Measurements of neutrino interactions with electrons in the final state at the NOvA near detector

Derek Doyle *on behalf of the NOvA Collaboration*

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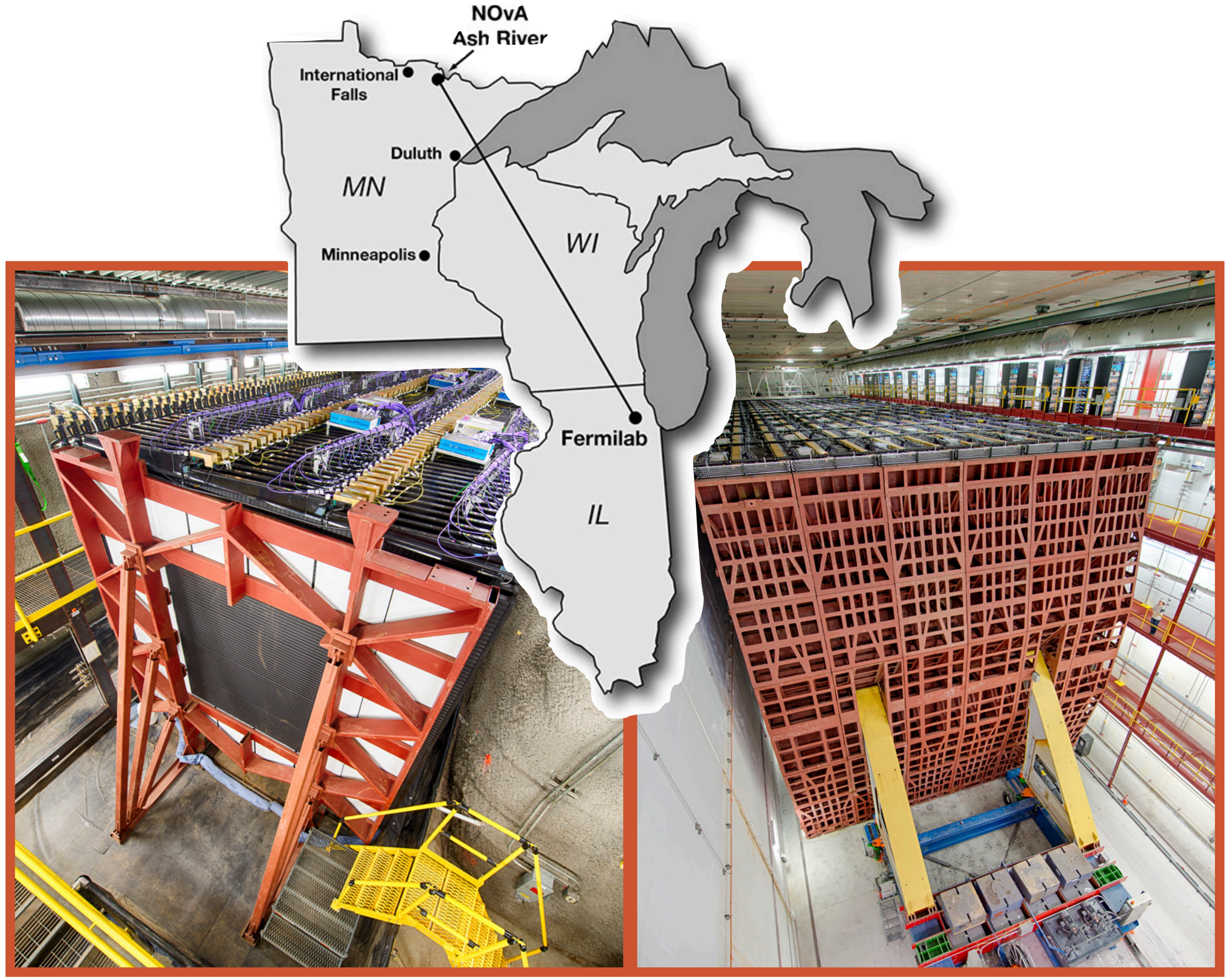
Outline

- NOvA Experiment
- Electrons in NOvA
- Analysis Updates
    - $\nu_e CC$ Inclusive
    - $\bar{\nu}_e CC$ Inclusive
    - Elastic $\nu - e$

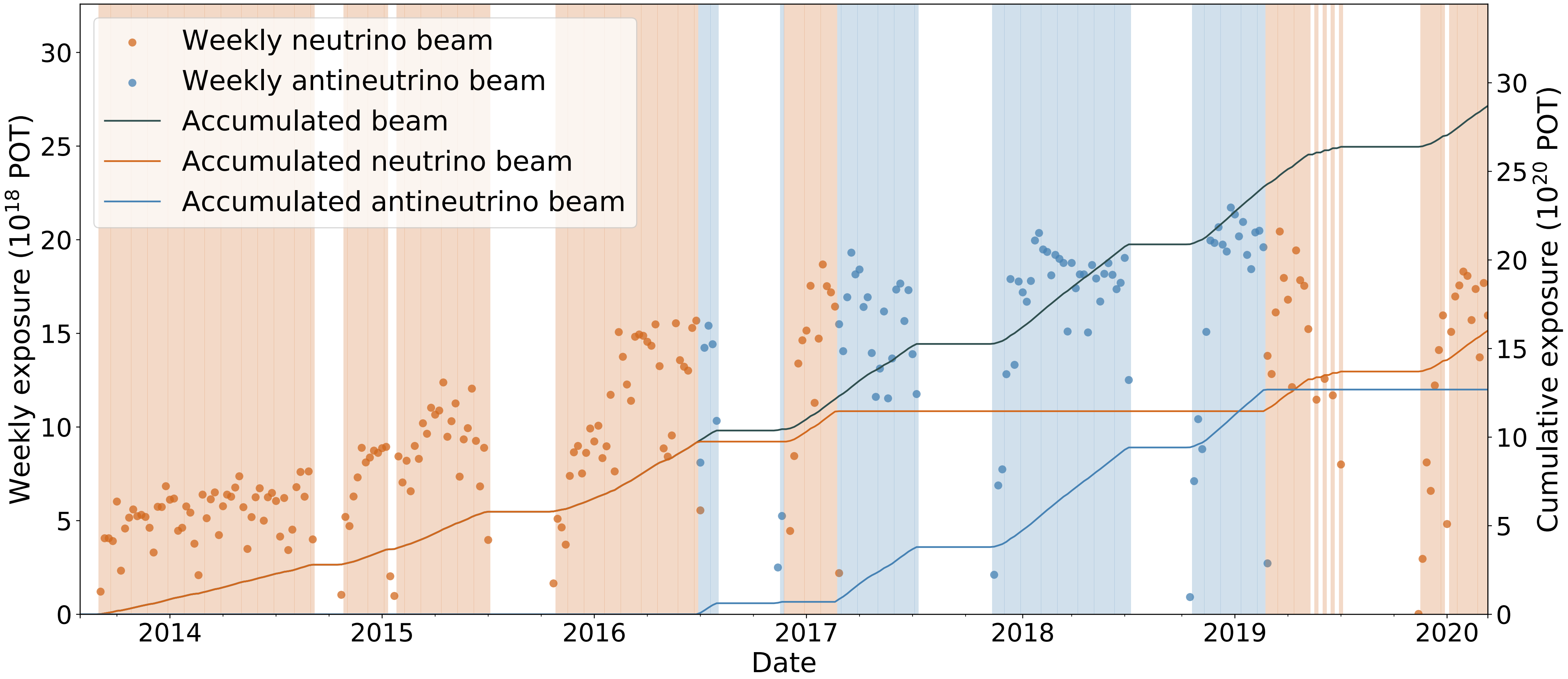
NOvA Experiment

- Long-baseline oscillation experiment
- Designed to measure oscillation parameters via $\nu_\mu \rightarrow \nu_e$
- Two functionally identical detectors
  - Reduce flux, cross section, and detector uncertainties
- Measure oscillation of neutrino and antineutrinos to maximize sensitivity to δ_{CP}
- Rich program of non-oscillation physics as well



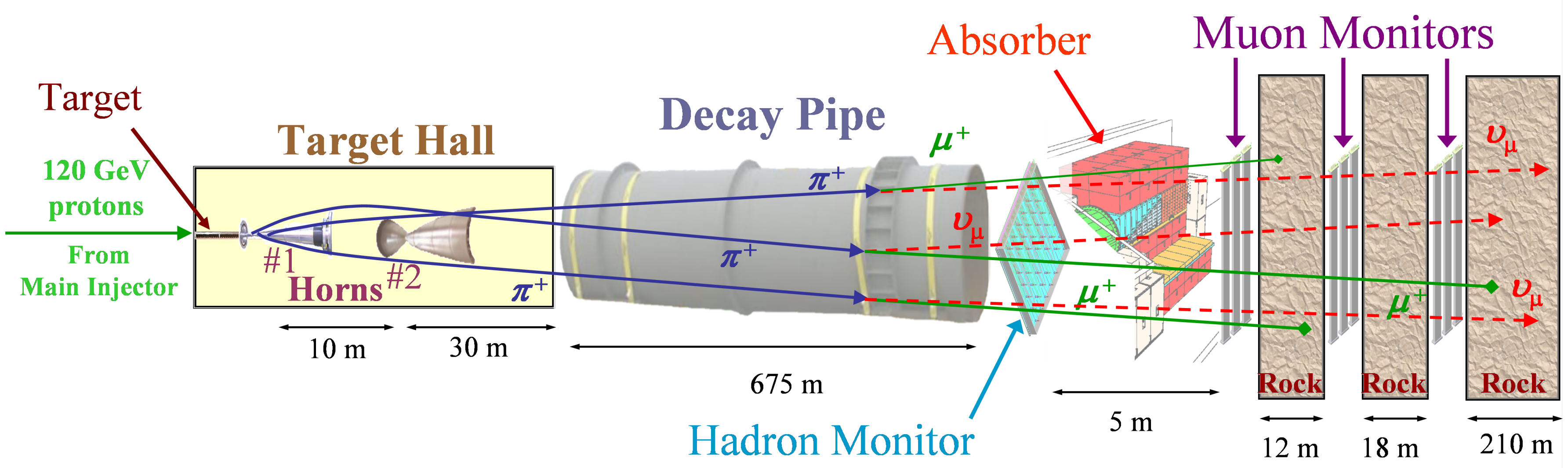
NuMI

- Collected almost 30×10^{20} POT of neutrino + antineutrino data since 2013
- Enables systematically limited multi-differential cross section measurements in the Near Detector



NOvA Flux

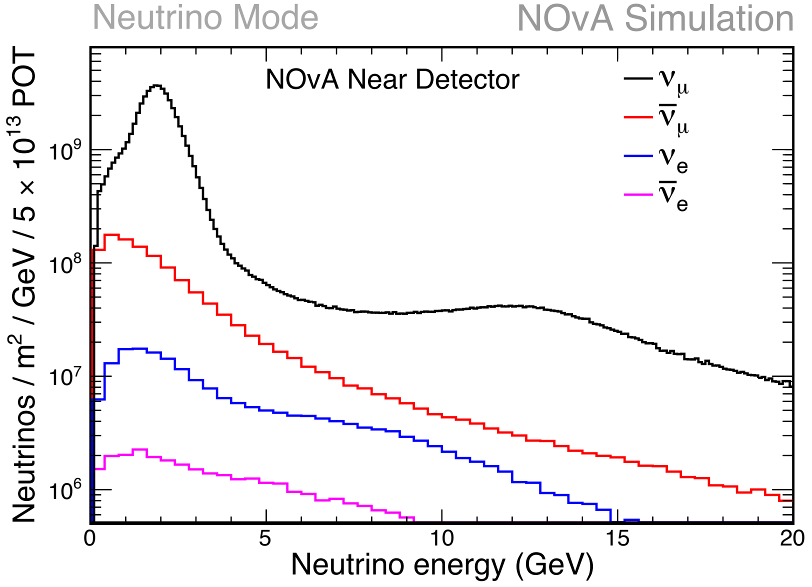
- NuMI produces primarily ν_μ to induce $\nu_\mu \rightarrow \nu_e$

