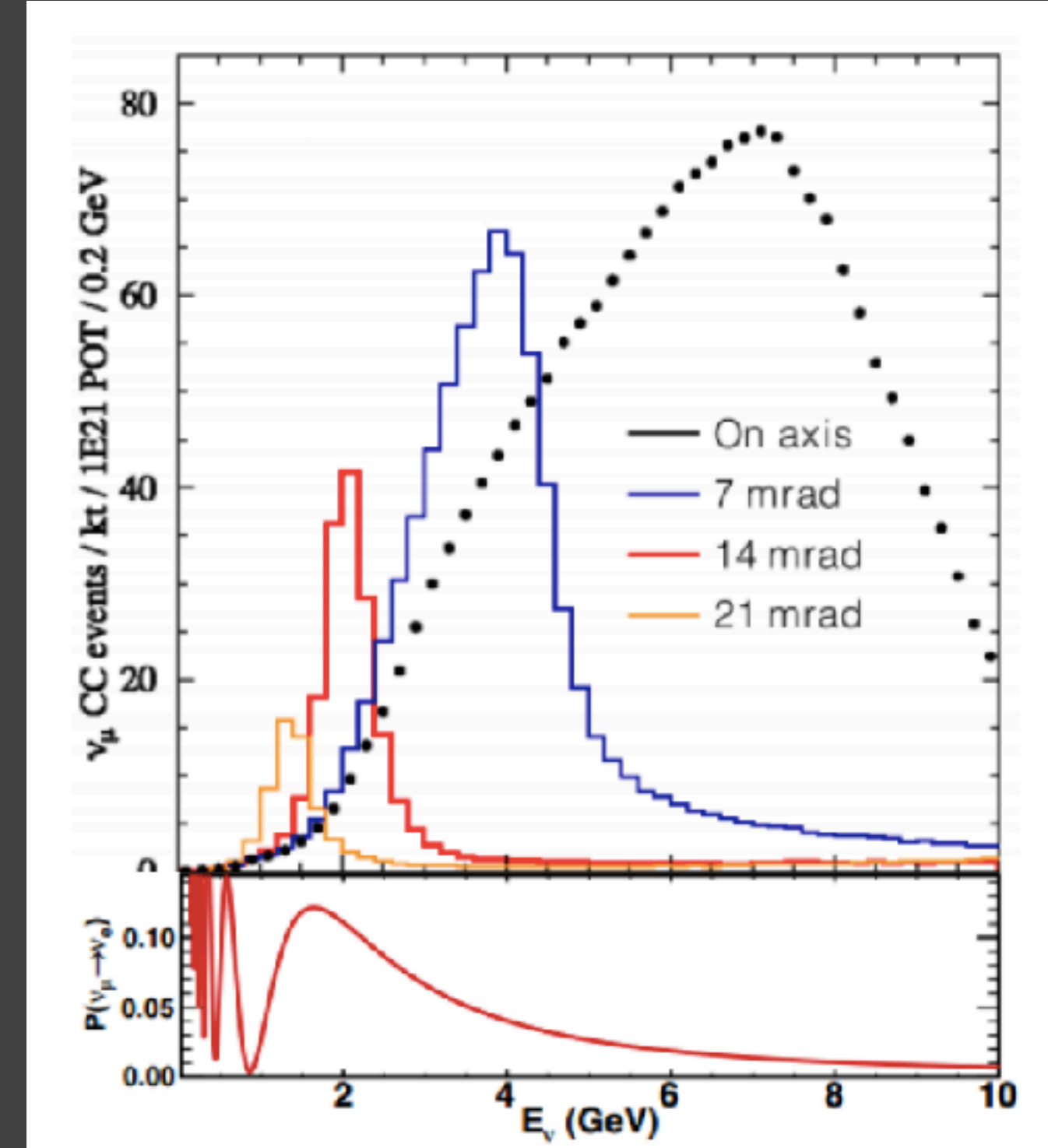# Neutrino Energy Estimation Techniques in NOvA

