NuFACT 2023

# Measurement of Neutrino-electron Elastic Scattering in the NOvA Near Detector


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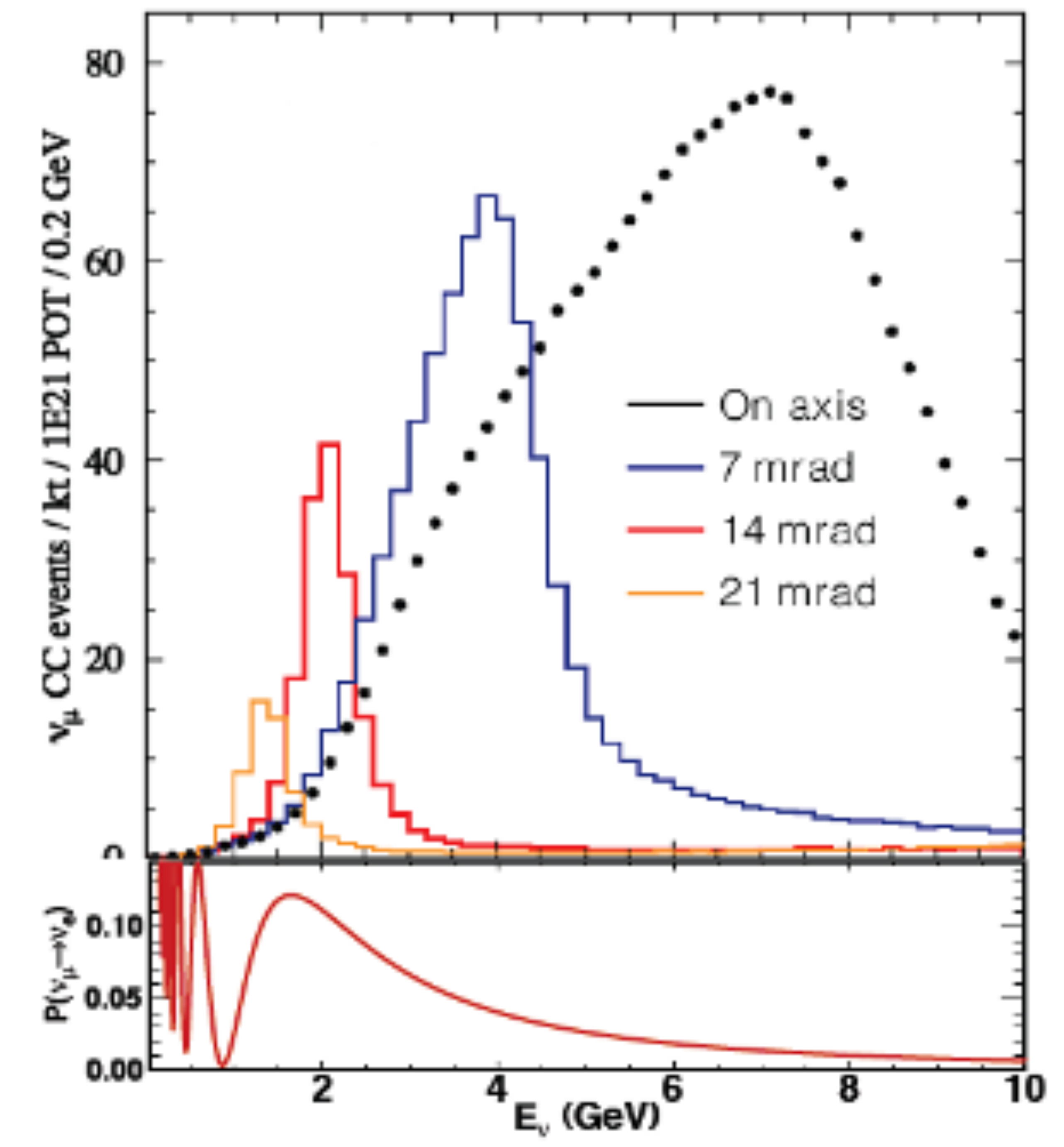
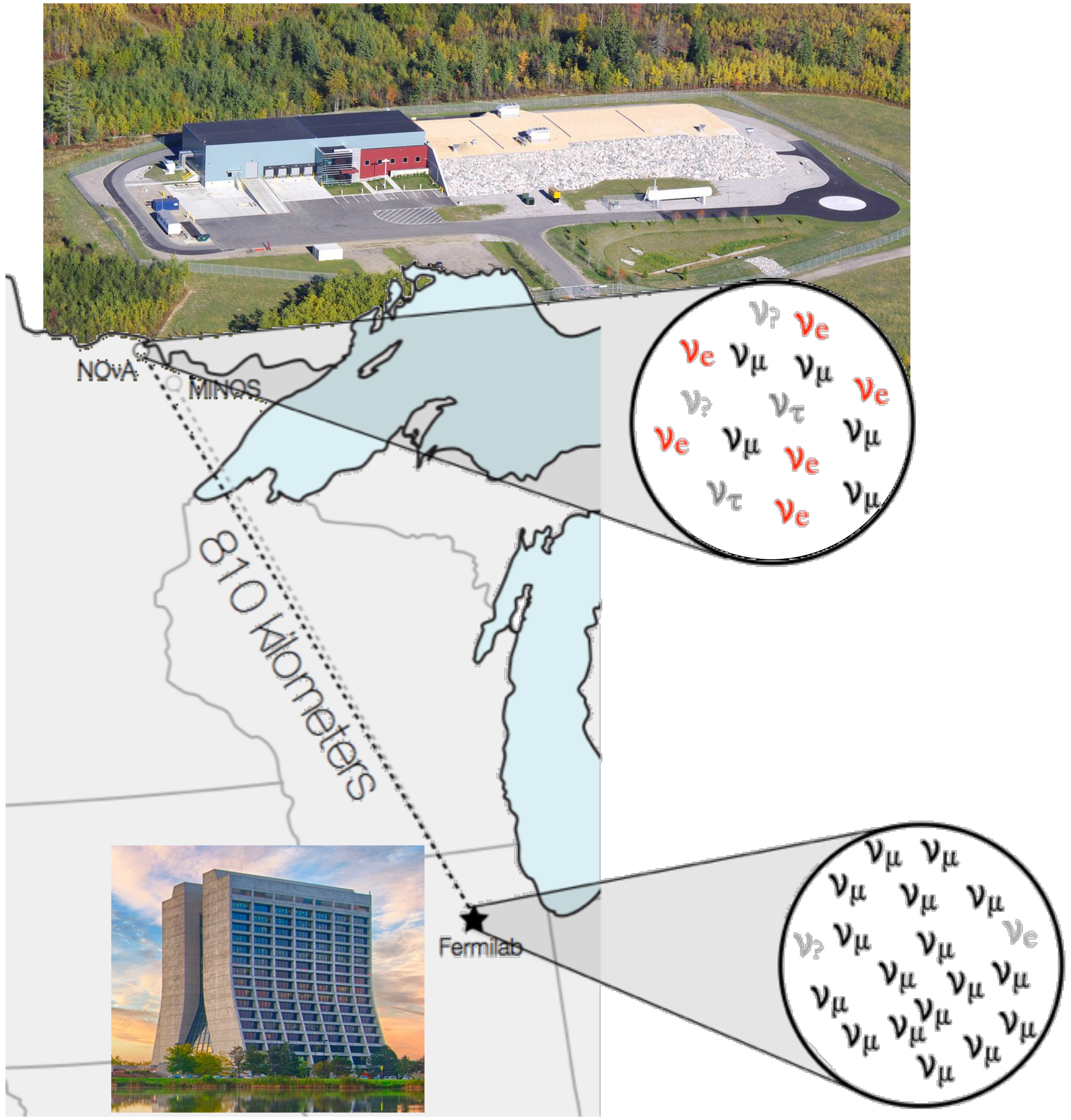
# NOvA (NuMI Off-Axis $\nu_e$ Appearance)