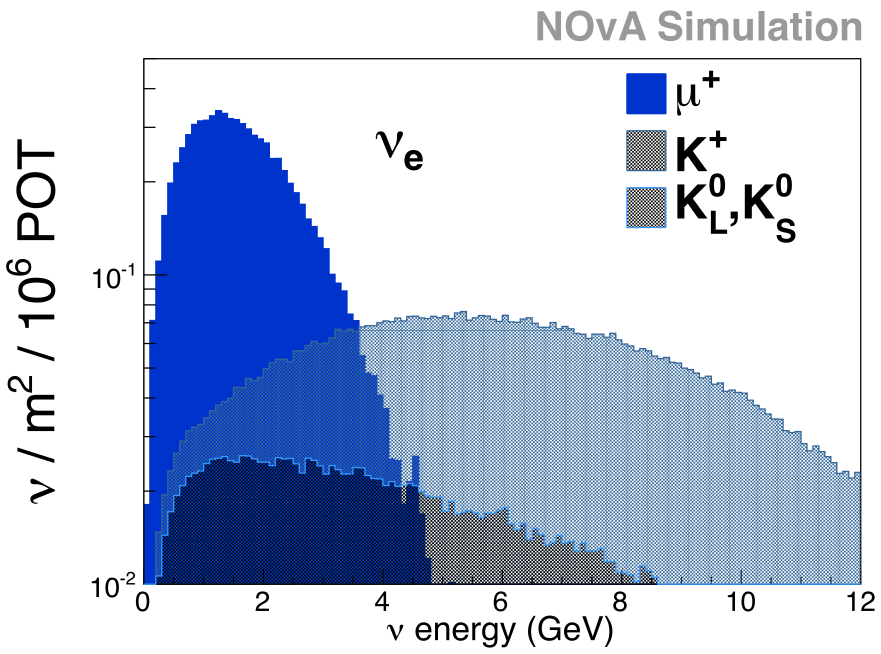


- $< 1\ \%\ \nu_e(\bar{\nu}_e)$ components

$$K^+ \rightarrow \pi^0 e^+ \nu_e \qquad K^0 \rightarrow \pi^\pm e^\mp \nu_e \qquad \mu \rightarrow e \nu_e \nu_\mu$$

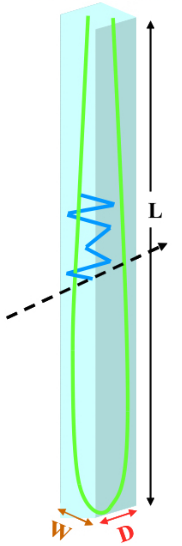
- Simulation based on Geant4 with constraint from external measurements

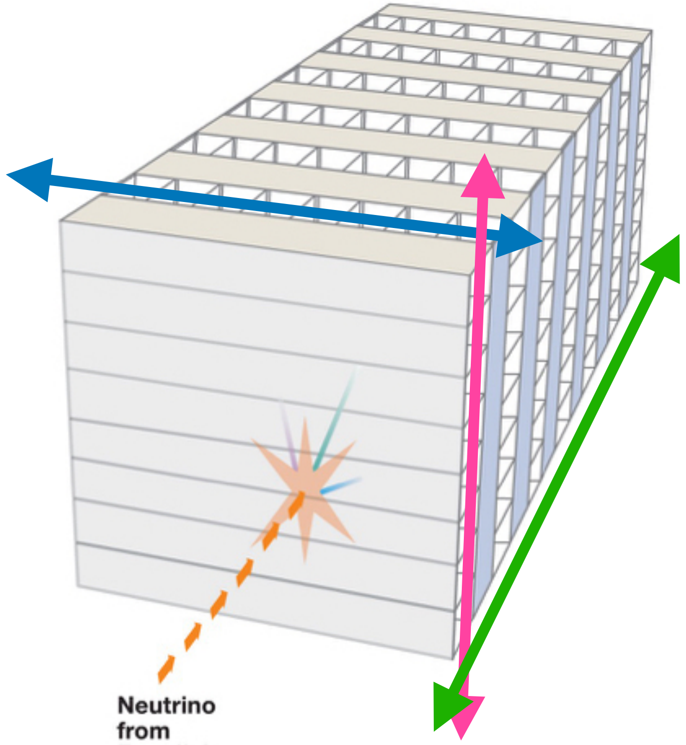


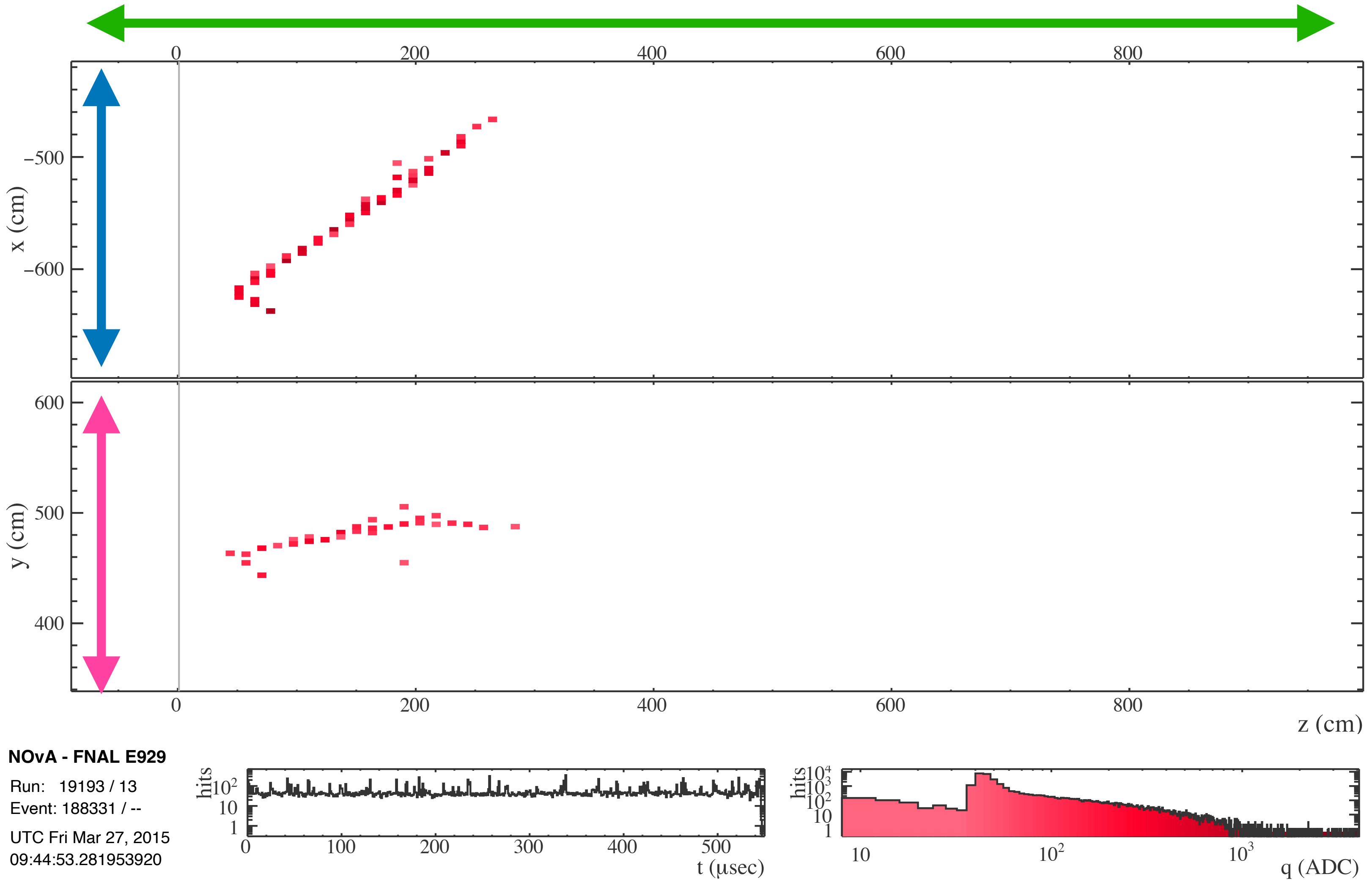


NOvA Detectors

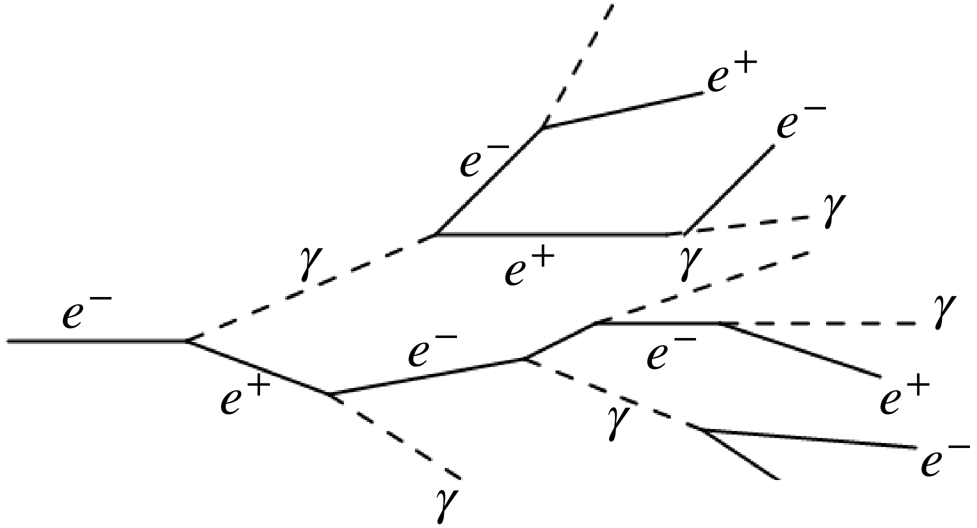
- Alternating planes of PVC “pixels” allow for 3D tracking
- Calorimetry by photon detection
- Radiation length - 6 planes (40 cm)
- Moliere radius - 2 cells (7 cm)