Nitish Nayak
University of California, Irvine
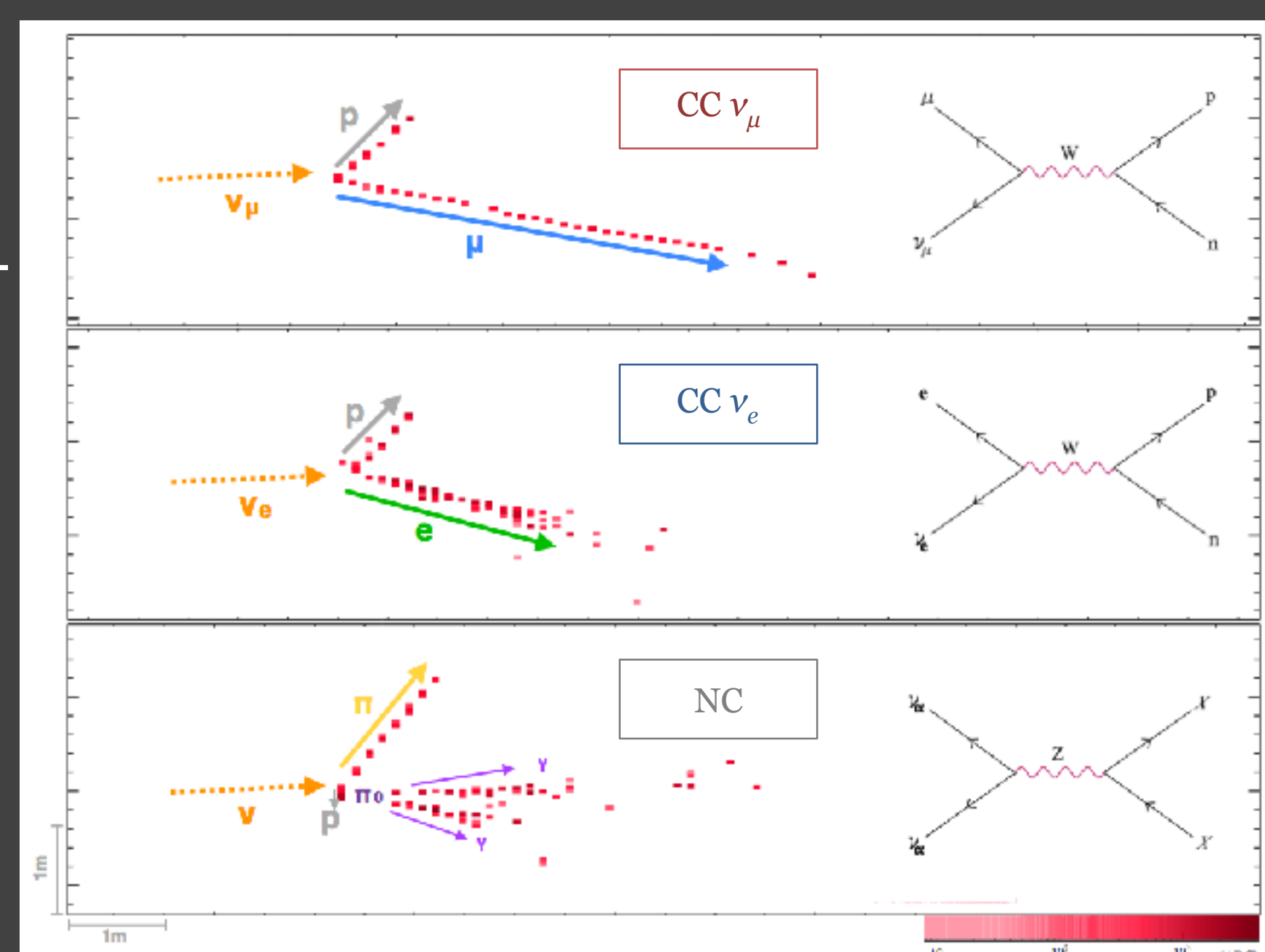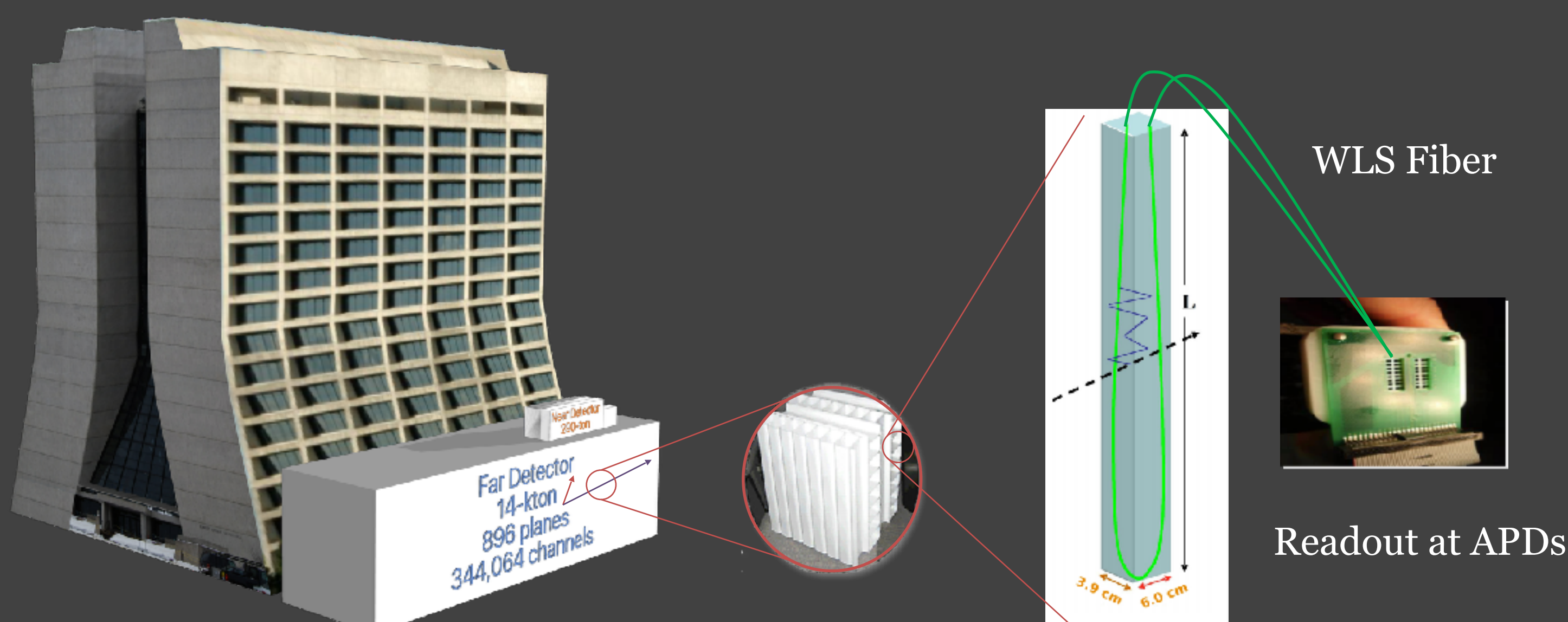## (For the NOvA Collaboration)