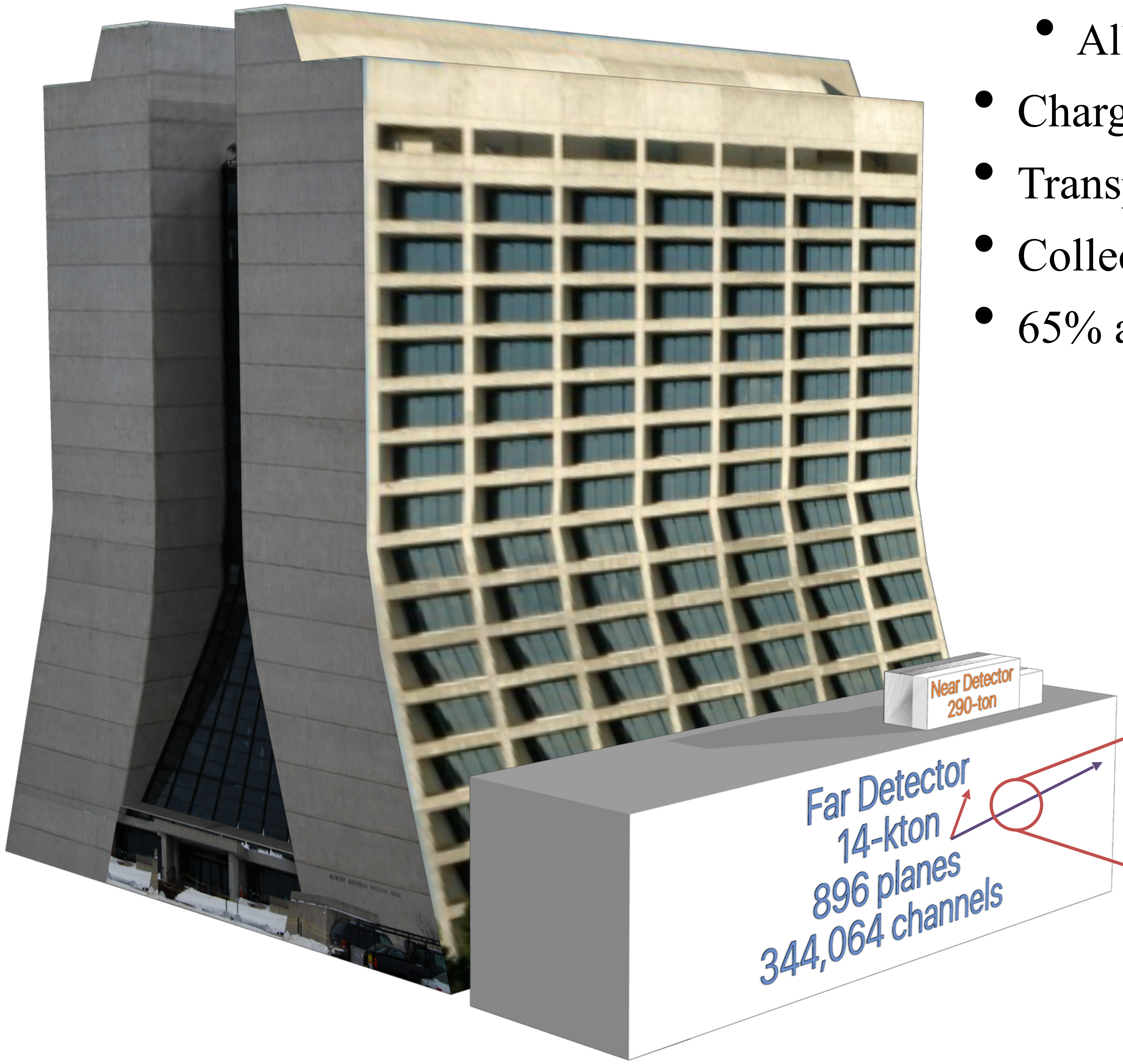
- Long baseline neutrino oscillation experiment, optimized for measuring $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance
- 2 functionally identical tracking calorimeter detectors filled with mineral oil, located 14.6 mrad off-axis from NuMI beamline
  - The near detector (ND) is 1 km away from the neutrino beam target
    - 300t, 300 ft underground
  - The far detector (FD) is 810 km away
    - 14 kt on surface
- Beam flux uncertainty essentially affect all analyses using neutrino beam data
  - The near detector allows an in-situ measurement of the flux using neutrino-electron elastic scattering channel