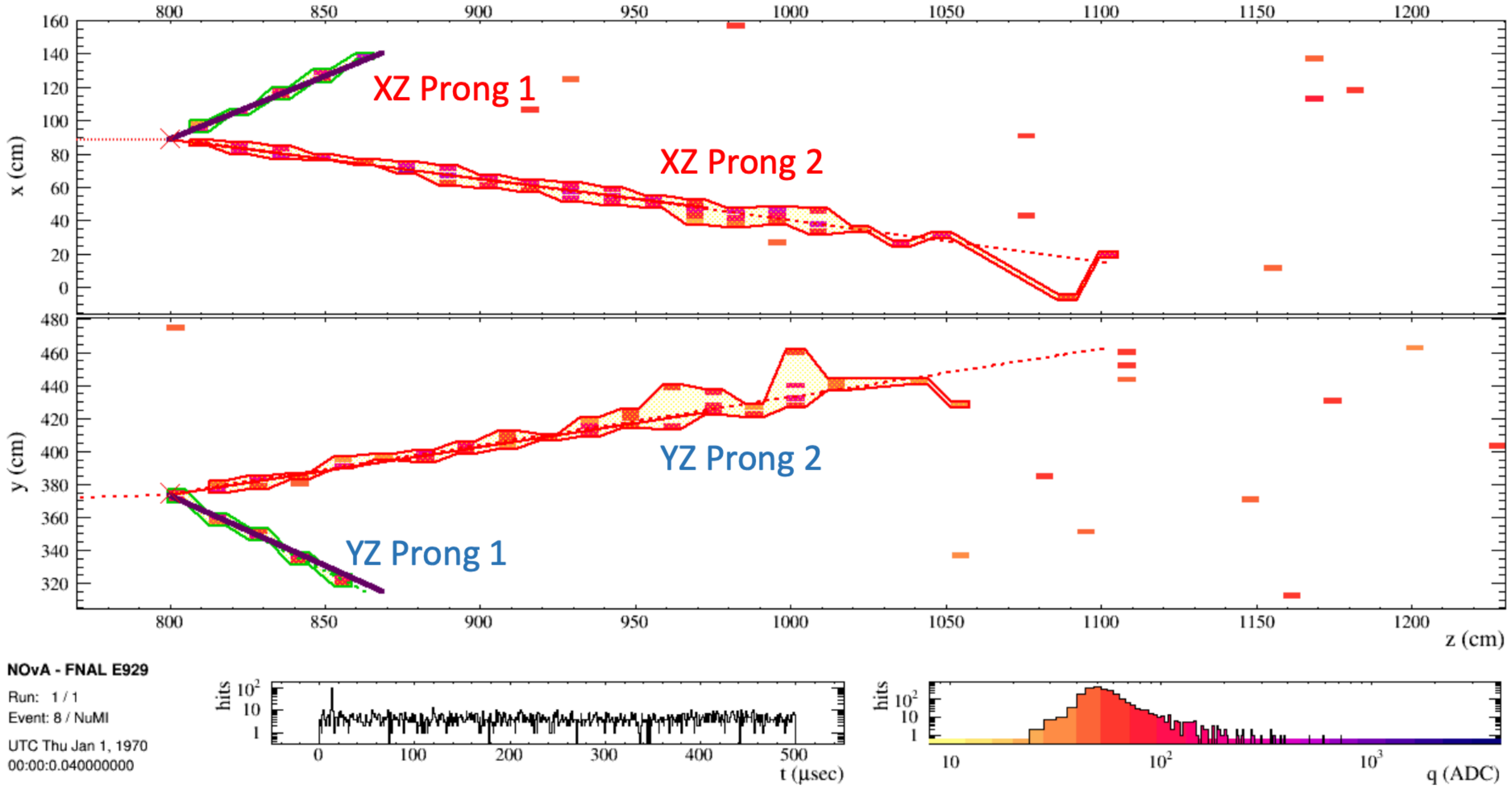
Electron Reconstruction in NOvA



- Electrons produce electromagnetic showers
- Electrons, positrons, and photons produce identical signatures

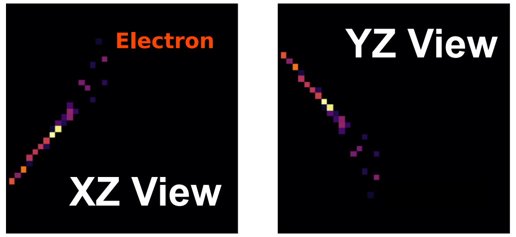
1. A vertex is found
2. Fuzzy clusters originating from a vertex are formed in each view into 2D prongs
3. 2D prongs are matched to form 3D prongs

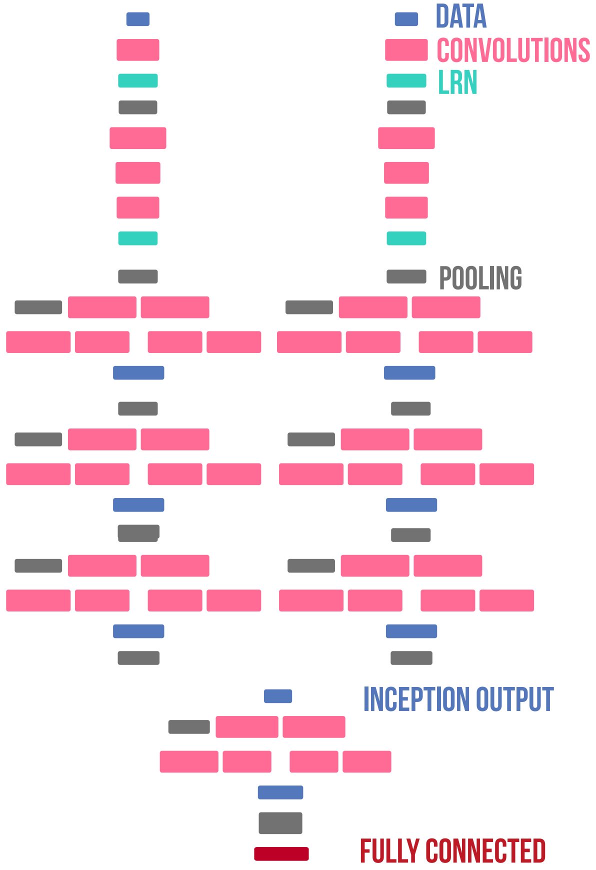
- *Resulting prongs have direction and energy*
- *~14% average electron energy resolution*
- *~8 degree average electron angle resolution*

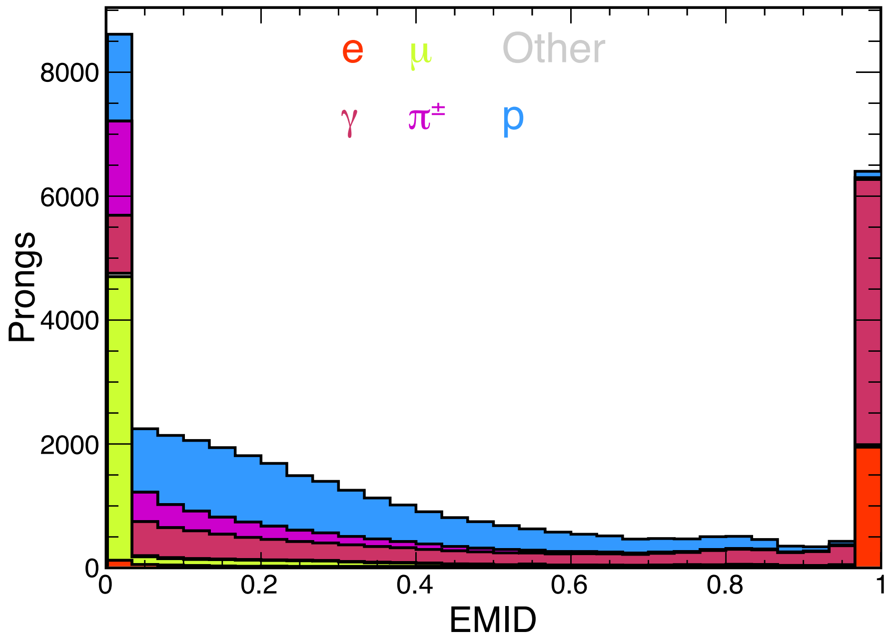


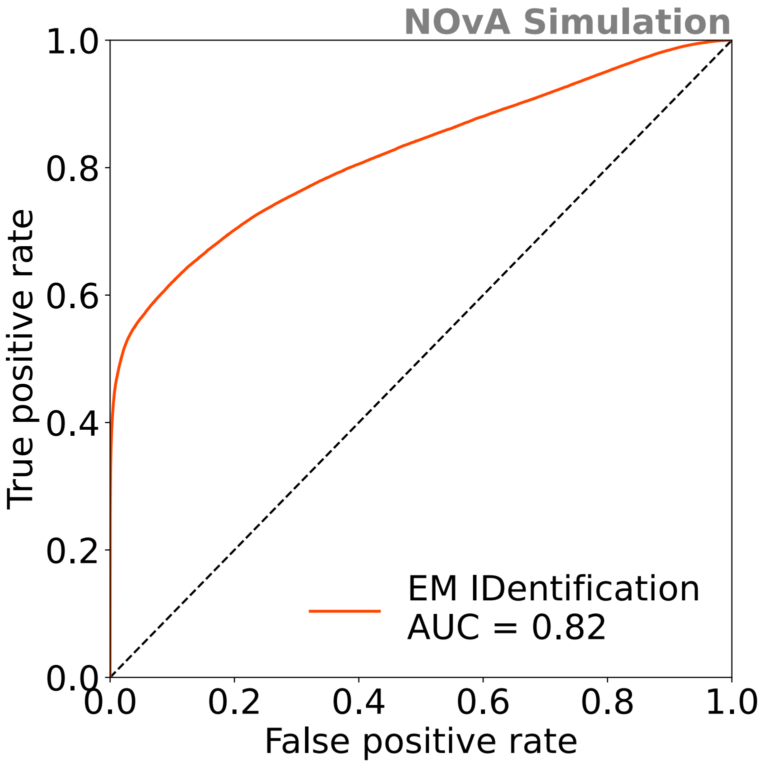
Electron Reconstruction in NOvA

- NOvA has has developed CNN algorithms for the oscillation analysis to identify interaction flavor and final state particle type
- Perform very well but biased toward GENIE final states
- CNN trained on generator-free sample of individually simulated particles for cross section measurements
- Siamese MobileNet V2 network classifies 3D prongs
  - $e^{-}, \gamma, \pi^{\pm}, \mu, p$
- Performs well at identifying EM showers



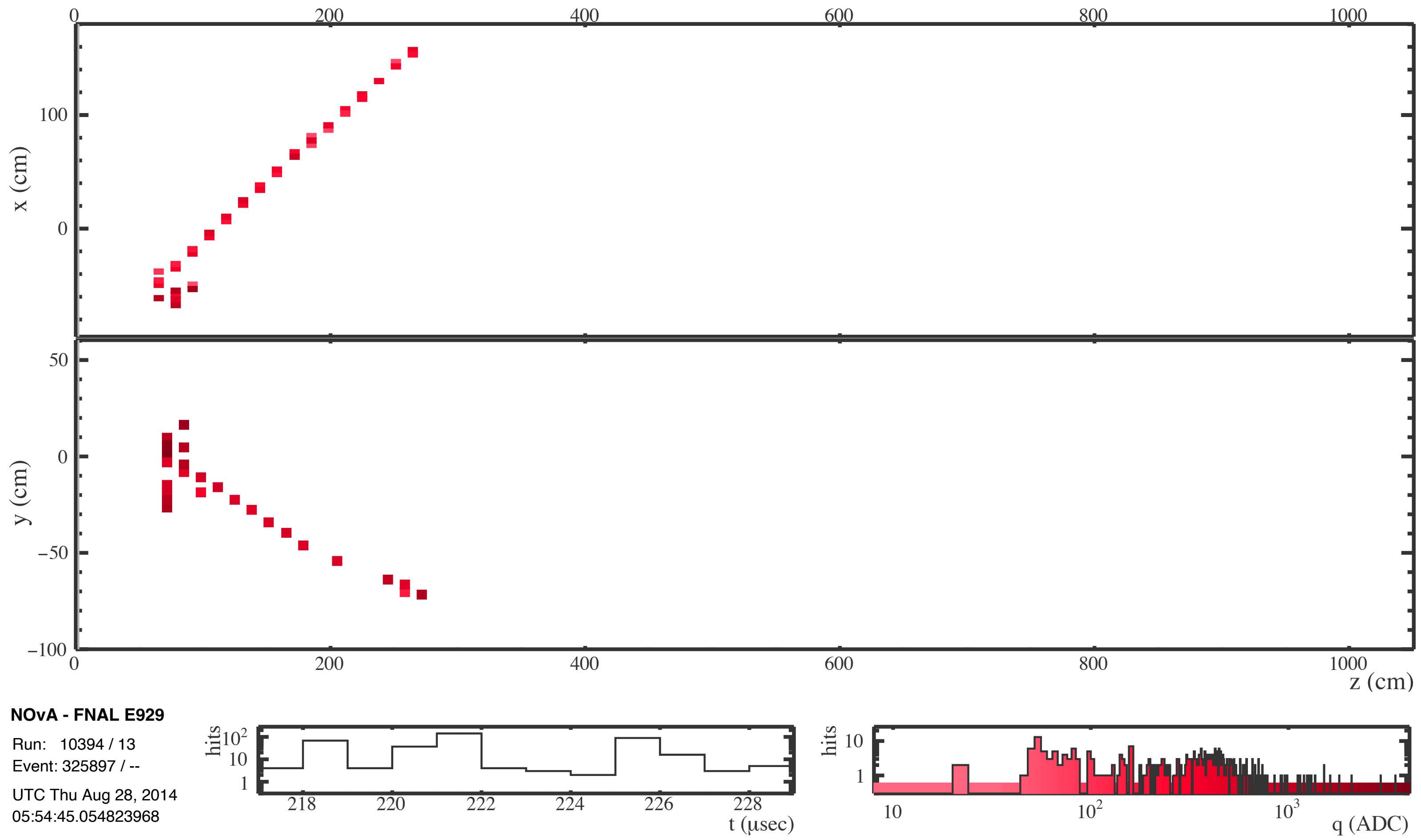






Muon Removed Electron Added

- Identify the reconstructed muon
- Remove hits associated with muon
- Overlay a simulated electron with removed muon kinematics
- We're able to produce a high-statistics sample of $\nu_e CC$ interactions using MRE technique
- Study the effect of hadronic mismodeling on selection efficiency and background subtraction
- We see consistent selection efficiencies between MRE MC and data samples