1. 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 ($\pm 30\%$), sensitive to mass hierarchy
- Far/Near detector sited 14 mrad off-axis, narrow-band beam around oscillation maximum
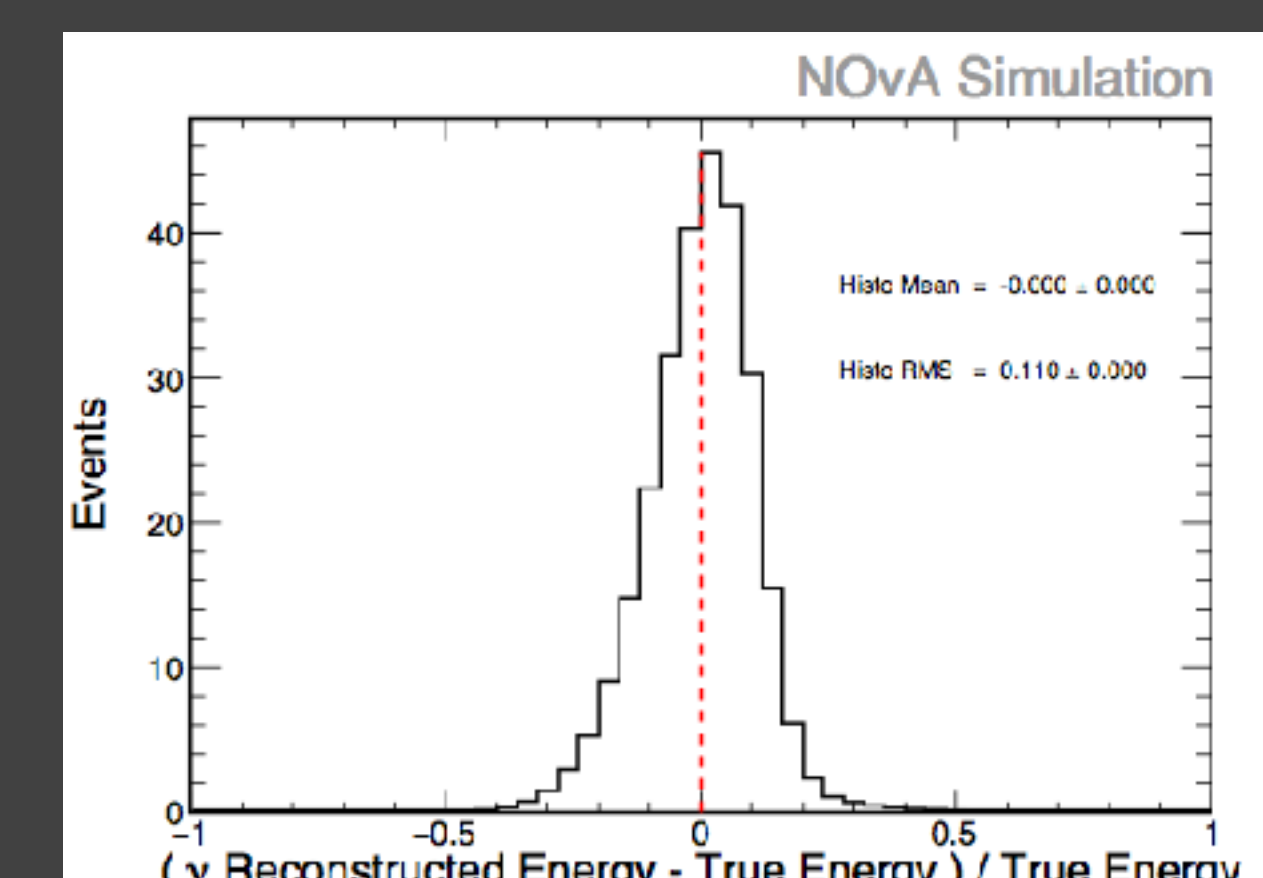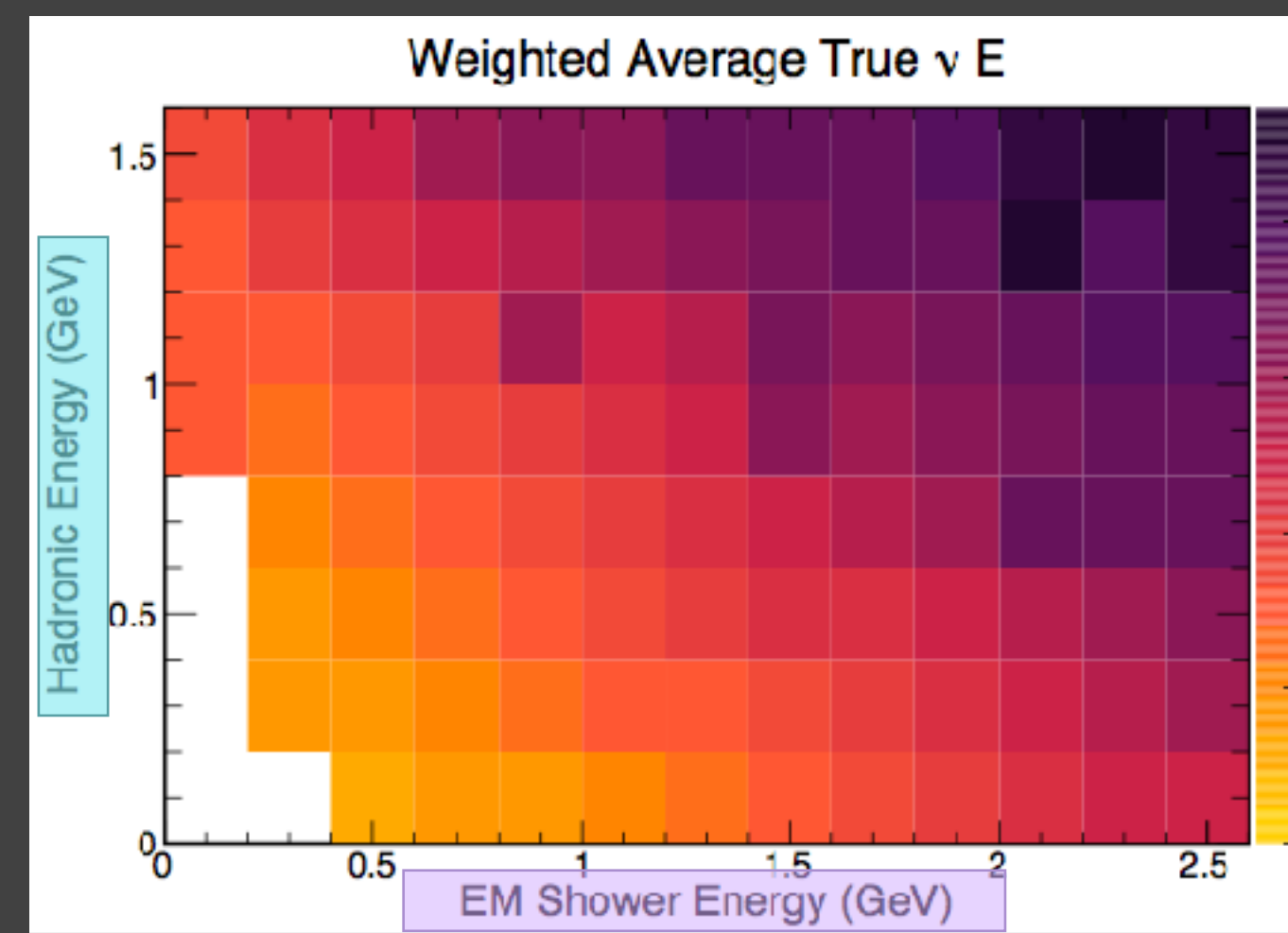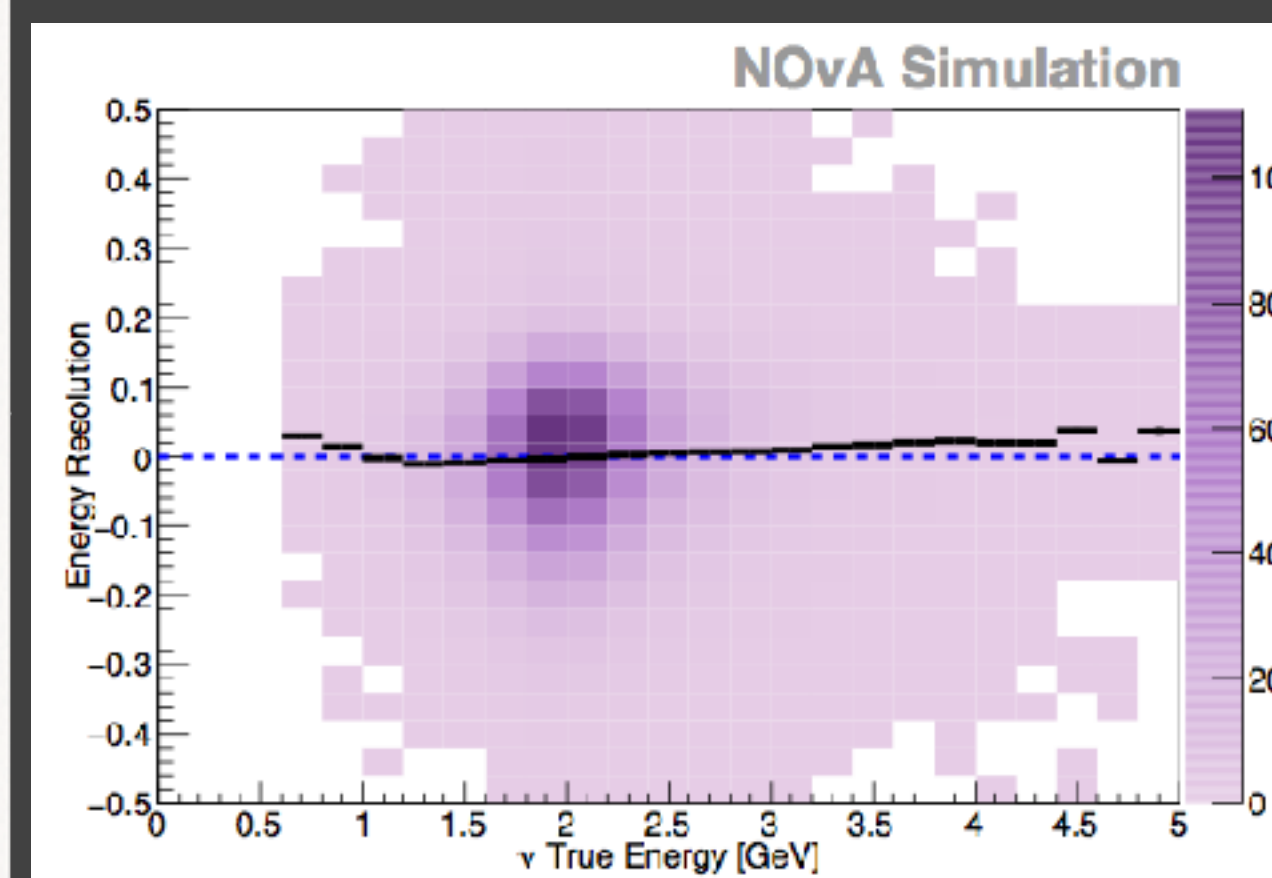
2. Detection Principle