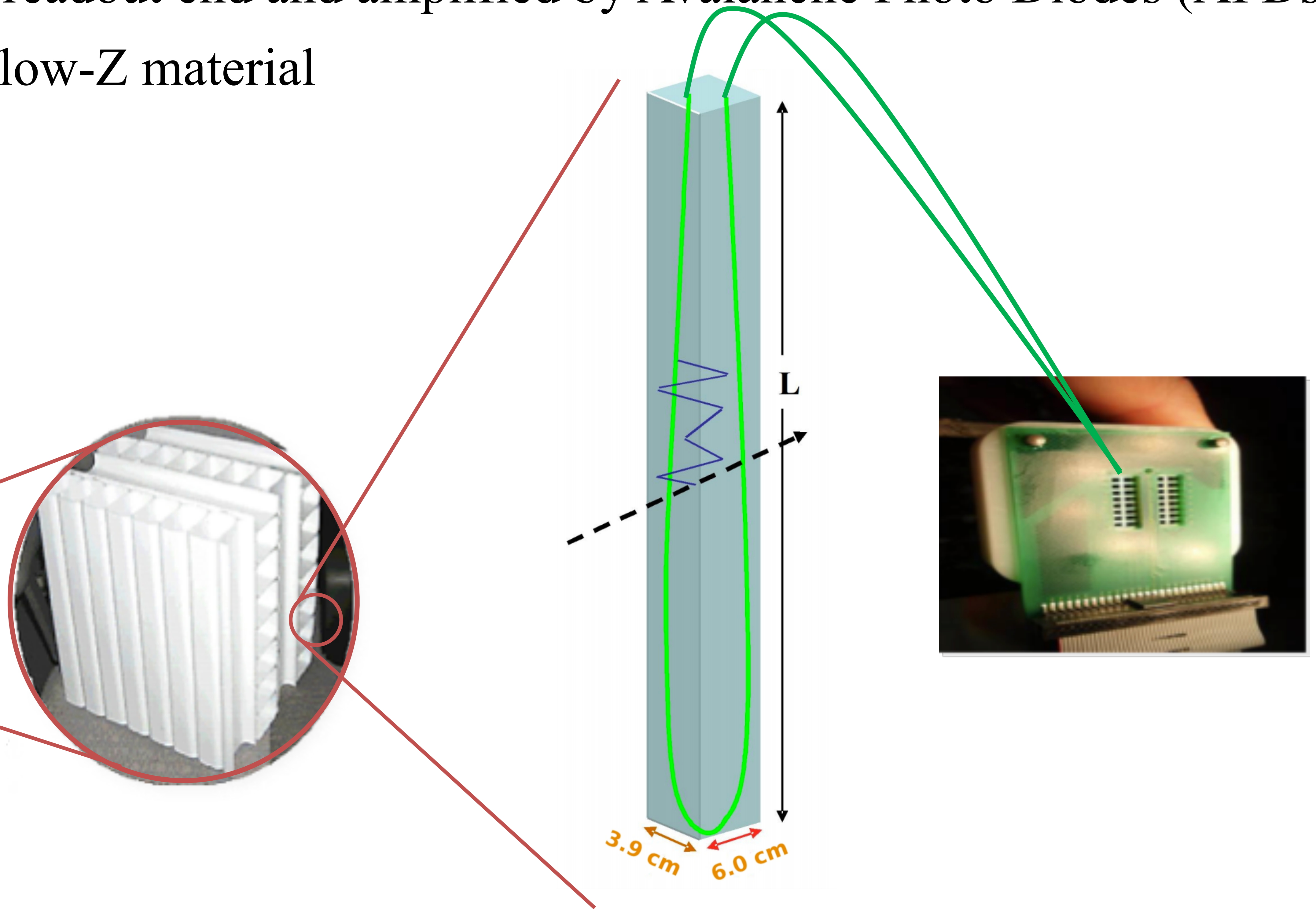


# NOvA (NuMI Off-Axis $\nu_e$ Appearance)

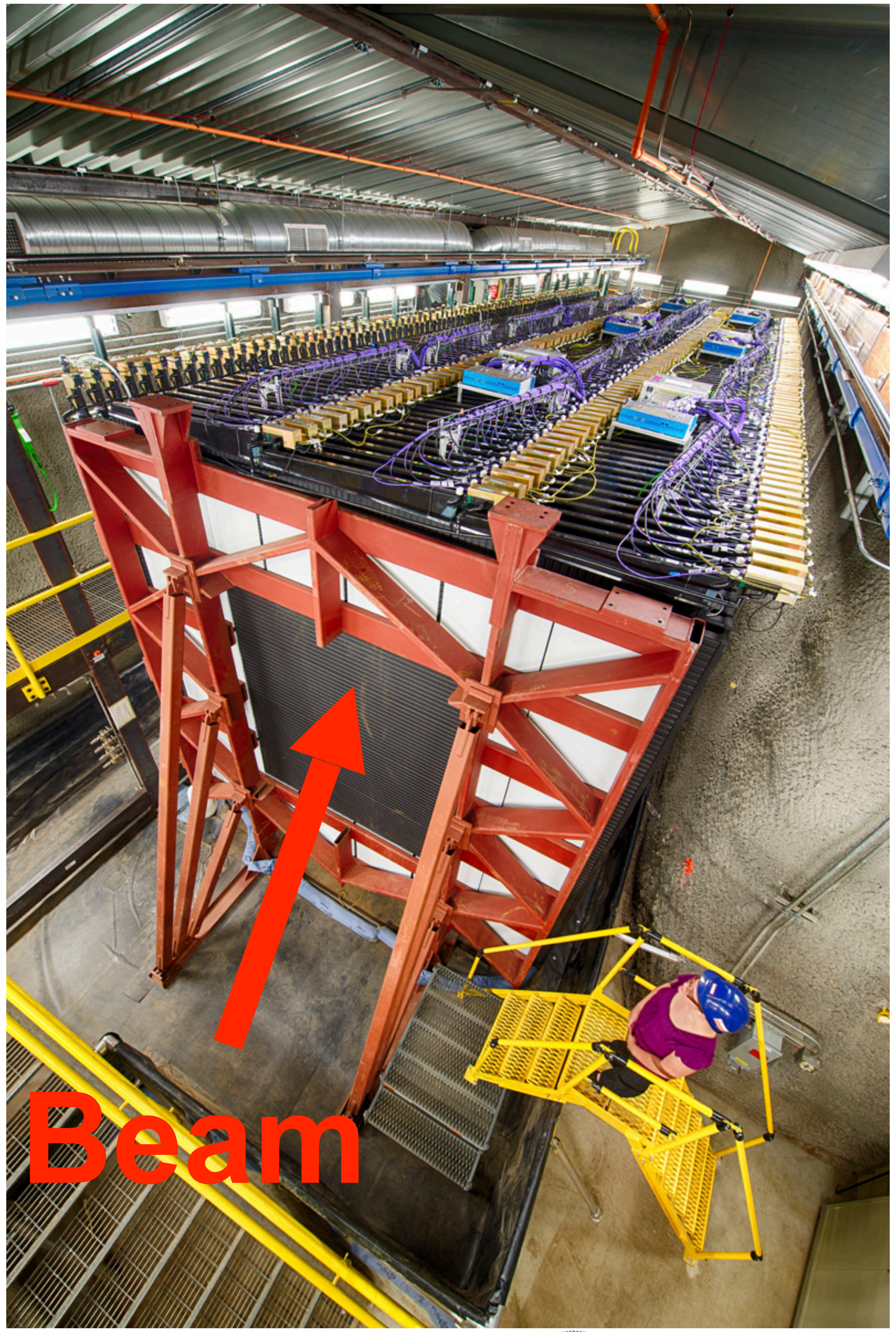
- Plastic cells are stacked in alternating directions
  - Allow 3D reconstruction
- Charged particles excite the scintillator producing light
- Transported by wavelength shifting fibers
- Collected at readout end and amplified by Avalanche Photo Diodes (APDs)
- 65% active, low-Z material



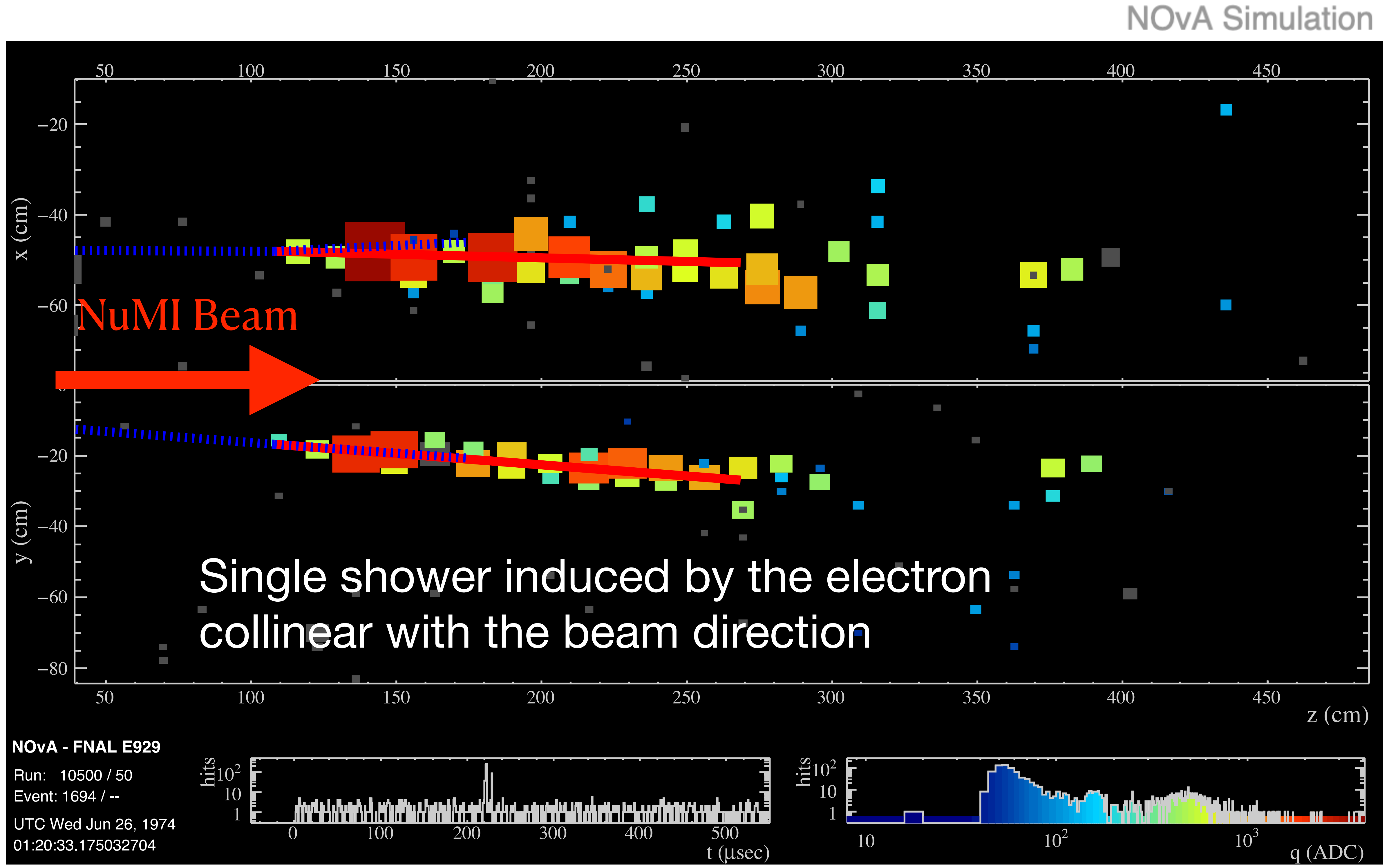
# The NOvA Near Detector

- The near detector (ND) is 1 km away from the neutrino beam target and lies 100 m underground at Fermilab.
- It is located 14.6 mrad off-axis from the NuMI beam line, results in a narrow-band neutrino flux peaked at ~2 GeV with ~1 GeV FWHM.
- 300t tracking calorimeter, constructed from extruded PVC cells filled with liquid scintillator.
- High neutrino flux at Near Detector:
  - Used as a control for the oscillation analyses.
  - Provides a rich dataset for measuring neutrino cross sections.