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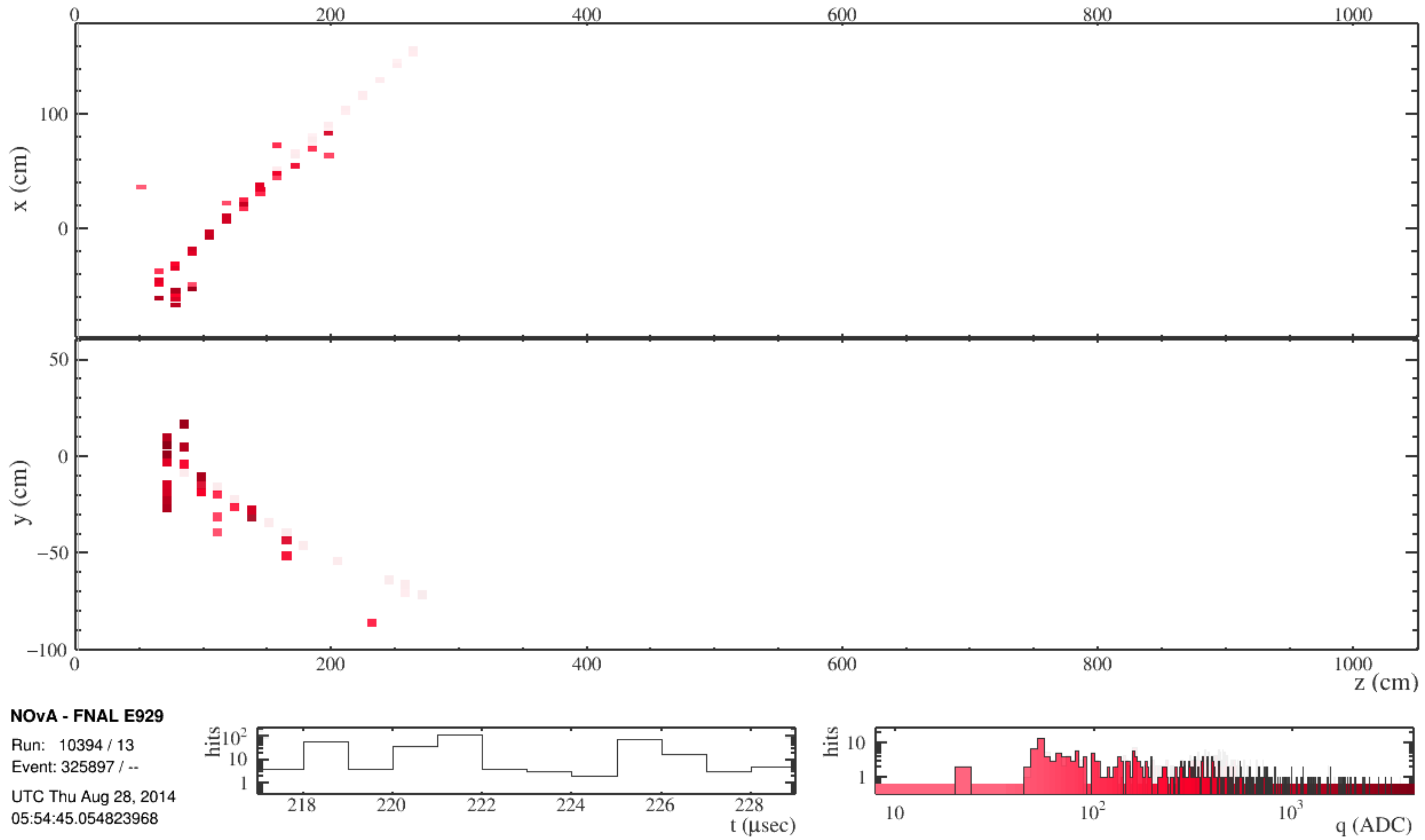

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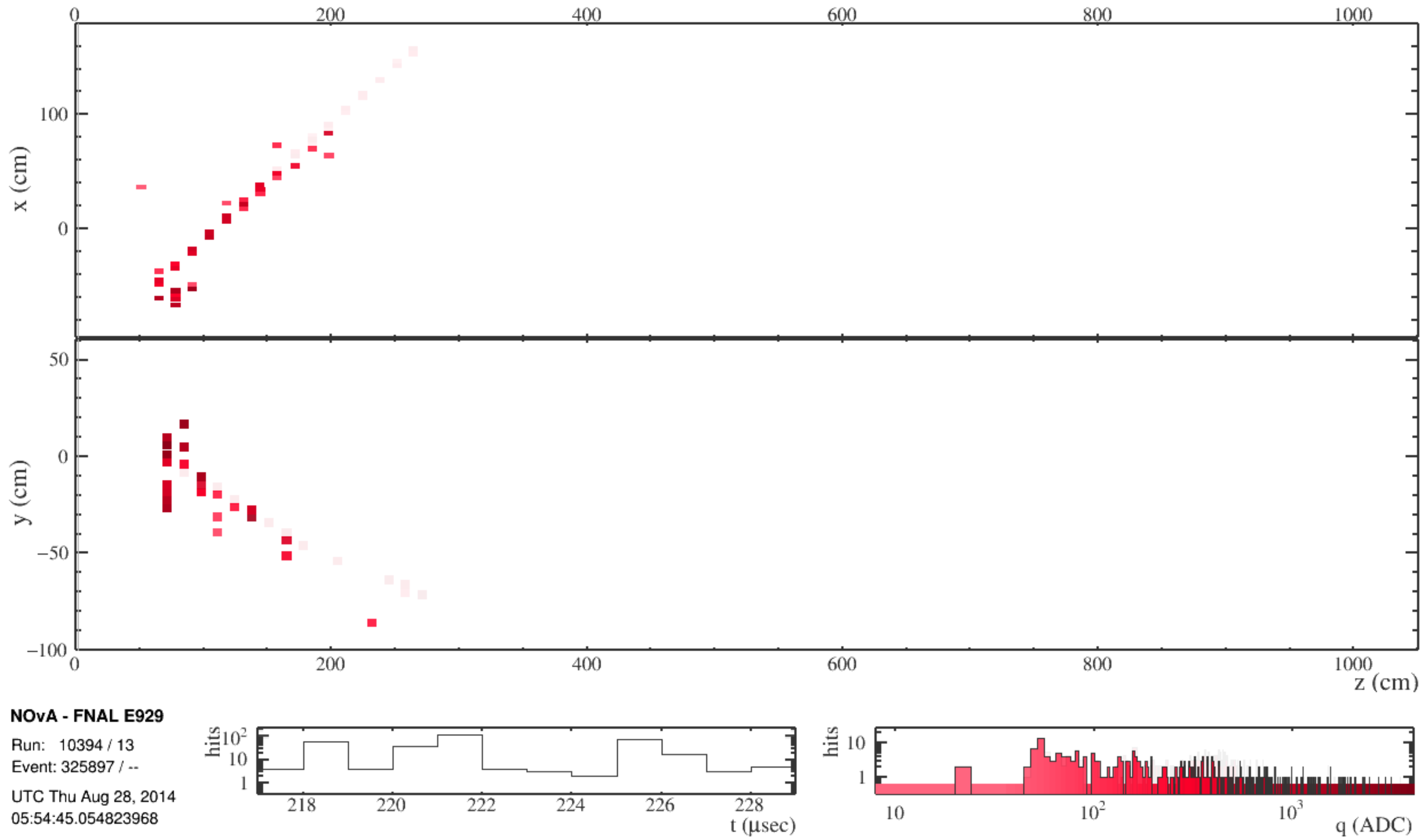

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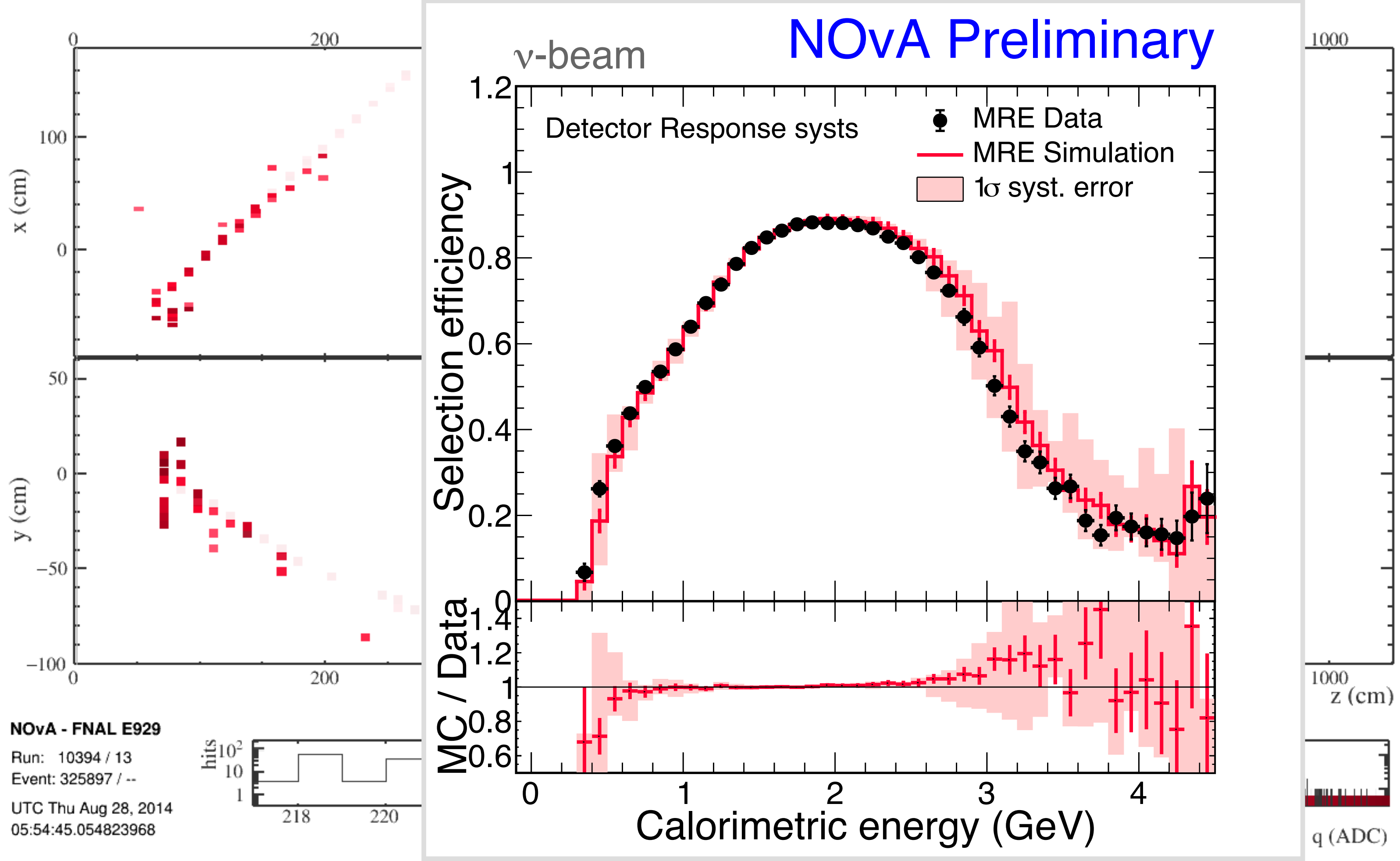
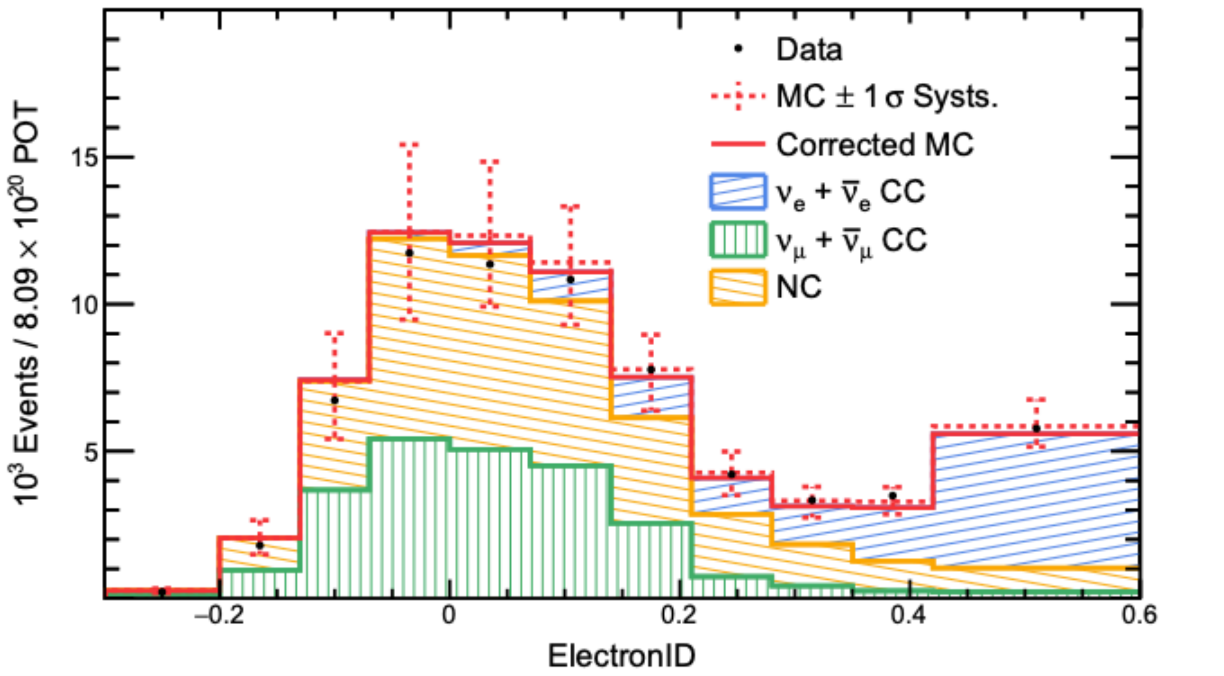