WLS Fiber

Readout at APDs

- Tracking Calorimeter with Low-Z scintillator (mineral oil-based)
- Finely segmented
- Good $e^-/\mu^-/\pi^0$ separation
- Radiation Length ~ 6 cell depths -> Good energy resolution

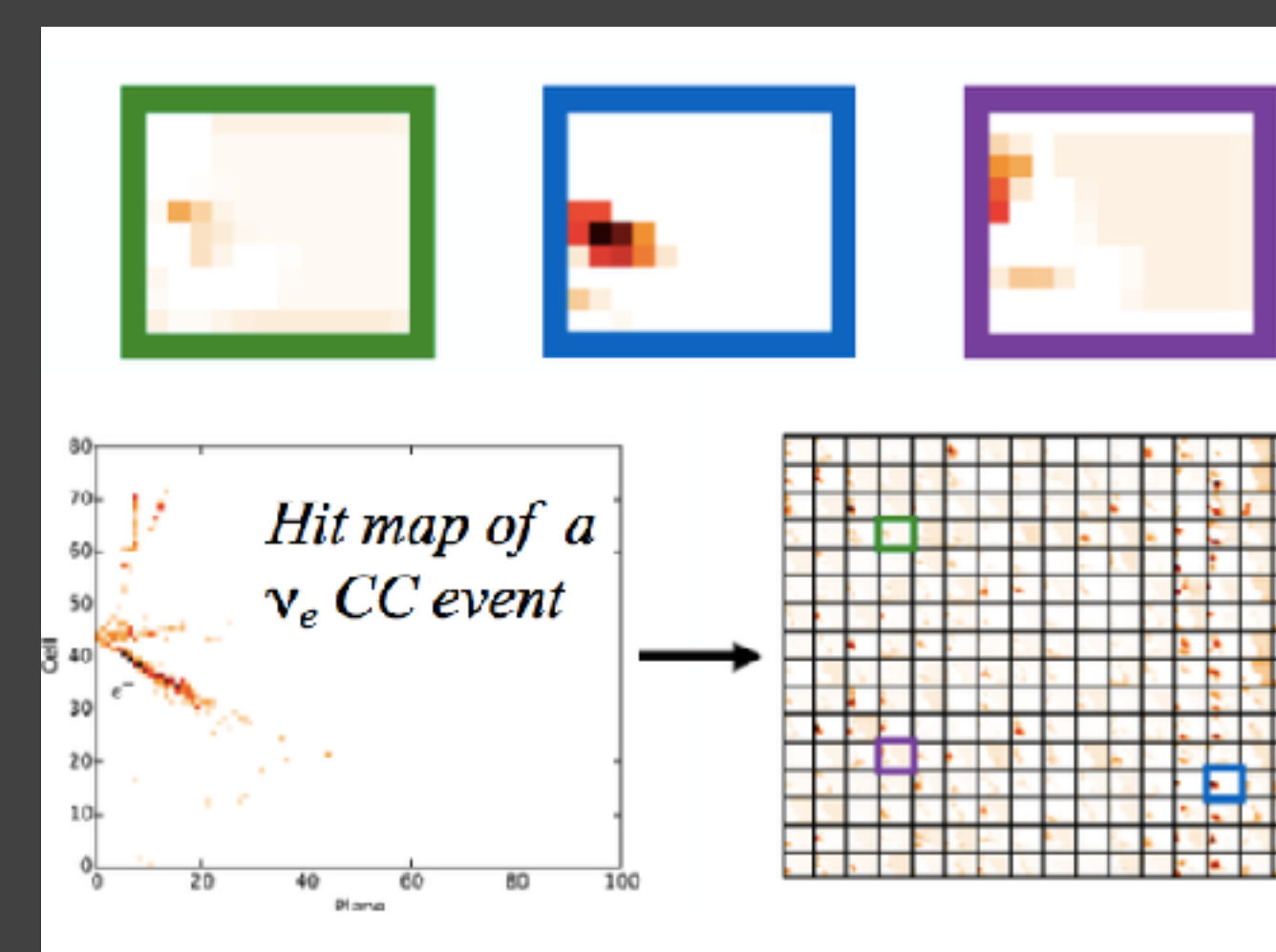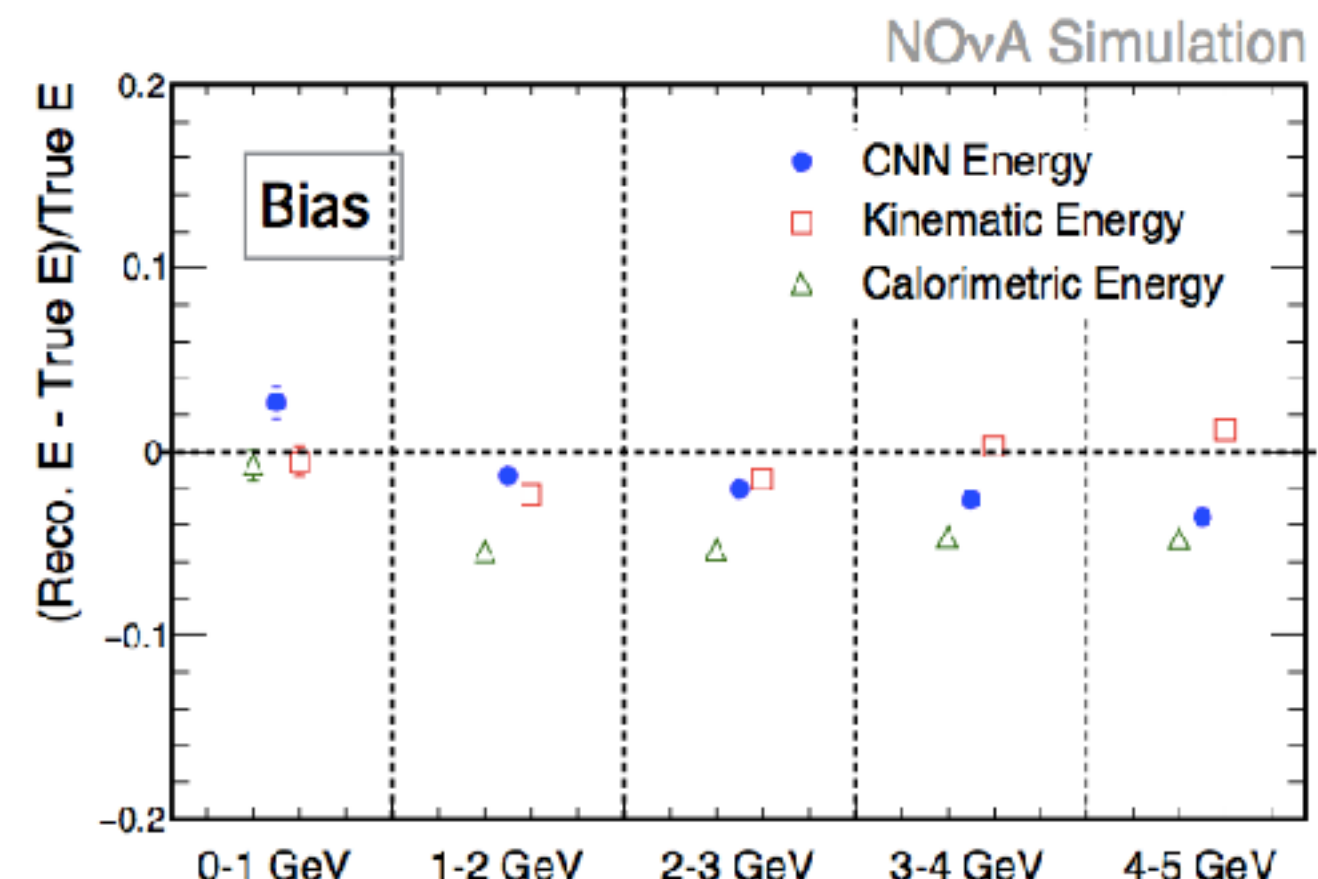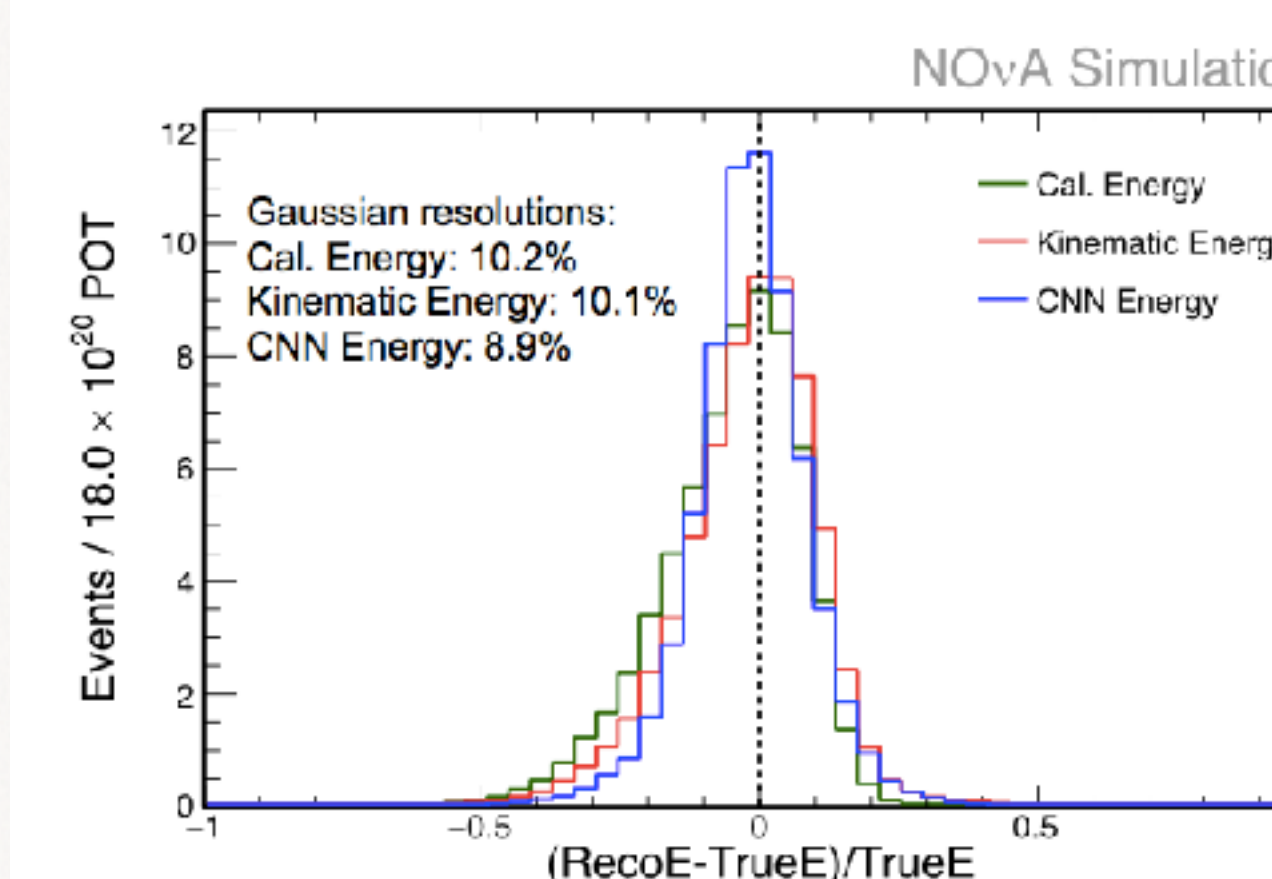## 3. ν_e Energy Reconstruction