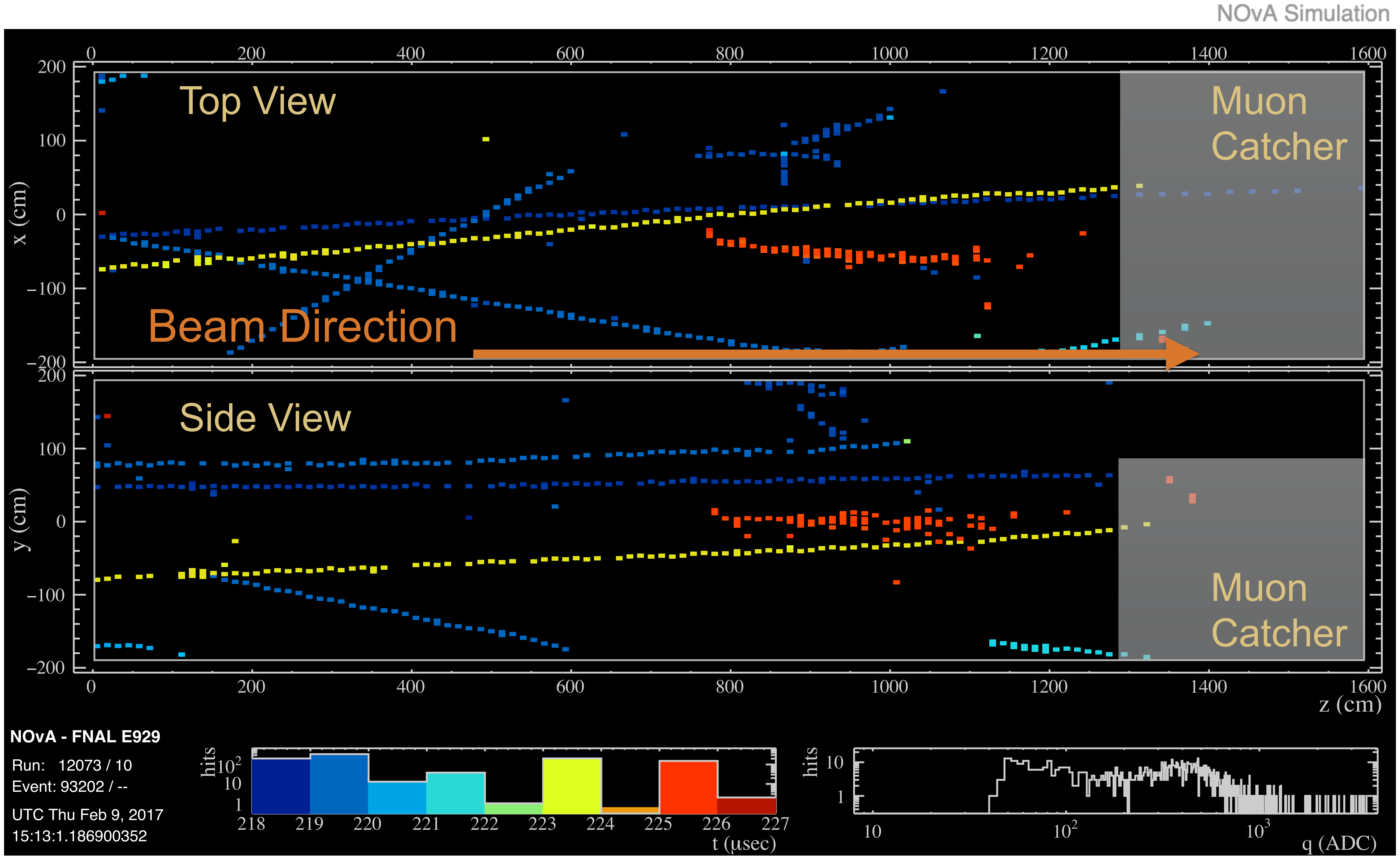


# The NOvA Near Detector

- Segmented liquid scintillator detector provides 3D tracks and calorimetry.
- Optimized for EM shower measurements: X0 = 38 cm (6 cell depth, 10 cell width).
- Good time resolution (~ 5 ns) and spatial resolution (~ few cm).
- Allow clear separation of interactions.



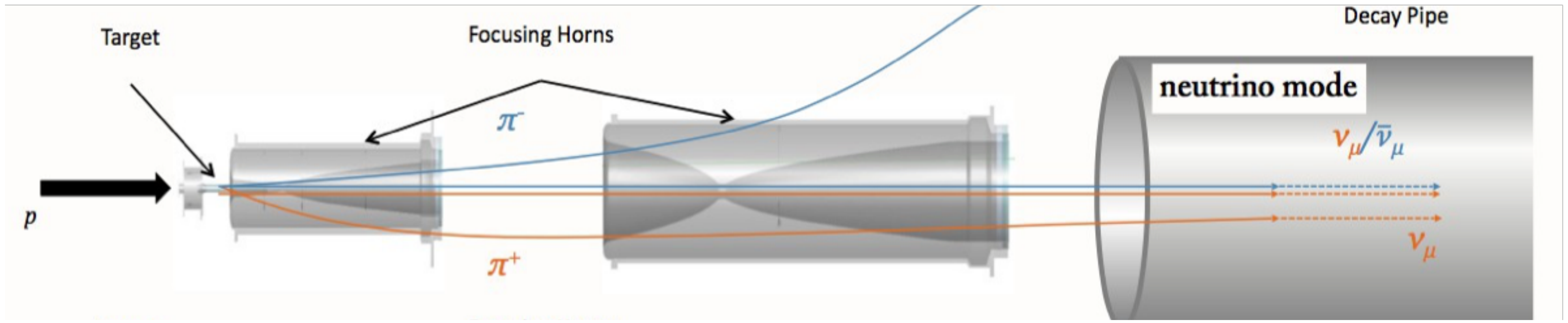
# NOvA Reconstruction

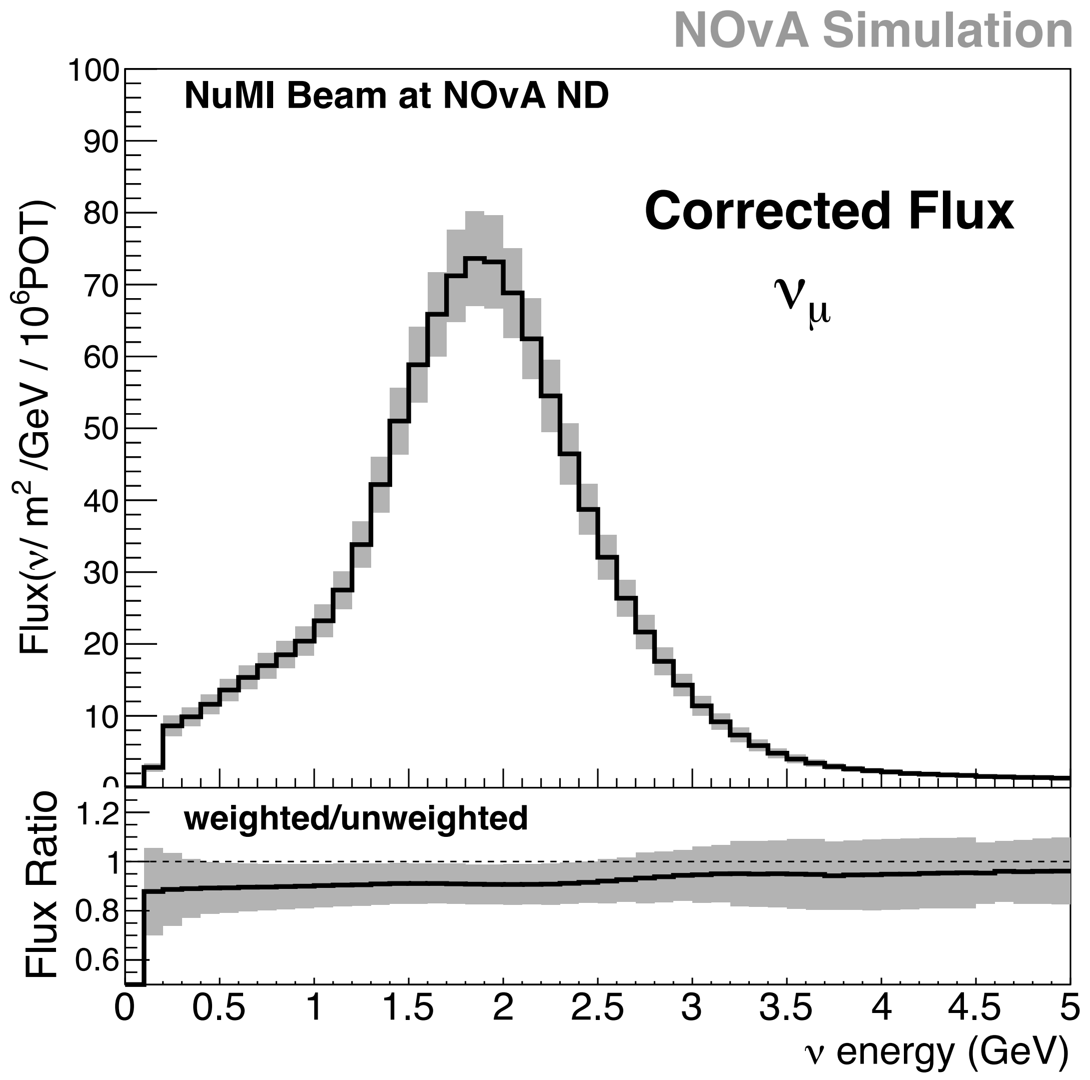



- Hits associated in time and space are used to form a candidate interaction.
- Tracks and showers are reconstructed from these hits.