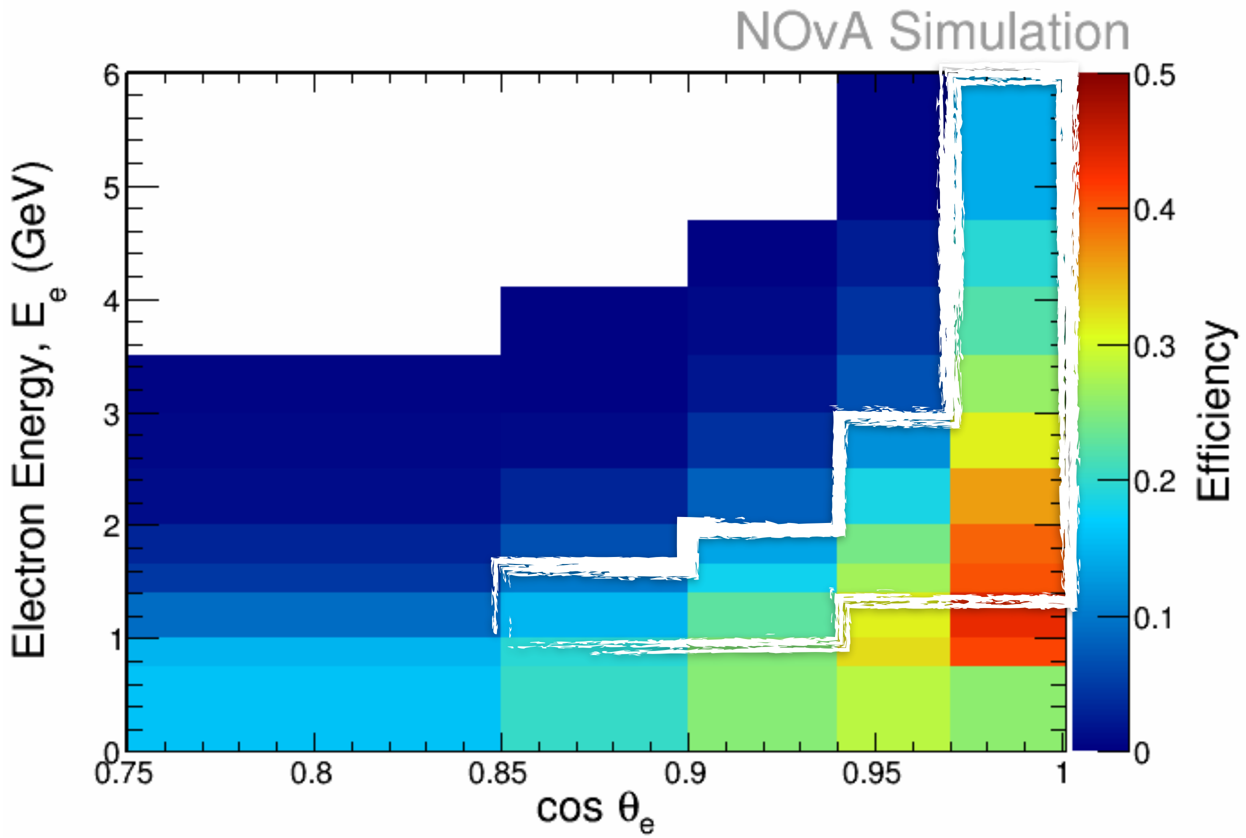
$\nu_e CC$ Inclusive

arXiv:2206.10585

- First ever double-differential in electron kinematics
- Boosted Decision Tree (BDT) ElectronID combines event context and CNN score to aid in electron identification
- Template fit correlates shape uncertainties between signal and background components
- $9{,}200 \pm 1{,}000\ \nu_e CC$ signal events
    - $24\ \%$ efficient
    - $13\ \%$ pure

Source	Avg. Uncertainty (%)	Avg. Correlation
Flux	10.3	0.90
ν-A Model	9.8	0.64
Calibration	5.9	0.05
Detector Model	5.6	0.21
Other	2.8	0.03
Statistical	7.4	0.02
Total	18.2	0.59





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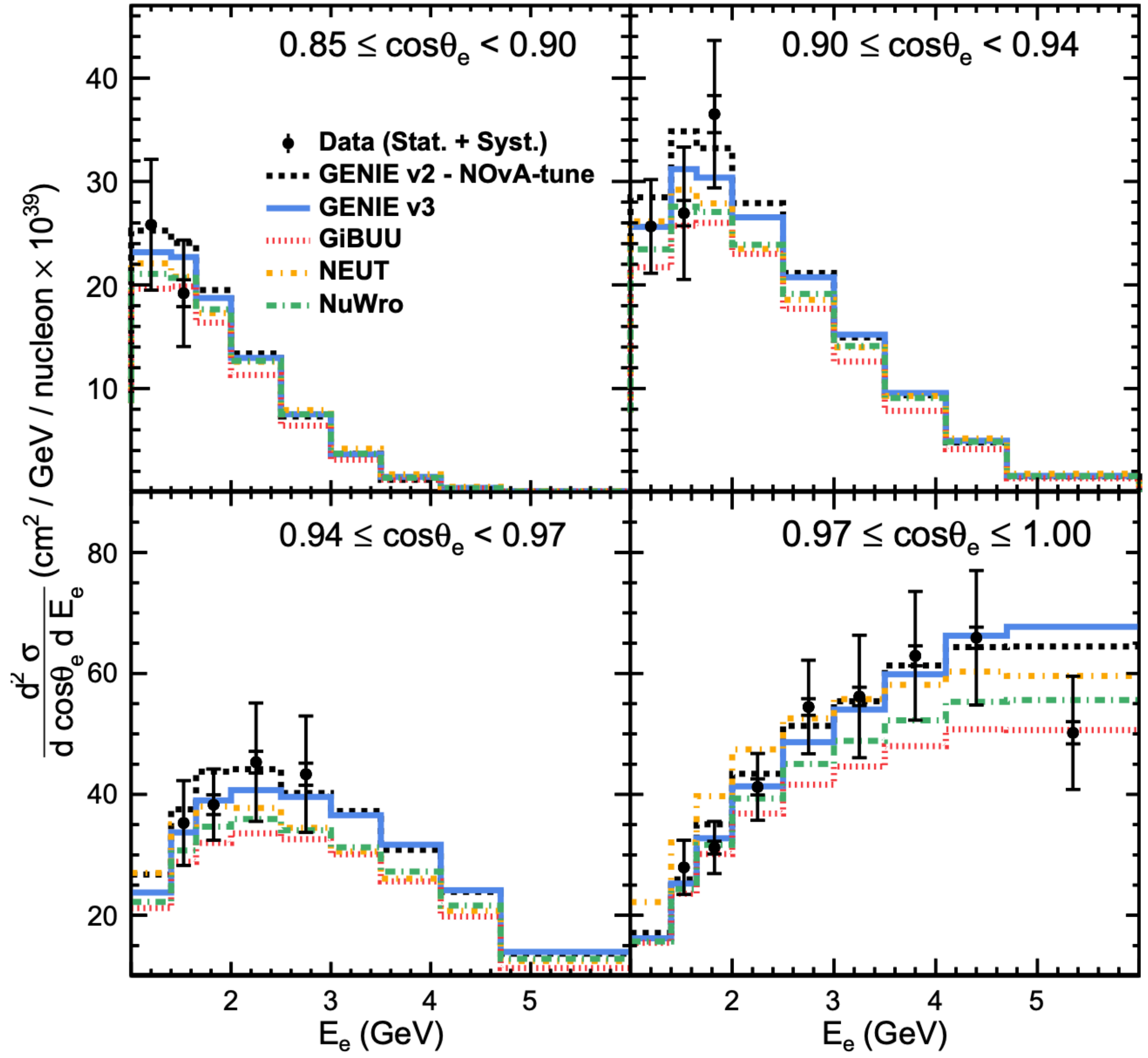
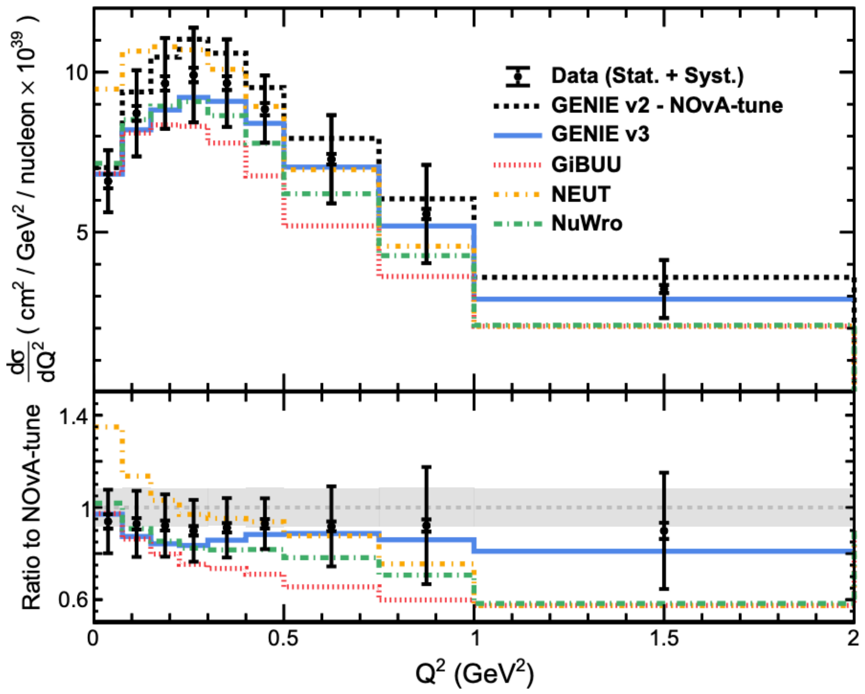


