. Variable Importance. Particle Level