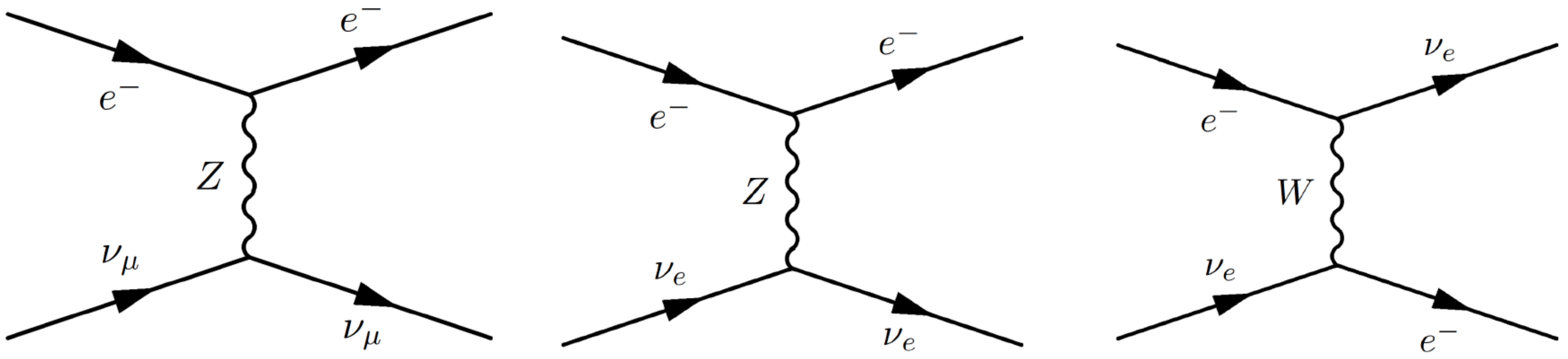
# Neutrino Source

- NuMI beam: $\nu_\mu$ or $\bar{\nu}_\mu$
  - colliding a proton beam on a solid target and focusing the resulting particles through focusing horns
  - carries large uncertainties from hadron productions on targets and beam transport.
- Neutrino cross-section measurements performed at the near detector are affected by the large uncertainty on the absolute neutrino flux
- External hadron production measurements are used to correct and constrain the flux, and the uncertainties on those measurements result in ~ 10% uncertainty on the flux prediction



# Neutrino-Electron Elastic Scattering



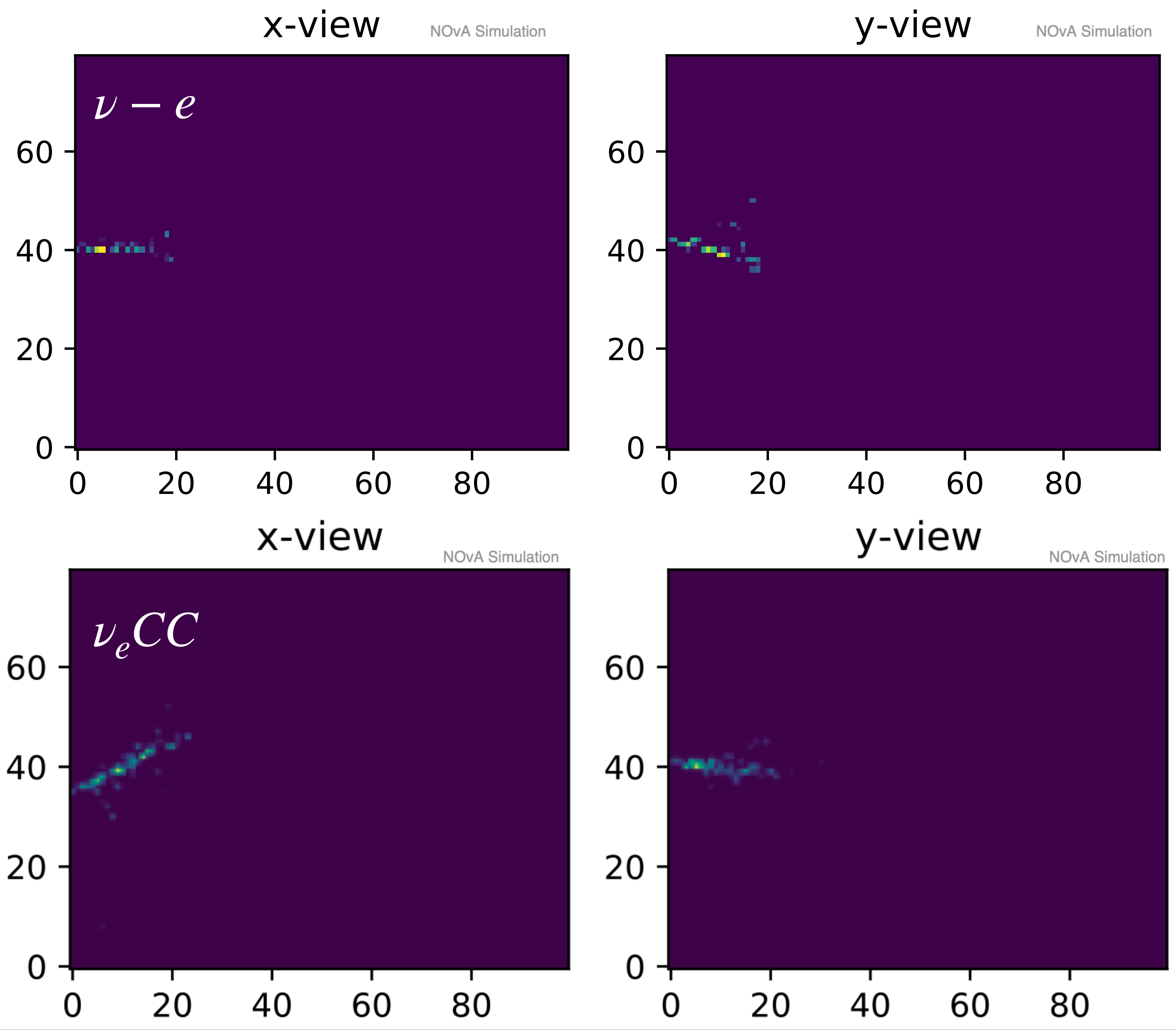

$$N_\nu^{\text{obs}} \propto \int \Phi_{\text{flux}}(E_\nu) \cdot \sigma(E_\nu)\, dE_\nu$$