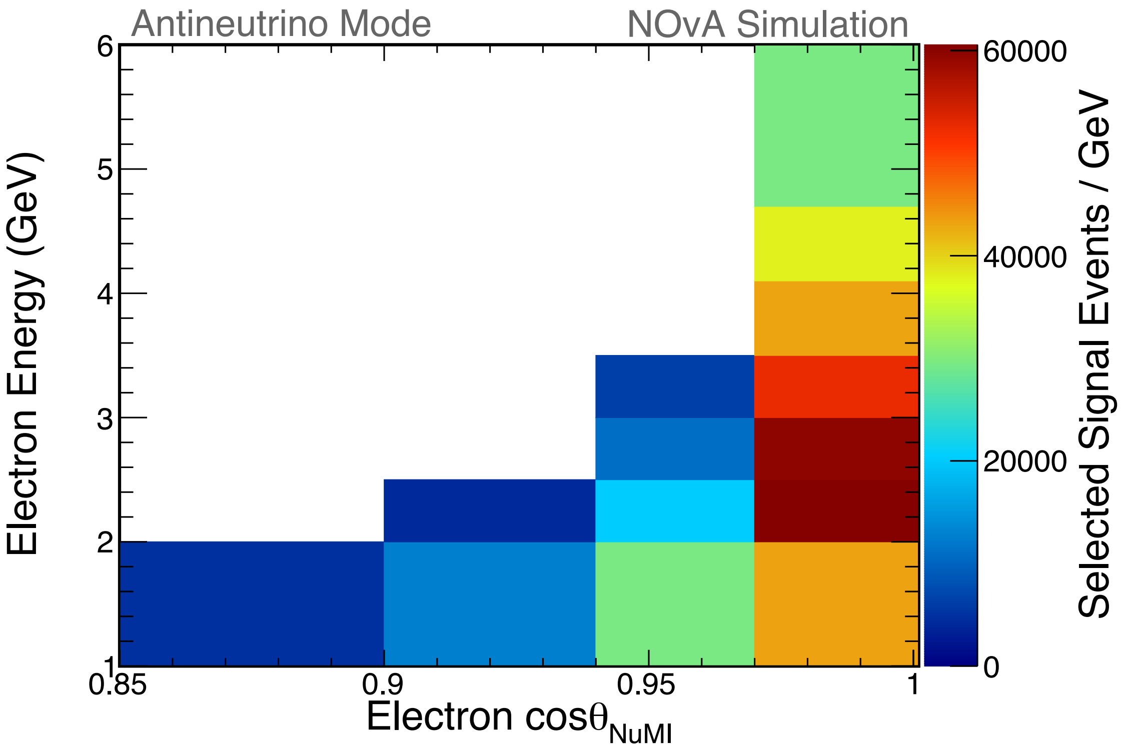


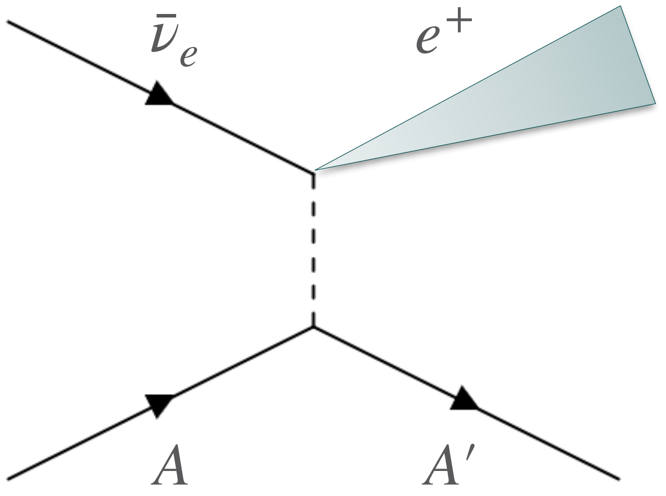
Generator	$\frac{d^2\sigma}{d\cos\theta_e dE_e}$	$\sigma(E_\nu)$	$\frac{d\sigma}{dQ^2}$
GENIE v2 - NOvA-tune	24.1	13.4	1.3
GENIE v2.12.2	24.3	14.3	19.6
GENIE v3.00.06	27.4	21.6	3.4
GiBUU 2019	17.5	16.0	14.7
NEUT 5.4.0	25.1	16.9	45.0
NuWro 2019	18.7	15.3	10.0
d.f.	17	12	9

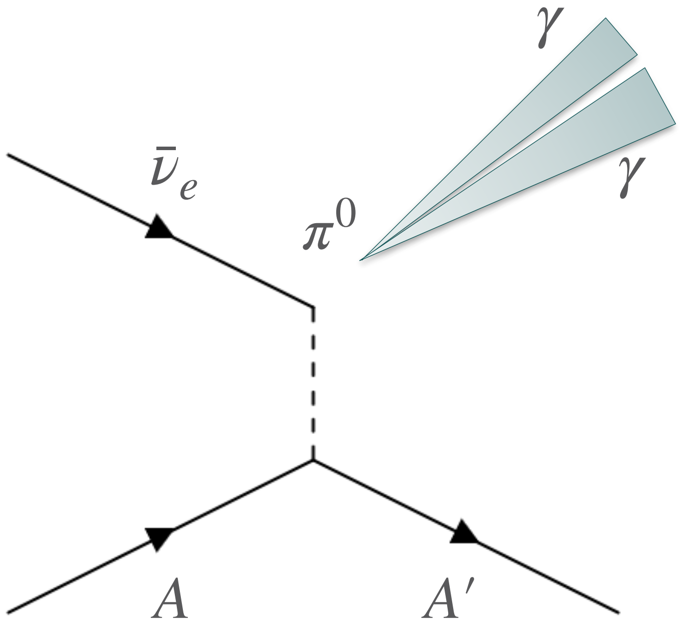
Table: χ^2 of model prediction compared to measurement.

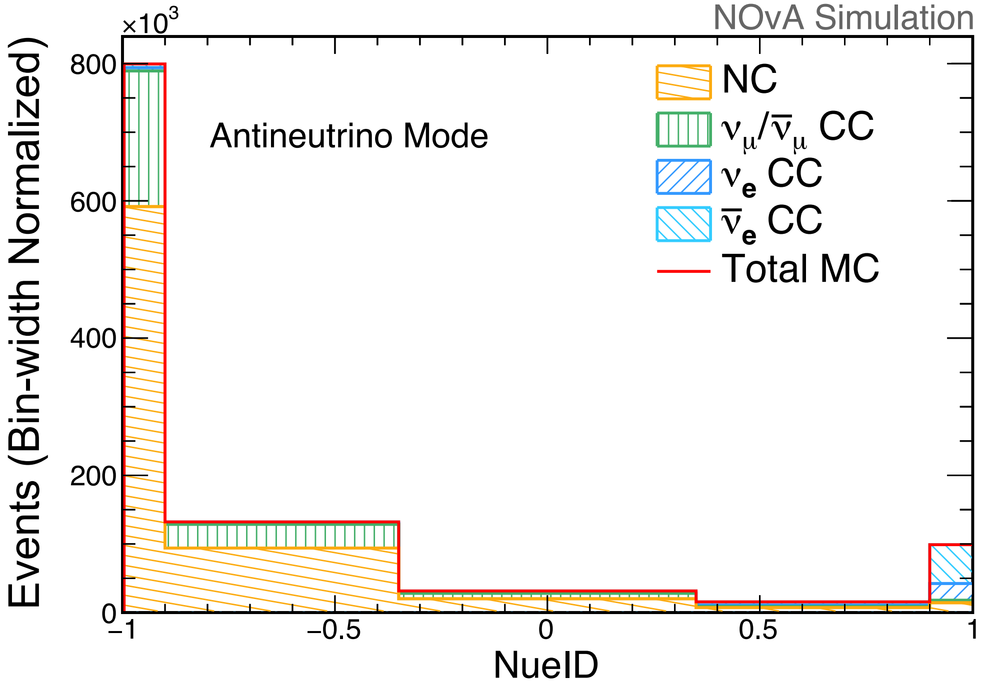
$\bar{\nu}_e CC$ Inclusive

- Set to be first double-differential $\bar{\nu}_e CC$ inclusive measurement
- Expecting over $10{,}000$ signal events
- Improved $\nu_e + \bar{\nu}_e CC$ classification BDT sensitive to NC $\pi^0 \to \gamma\gamma$
  - Prong CNN, Shower Width, Gap, dE/dx profile



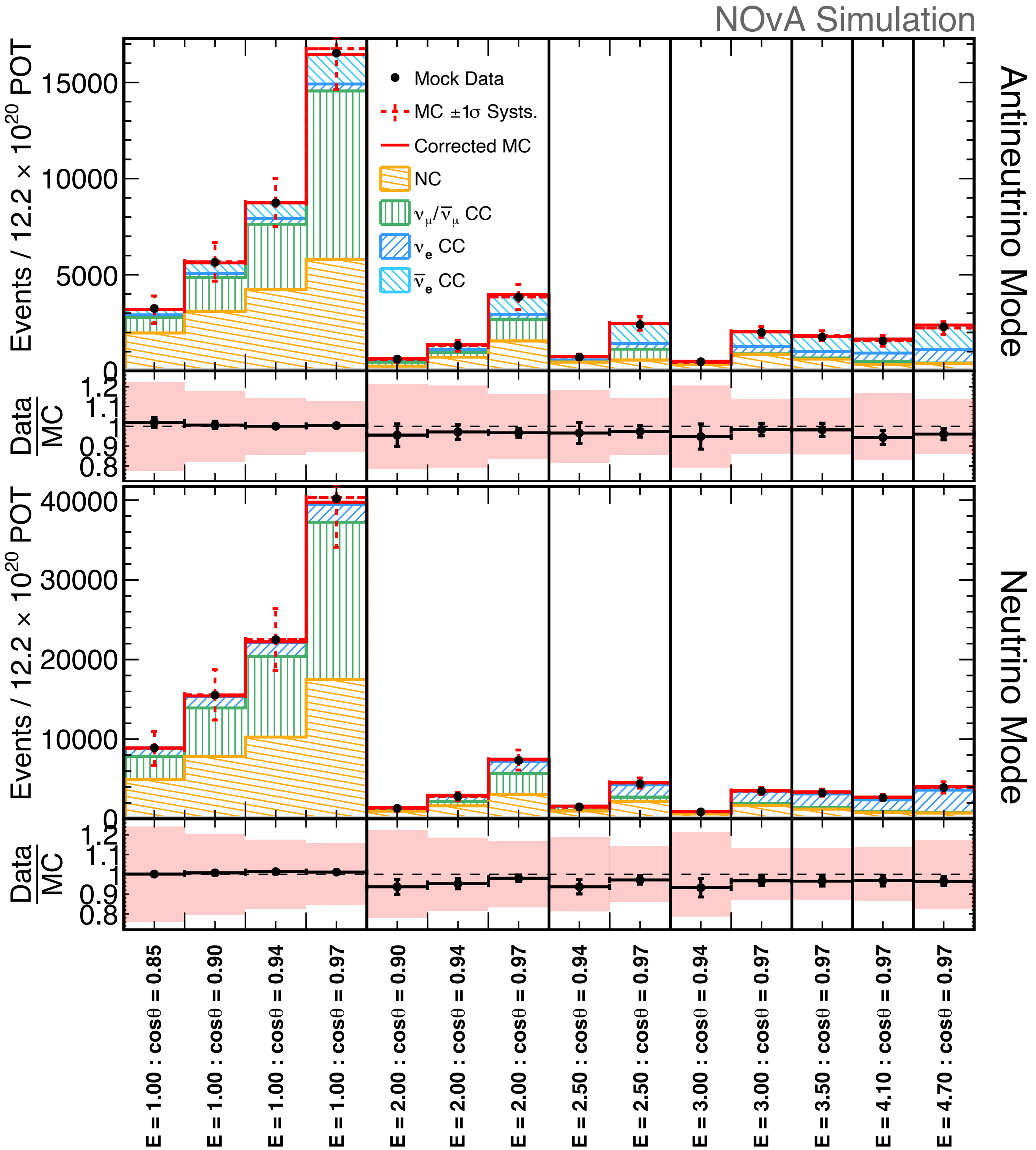






$\bar{\nu}_e CC$ Inclusive

- $\nu_e CC$ is a significant irreducible background —1/3 signal rate
- Developed simultaneous template fit to neutrino and antineutrino mode data using NueID
- $\nu_e CC$ and $\bar{\nu}_e CC$ components vary independently
- Systematic effects are correlated between samples
- Leverages relatively pure $\nu_e CC$ sample and flux model
- Procedure enables future $\nu_e/\bar{\nu}_e$ cross section ratio