Weighted Average True ν E
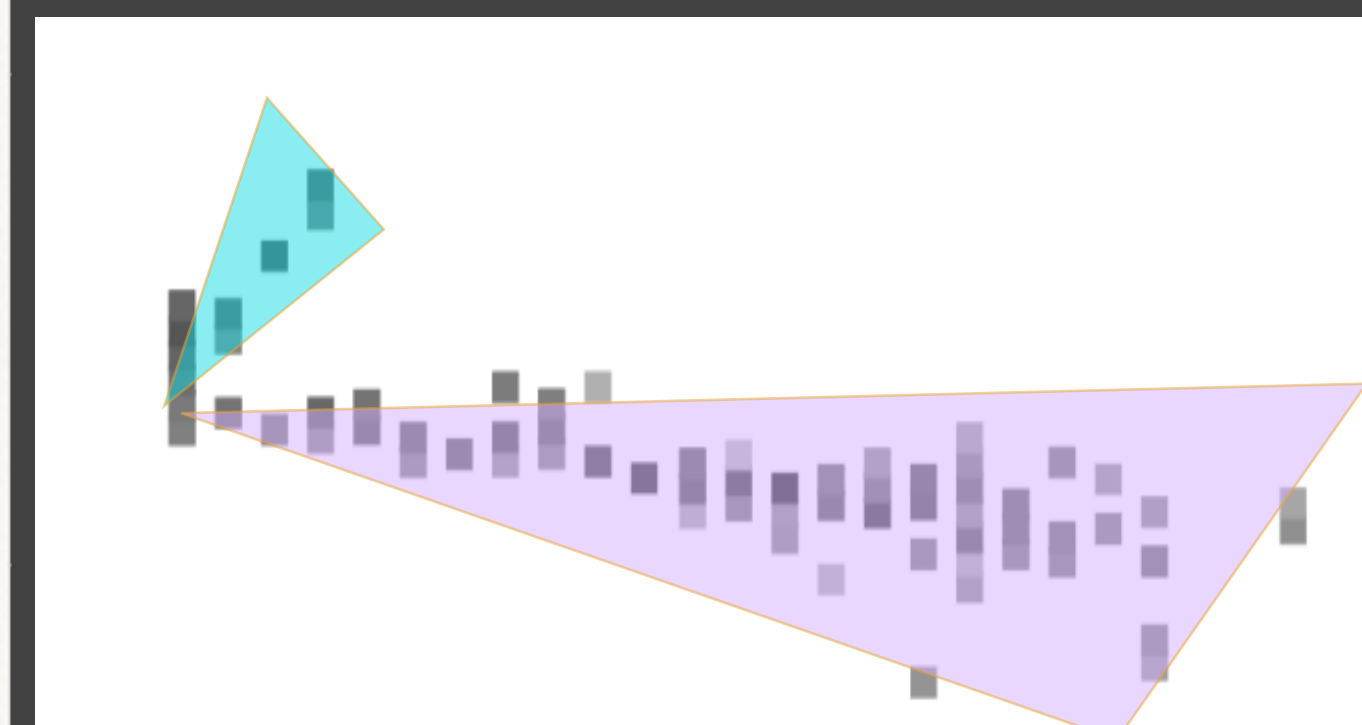
- Identify EM and hadronic clusters using a context-enriched CNN [1]
- Takes into account e/h detector response
  - Individual calorimetric energies are fit to true neutrino energy
  - $E(\nu_e) = A*E_{EM} + B*E_{HAD} + C*E_{EM}^2 + D*E_{HAD}^2$
  - Helps to keep resolution bias flat vs true energy
  - Overall neutrino energy resolution ~ 11%

NOvA Simulation

NOvA Simulation

(ν Reconstructed Energy - True Energy) / True Energy

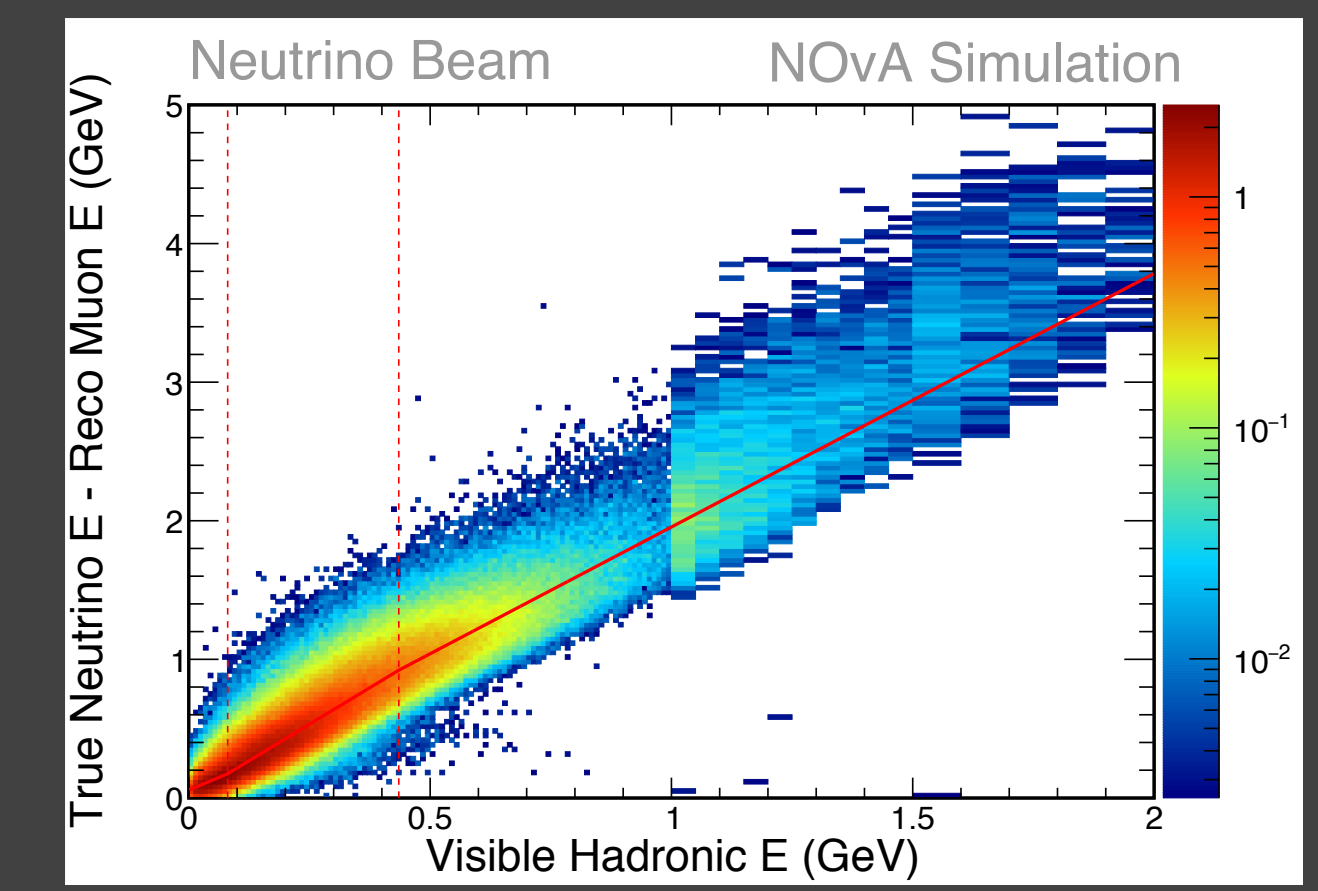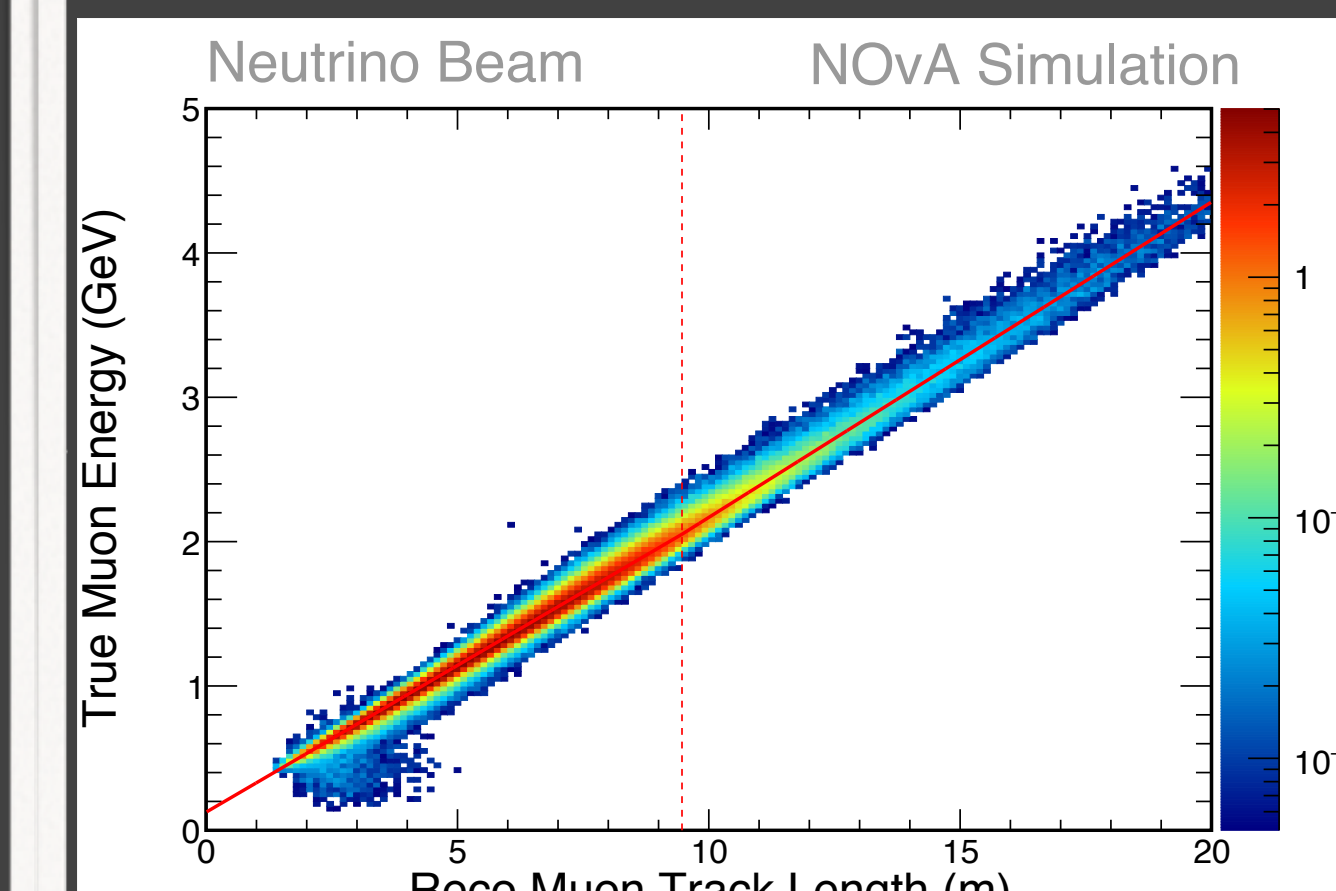## 4. ν_e Energy - Further Improvements