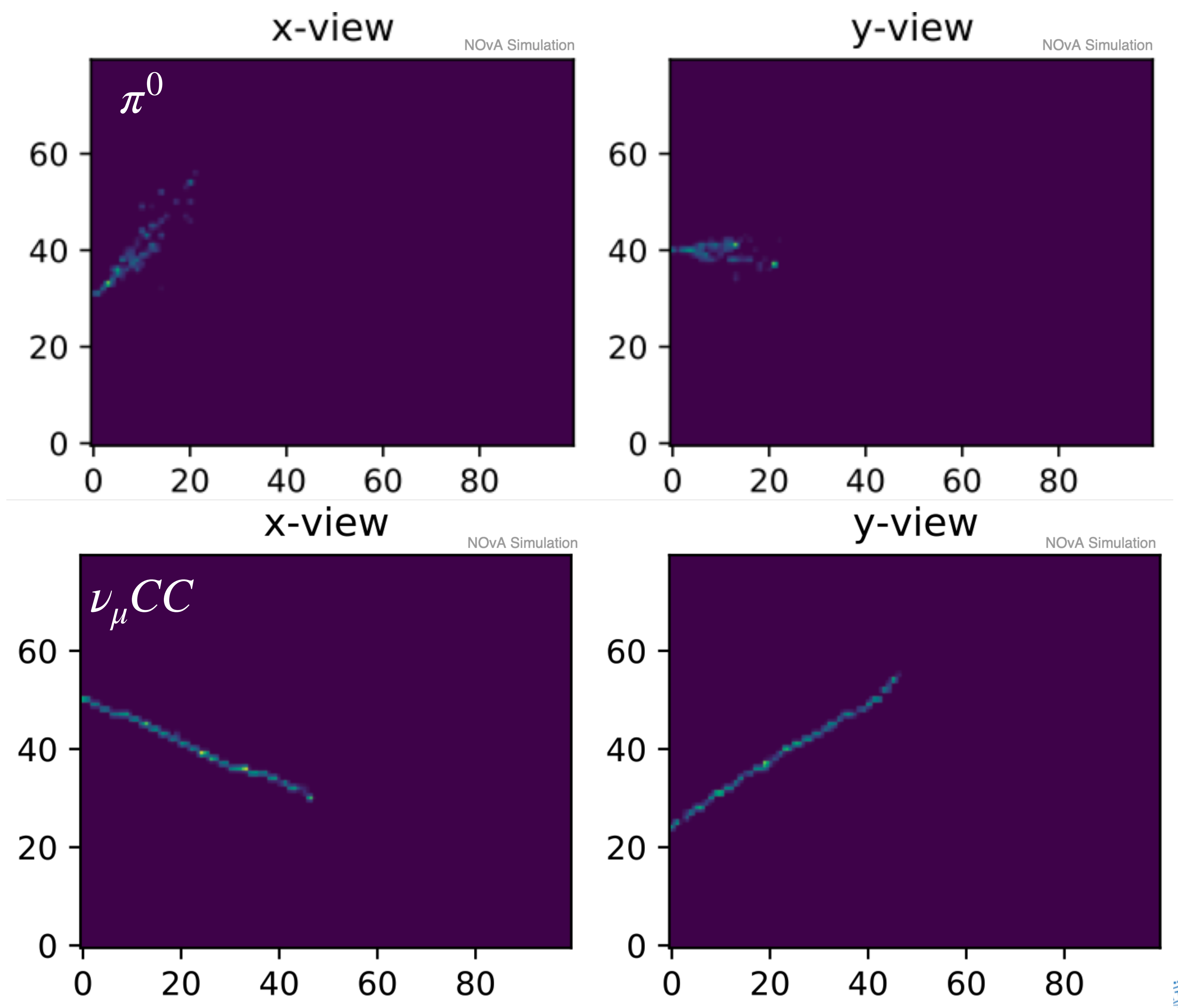
$$N_{\nu-e}^{\text{obs}}(E_e) \propto \int \Phi_{\text{flux}}(E_\nu) \cdot \frac{d^2\sigma(E_\nu, E_e)}{dE_e dE_\nu} dE_\nu$$

- Neutrinos can elastically scatter off electrons via neutral current or charge current exchange.
- $\nu - e$ is a pure leptonic process, whose amplitude can be precisely calculated in the standard model at the 1% level (precision of $\sin^2\theta_W$).
- The cross section is very low (~ 1/2000 of the total charged-current cross section).
- Using $\nu - e$ to measure the flux of the neutrino beam, which is helpful for all cross-section measurements.

# CNN-Based Classifiers for event selection

- The topology of signal event requires one EM shower with no other particles in the final state.
- Event identifications are important for separating signals from substantial backgrounds.
- NOvA has developed a convolutional neural network (called CVN) to classify events ($\nu_e$ CC, $\nu_\mu$ CC, $\nu$ NC, Cosmics). The architecture is modified based on MobileNet_v2 with similar performance as ResNet whilst being ~4x faster.