Flux Uncertainties

- Flux uncertainties are a dominant source of uncertainty for most NOvA ND cross section analyses
- Comes directly from Hadron Production (HP) model uncertainties
- Dominated by HP models not constrained by external data
- Further reducing flux uncertainties will greatly benefit all NOvA cross-section measurements

$\nu_e CC$ *Inclusive*

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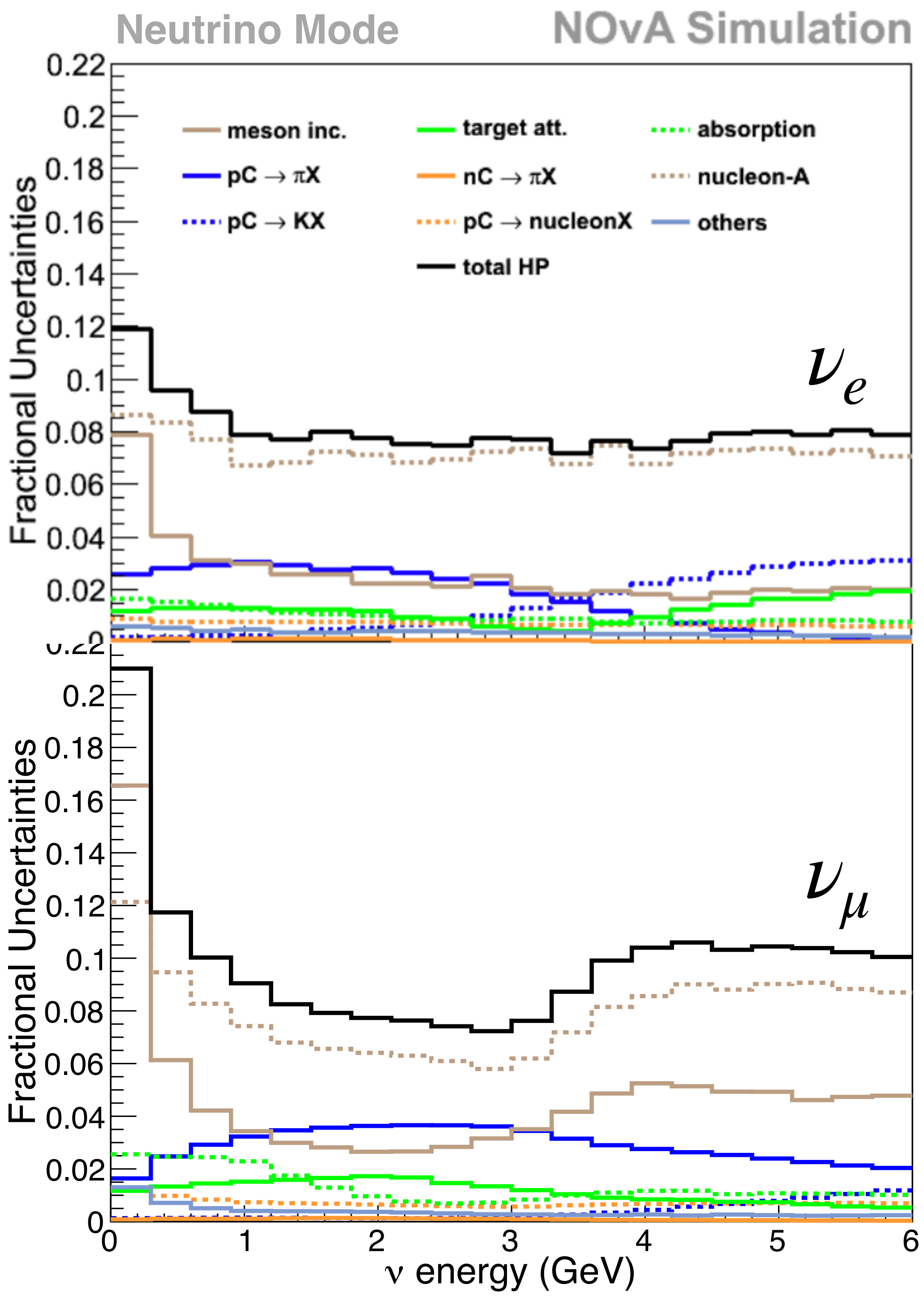
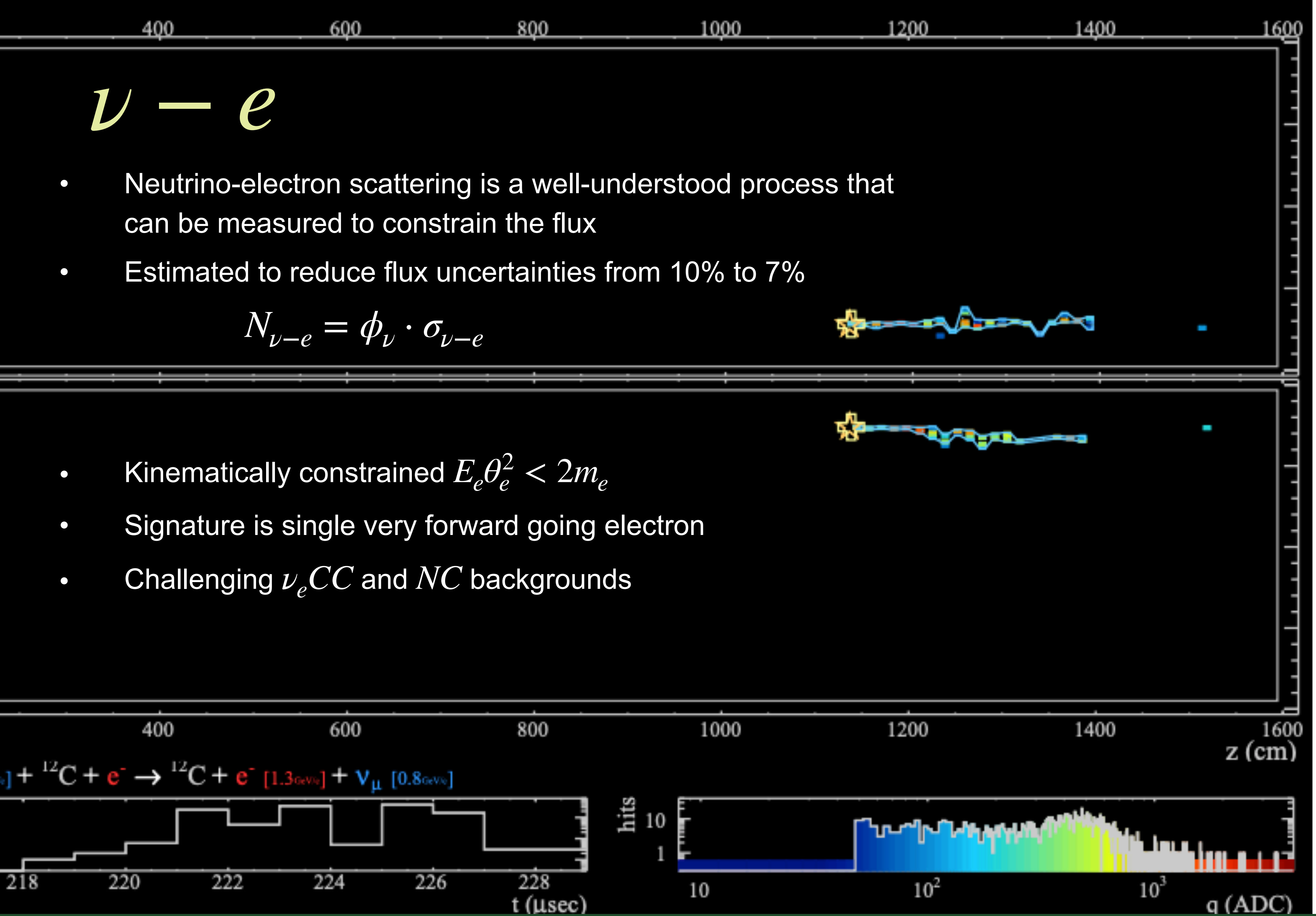


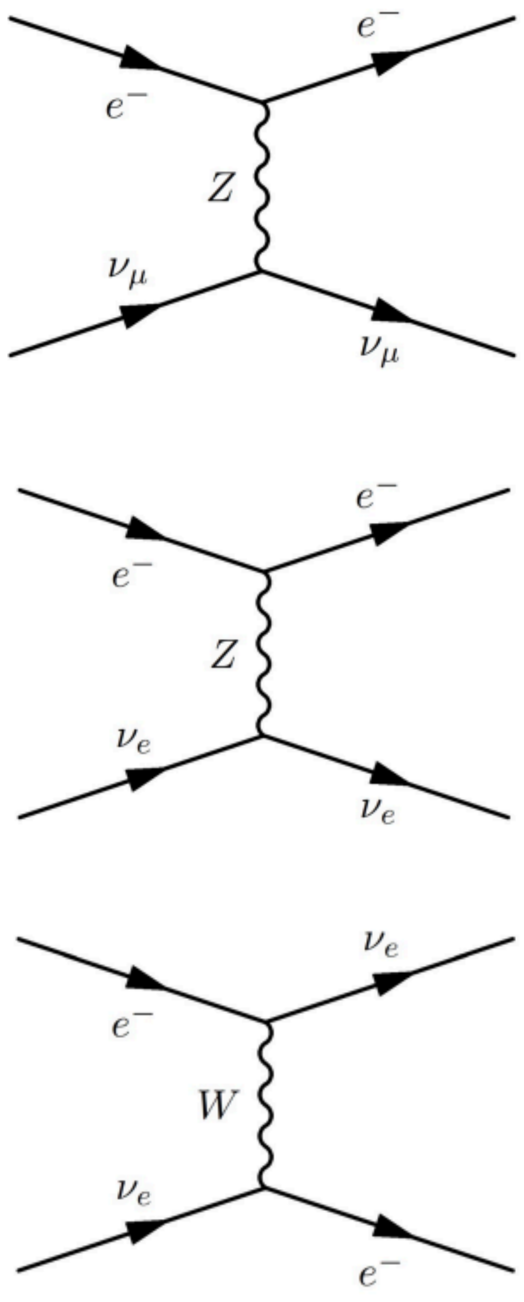
$\nu - e$

- Neutrino-electron scattering is a well-understood process that can be measured to constrain the flux
- Estimated to reduce flux uncertainties from 10% to 7%