- Use images of the ν_e CC interaction directly and feed it into a regression based CNN
- Minimal reconstruction dependence
- Flattened input true neutrino energy distribution to control bias
- Significantly better performance! [2]
- Better control over systematic uncertainties

A. Back, M. Groh - ML applications in NOvA (Poster)

Hit map of a ν_e CC event

NOvA Simulation

Gaussian resolutions:
Cal. Energy: 10.2%
Kinematic Energy: 10.1%
CNN Energy: 8.9%

(RecoE-TrueE)/TrueE

NOvA Simulation

Bias

(Reco E - True E)/True E

5. ν_μ Energy Reconstruction
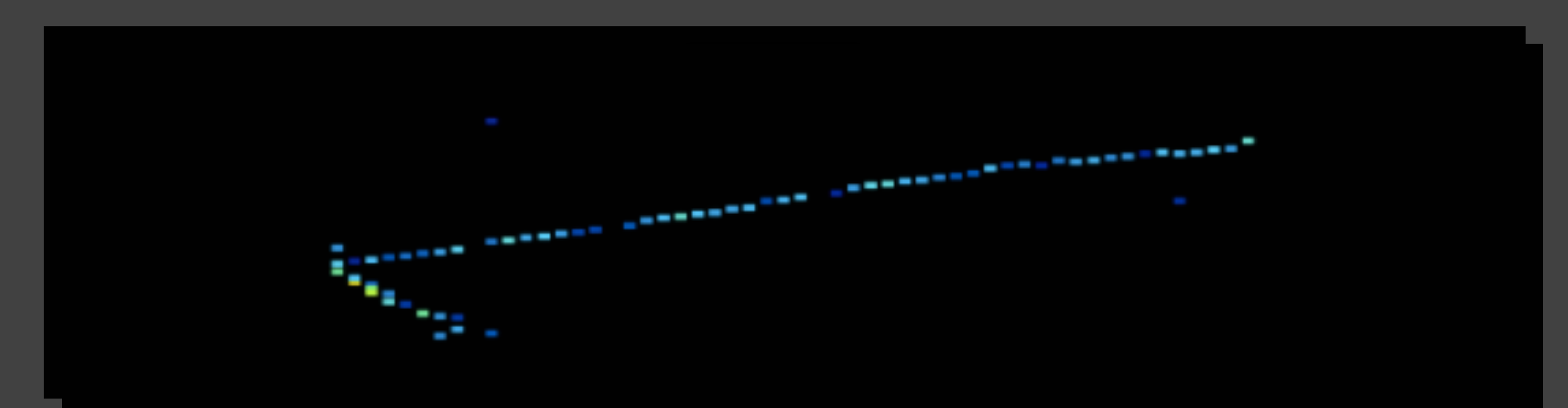
- Muon hits grouped by a kalman tracking algorithm
- Energy highly correlated with track length, resolution ~ 3%
- Hadronic energy estimated from visible hadronic activity using a spline-based fit
- Includes hadronic activity overlapping with muon track
- Takes into account different regions of phase space in the underlying interaction model
- Energy resolution ~ 26%
- $E(\nu_\mu) = E_{muon} + E_{hadron}$ with overall resolution ~ 6%