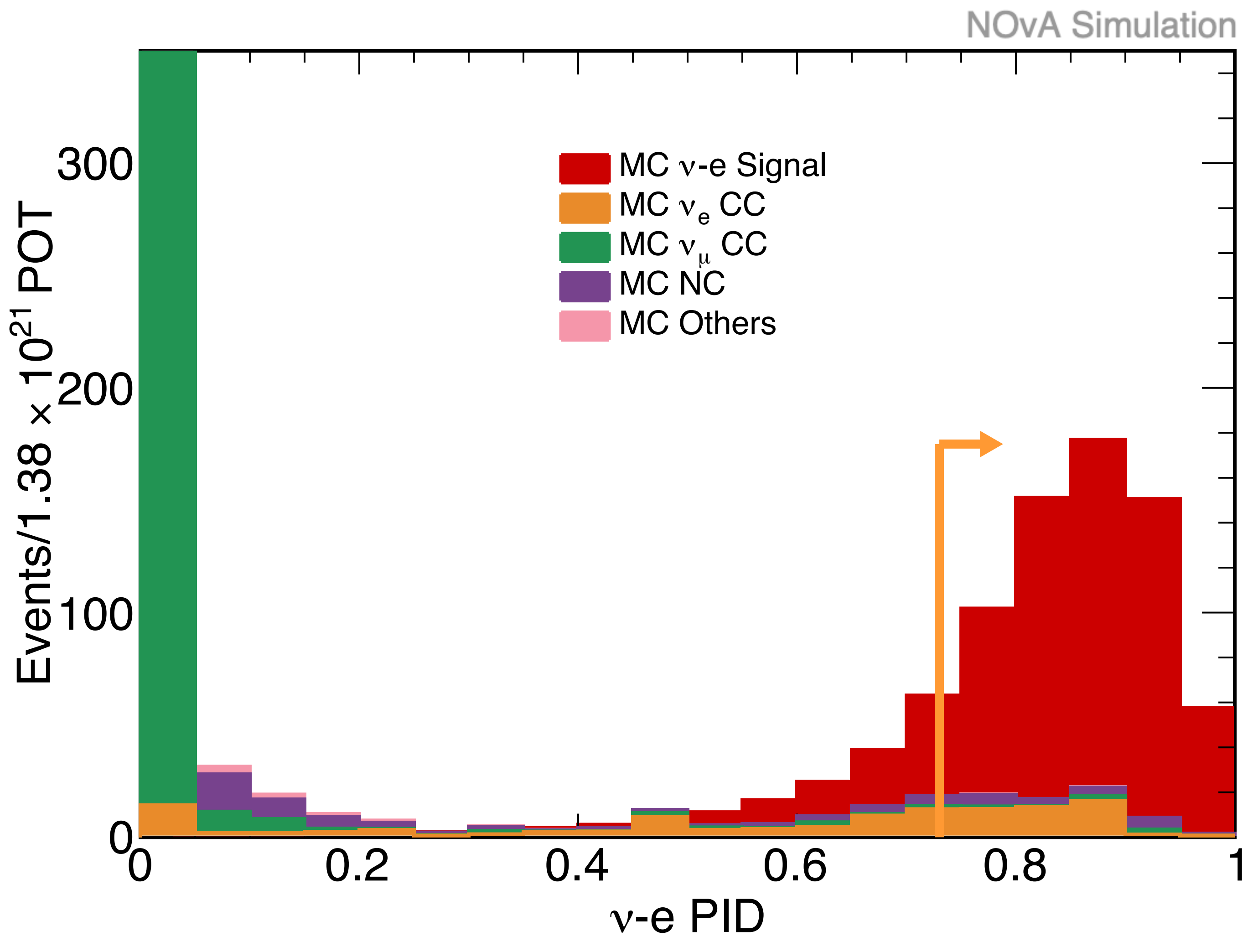


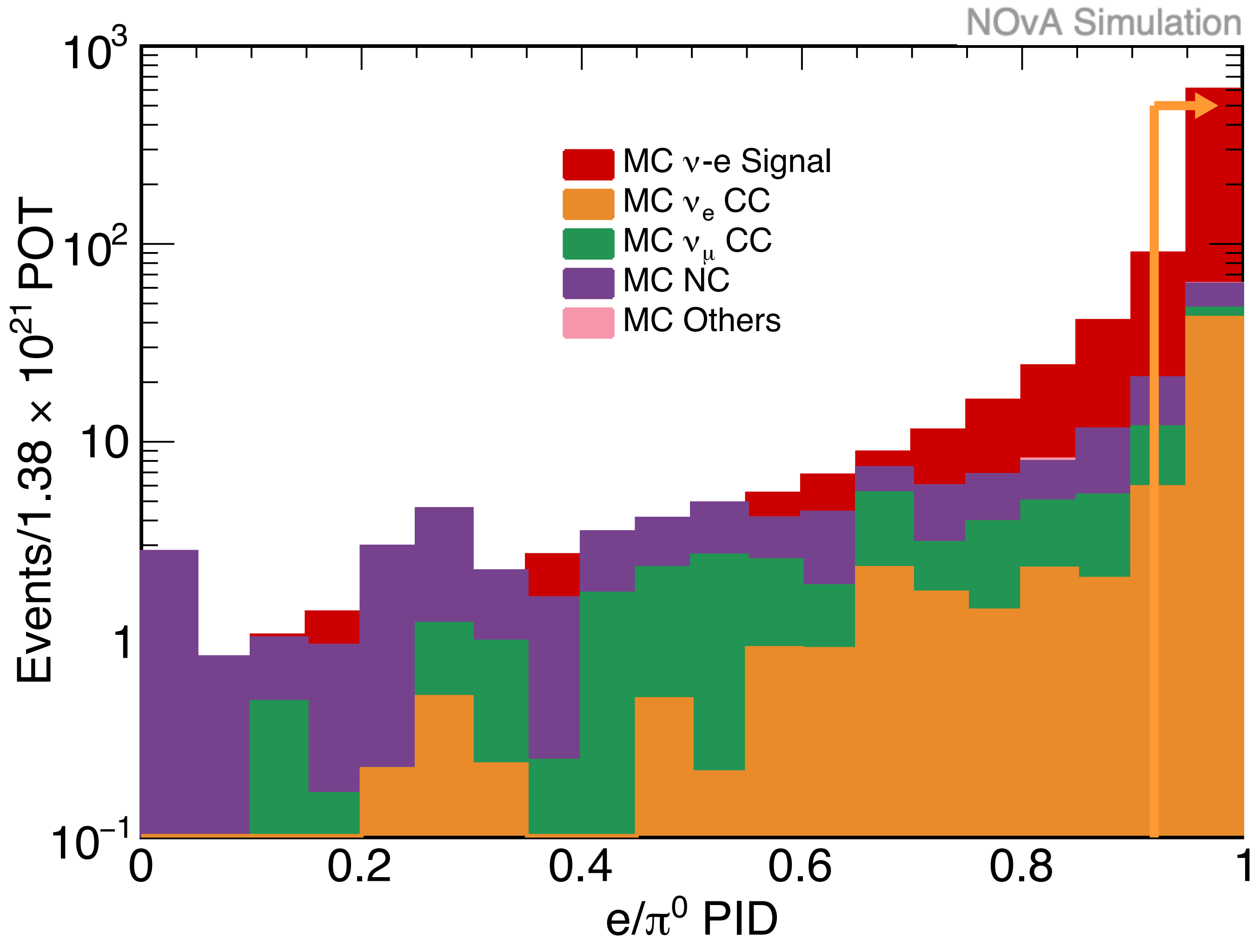




(Ref: arXiv:1604.01444)

# CNN-Based Classifiers for event selection

- Training:
  - Signal: Simulation of single electrons in the detector
  - Background: Inclusive MC of an enriched $\nu_e$ sample
  - Preselection was applied to remove events from the peripheral region
  - Reweighted training to to mitigate angular and energy dependencies
- Two event classifiers based on the same architecture were trained.
  - $\nu - e$ PID:
    - trained with four categories ($\nu - e$, $\nu$ induced $\pi^0$, $\nu_e CC$, Others)
    - to separate $\nu - e$ scattering events from backgrounds.
    - Also used in BSM search
  - $e/\pi^0$PID:
    - trained with only two categories ($\nu - e$, $\nu$ induced $\pi^0$)
    - to further rejects backgrounds with $\nu$ induced $\pi^0$ in the final state.