$$N_{\nu-e} = \phi_\nu \cdot \sigma_{\nu-e}$$

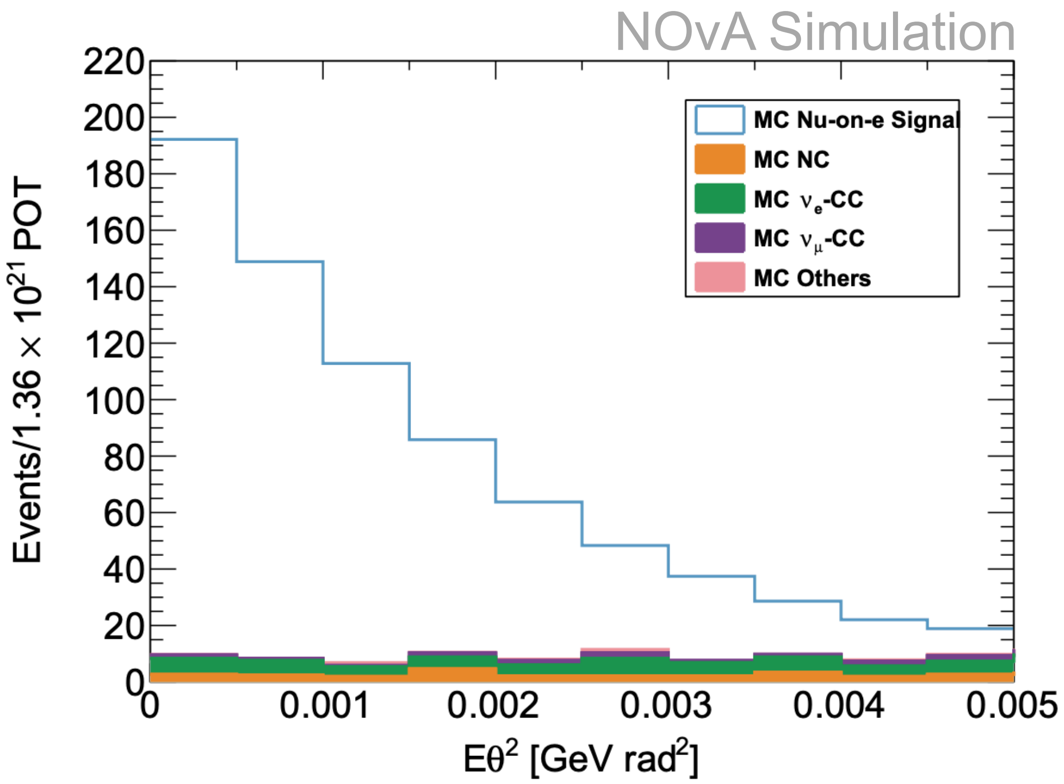
- Kinematically constrained $E_e\theta_e^2 < 2m_e$
- Signature is single very forward going electron
- Challenging $\nu_e CC$ and NC backgrounds

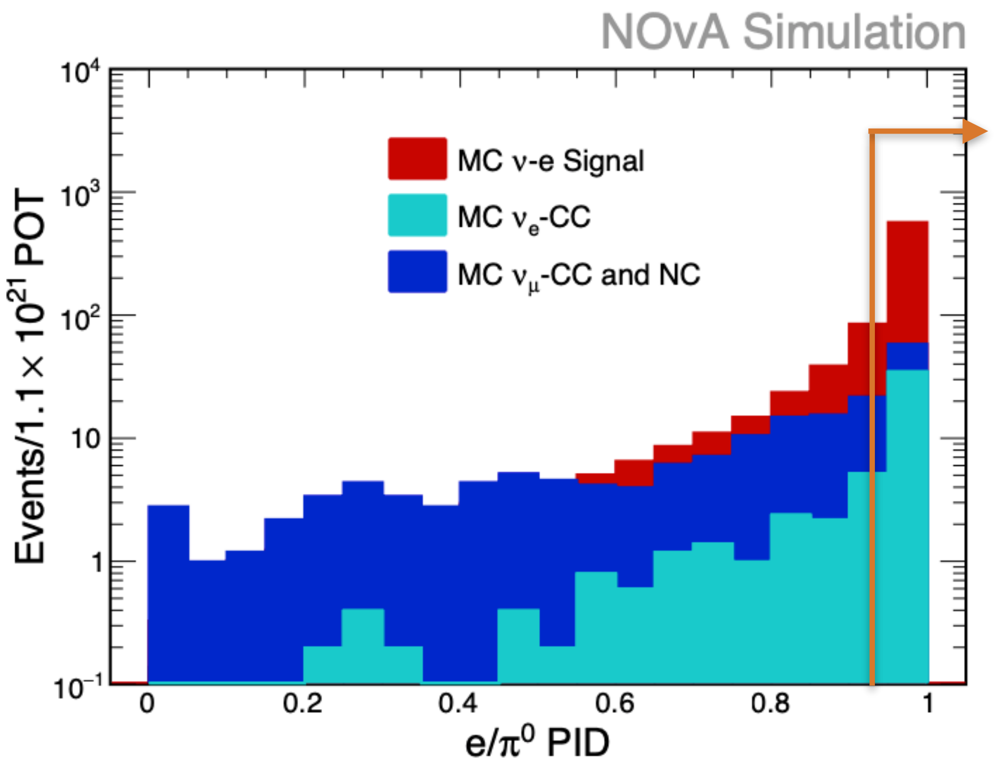


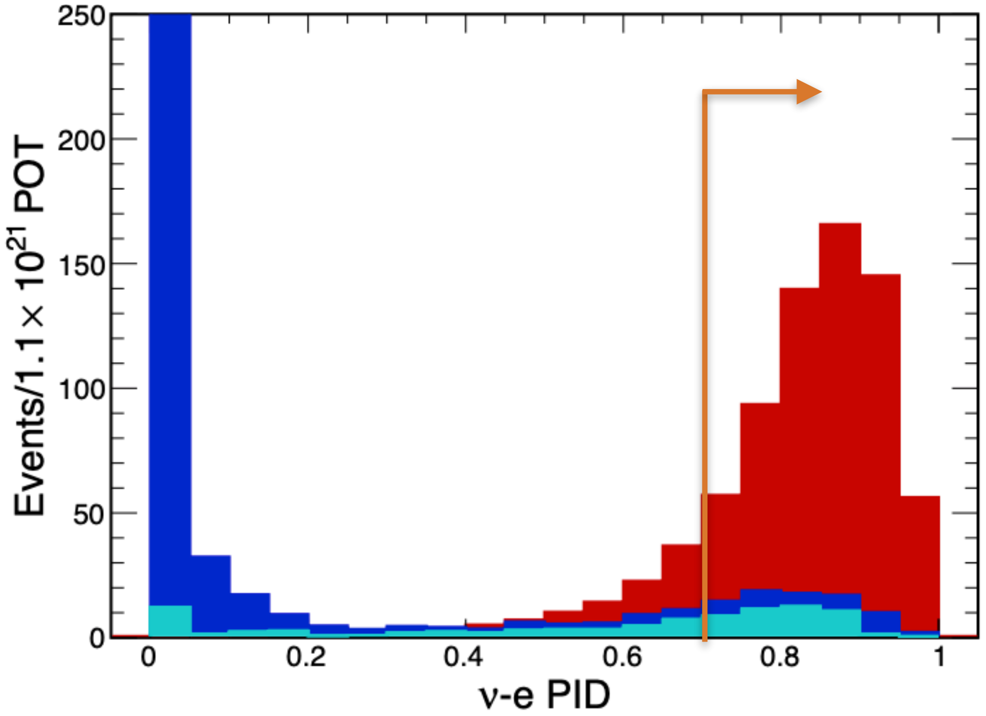


$\nu - e$

- A CNN-based classifier has been trained to identify signal $\nu - e$ events
  - Hybrid training sample of individually simulated electrons (signal) and GENIE (background) events
- Isolates pure sample of ~700 signal events
- Exploring MRE constraint of remaining background $\nu_e CC$

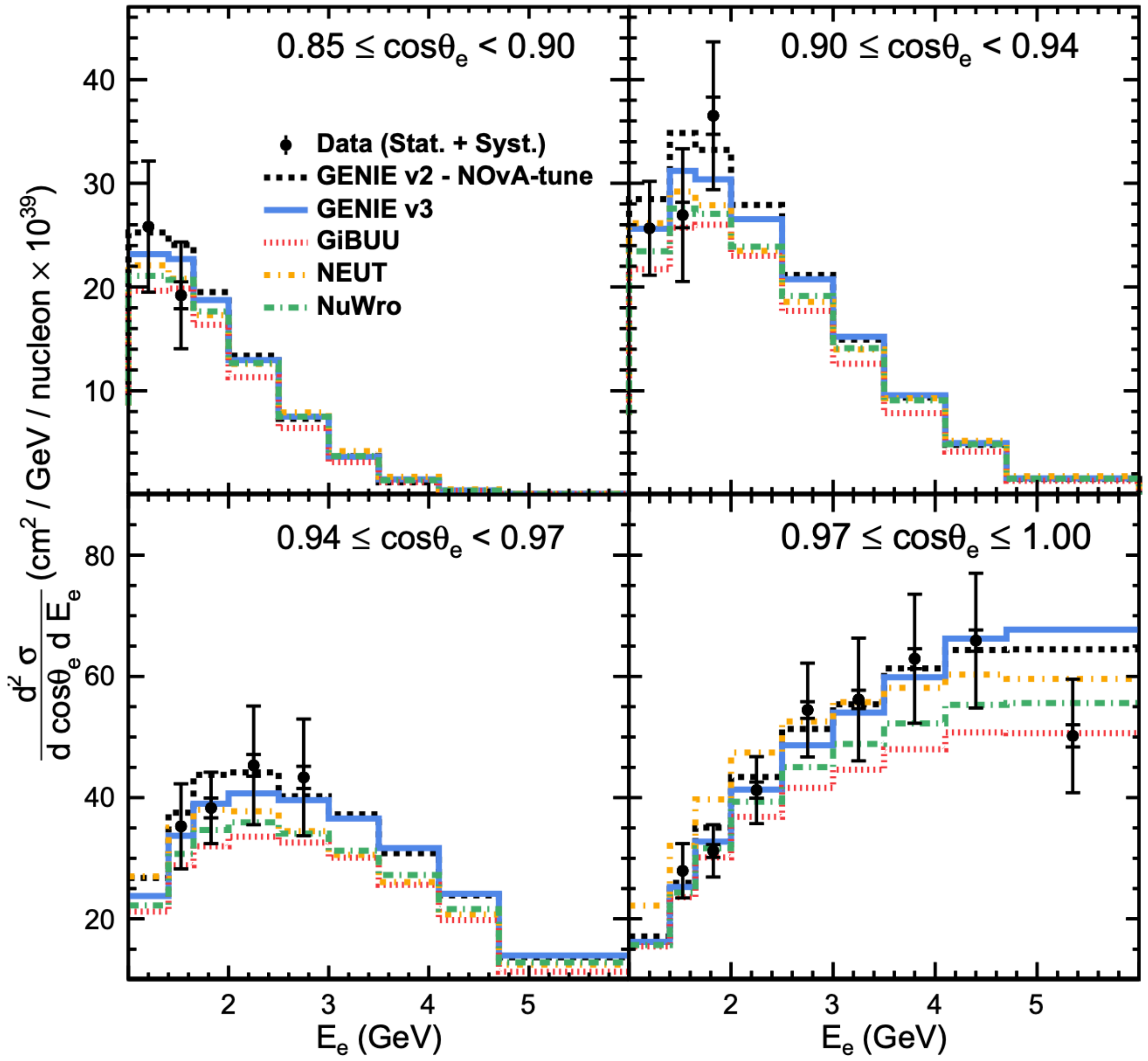






Future of NOvA Electron Analyses

- $\nu_e CC$ paper soon to be published to PRL
- Nearing final stages of $\bar{\nu}_e CC$ measurement with NOvA $\nu_e CC$ constraint
    - First ever double-differential
    - 10,000 signal events
- Measurement of $\nu_e/\bar{\nu}_e$ cross section ratio
- Flux constraint with $\nu - e$ measurement
    - Reduce flux uncertainties from ~10% to ~7%
    - 700 signal events



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