Neutrino Beam   NOvA Simulation

Neutrino Beam   NOvA Simulation
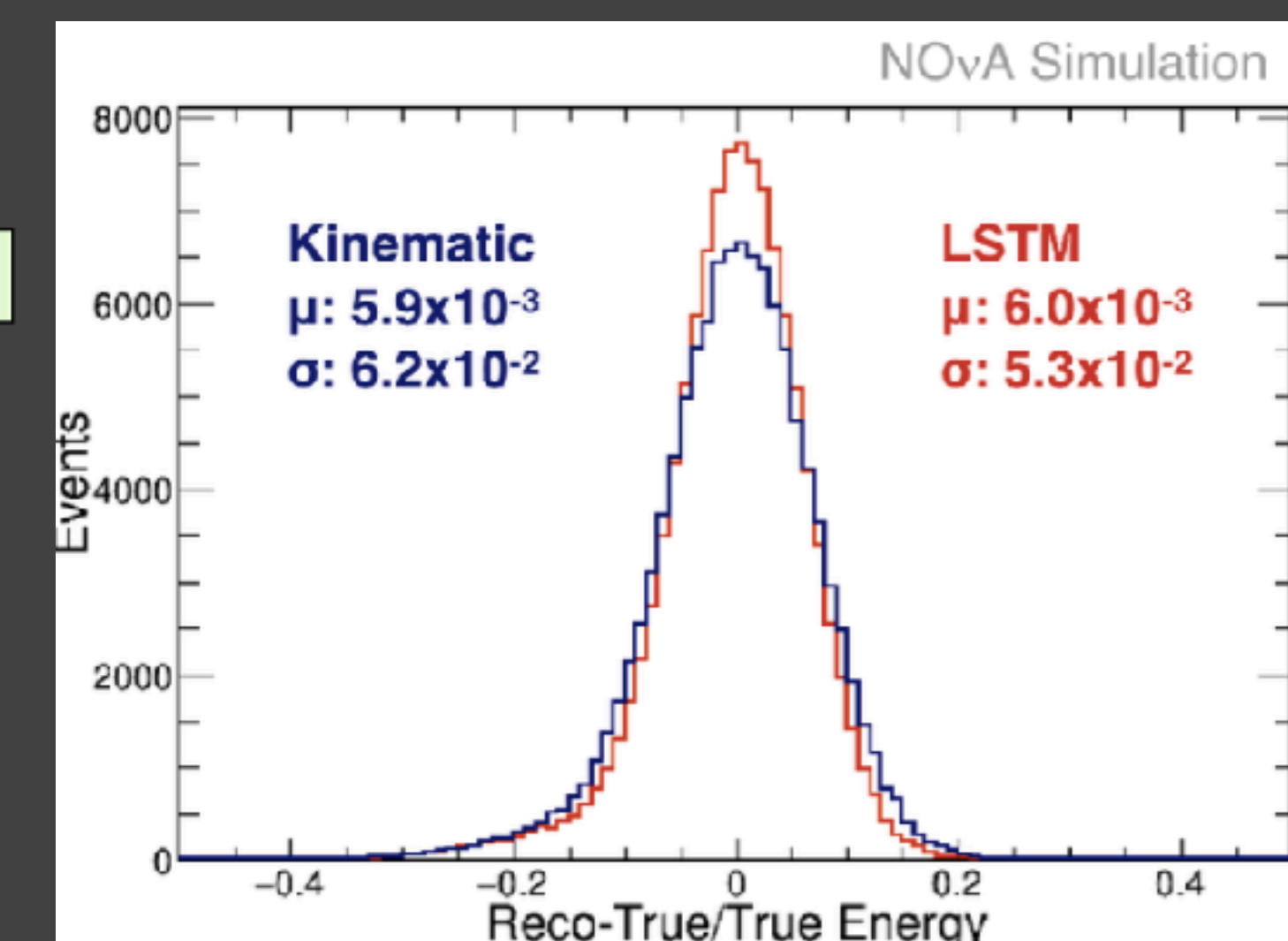
6. ν_μ Energy - Further Improvements

sequential output
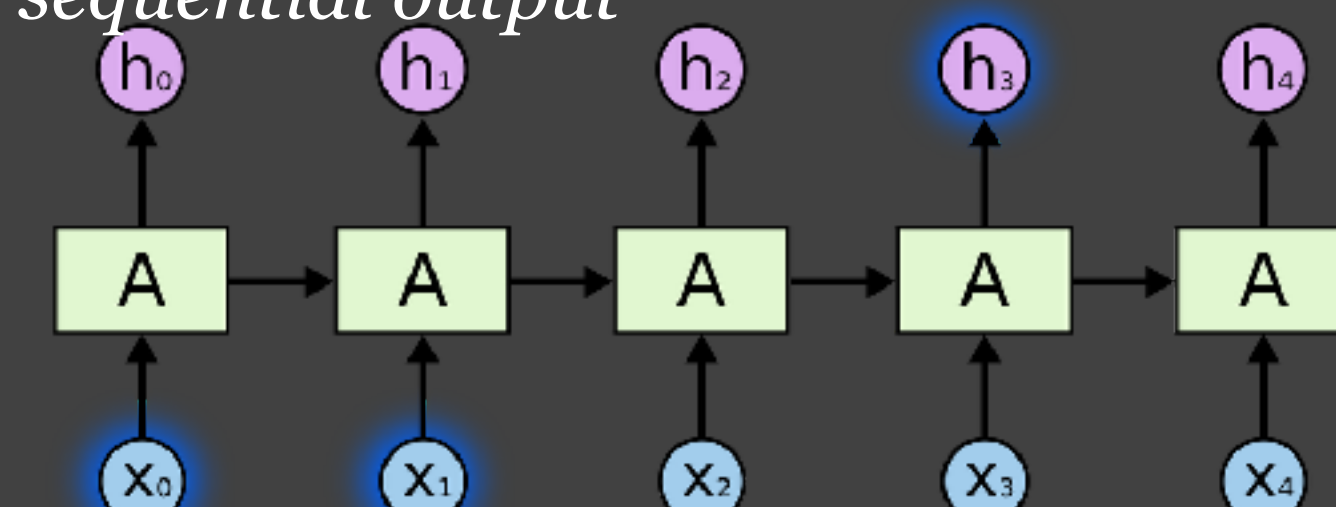
sequential input

- Tracking is more relevant for muons than calorimetry
- Makes more sense to use physics-related reconstructed quantities as input
  - Feed track lengths, track energies etc into a LSTM-based RNN
  - Useful when number of inputs not known apriori
  - Similar unbiased training yields very promising improvements too!

NOvA Simulation

Kinematic
μ: 5.9×10^{-3}
σ: 6.2×10^{-2}

LSTM
μ: 6.0×10^{-3}
σ: 5.3×10^{-2}

Reco-True/True Energy

[1]. F. Psihas, E. Niner, M. Groh et al. Phys. Rev. D 100, 073005

[2]. P. Baldi, J. Bian, L. Hertel, L. Li Phys. Rev. D 99, 012011

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