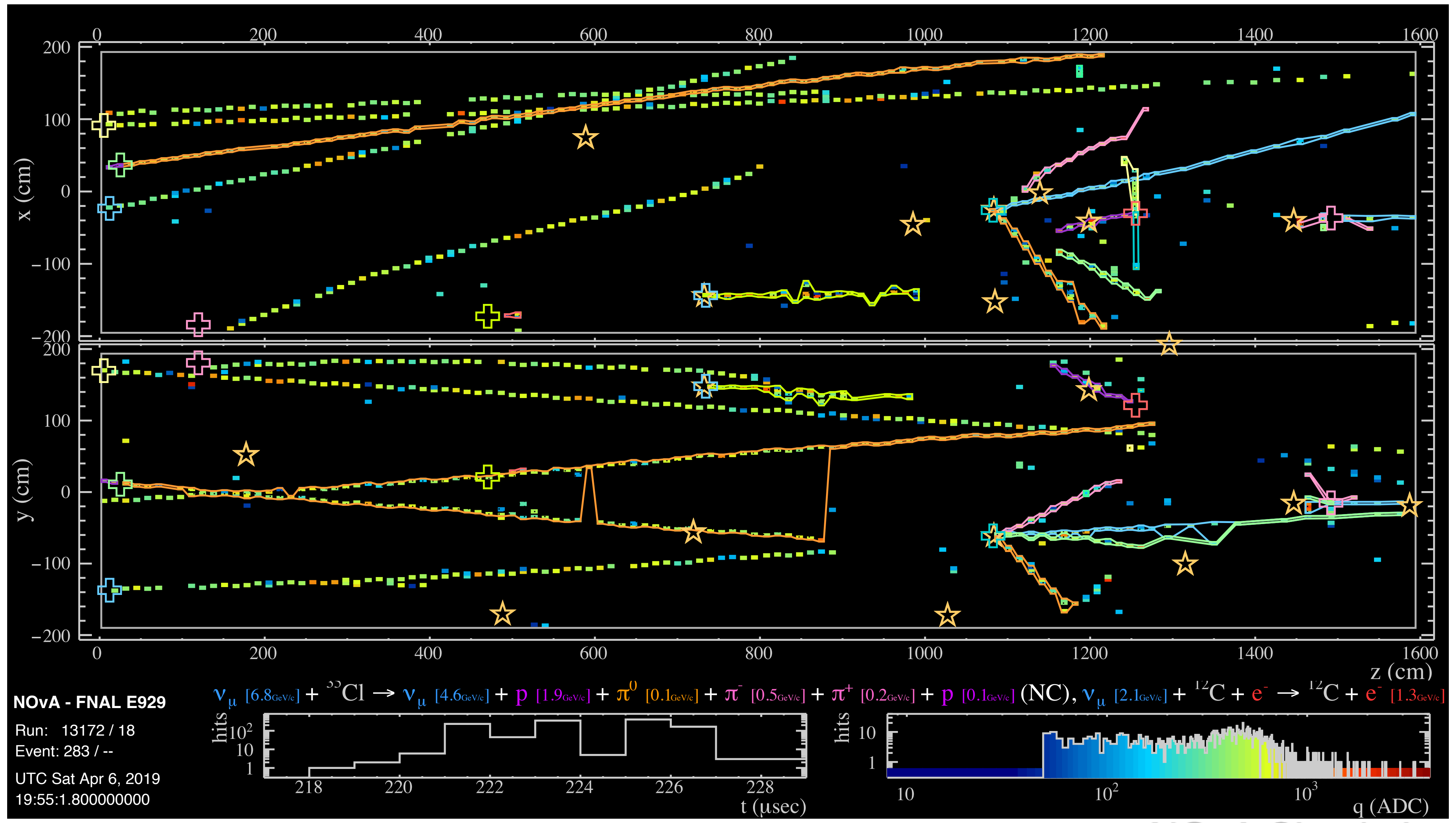


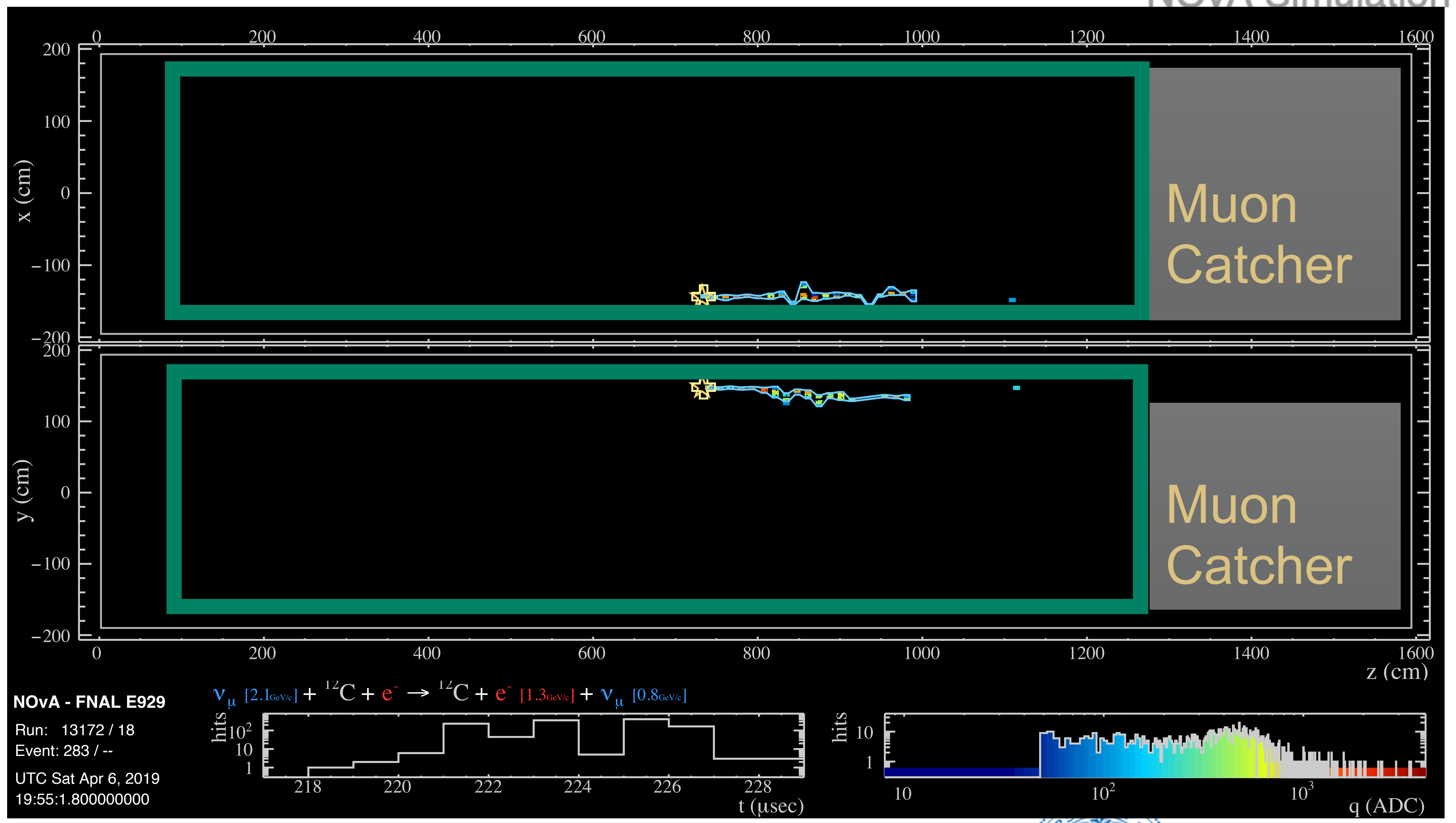
# $\nu - e$ Signal Selection

- Monte Carlo (MC) samples were used to study the event selection.
- Event Selection:
  - Pre-selection: remove obvious $\nu_\mu$ CC interactions.
  - Fiducial and Containment: define the fiducial region and suppress backgrounds induced by neutrino interactions in the rock (mostly upstream of the ND).
  - Single Particle Requirement: the topology of the signal event requires one EM shower with no other particles in the final state.
  - Energy of the primary shower: exclude low-energy events which are hard to distinguish.
  - Nu-on-e classifiers: separating signals from substantial backgrounds using the CNN technique.
  - $E\theta^2$: the scattered electron is very forward going.

NOvA Simulation



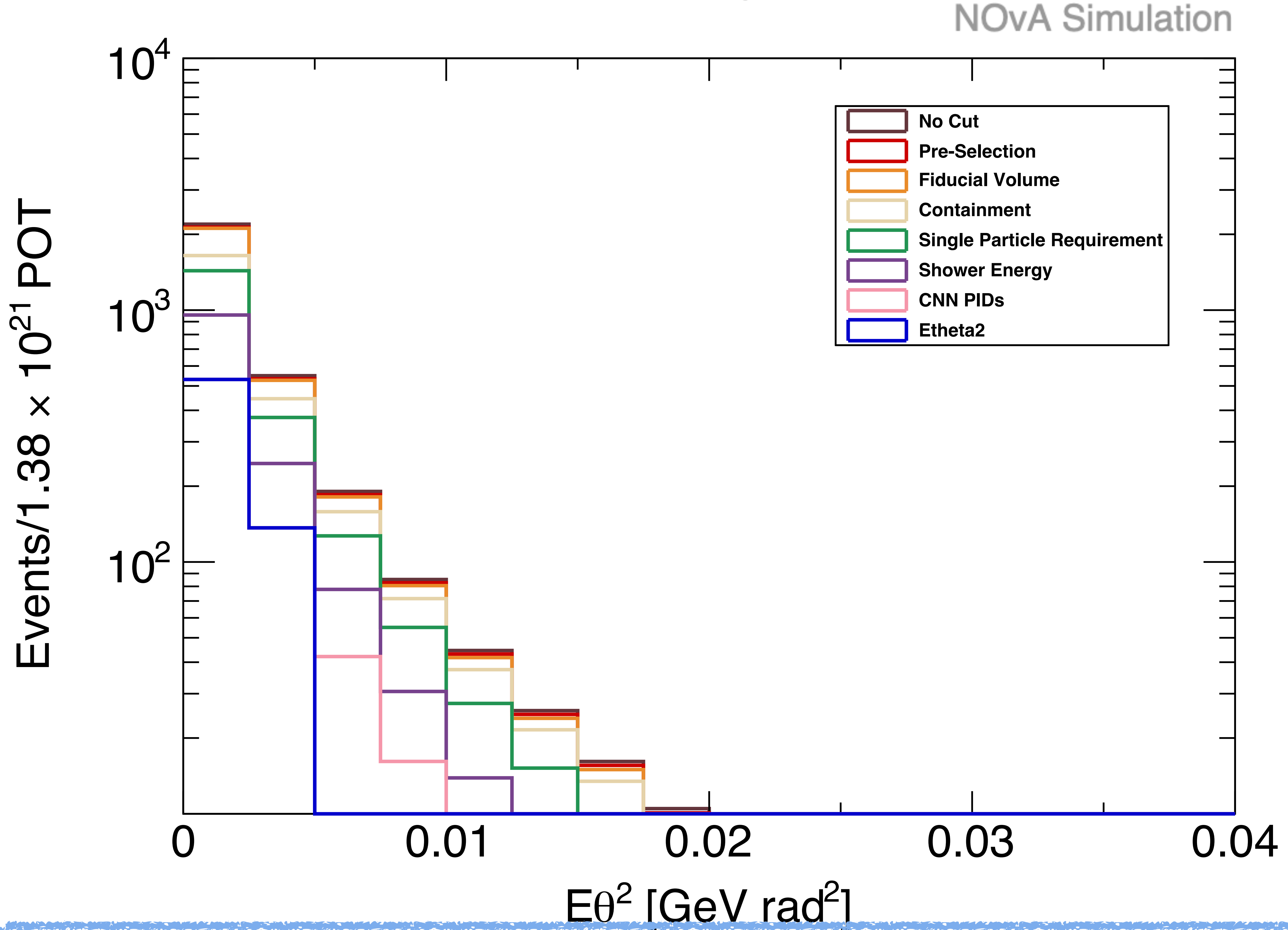

NOvA Simulation



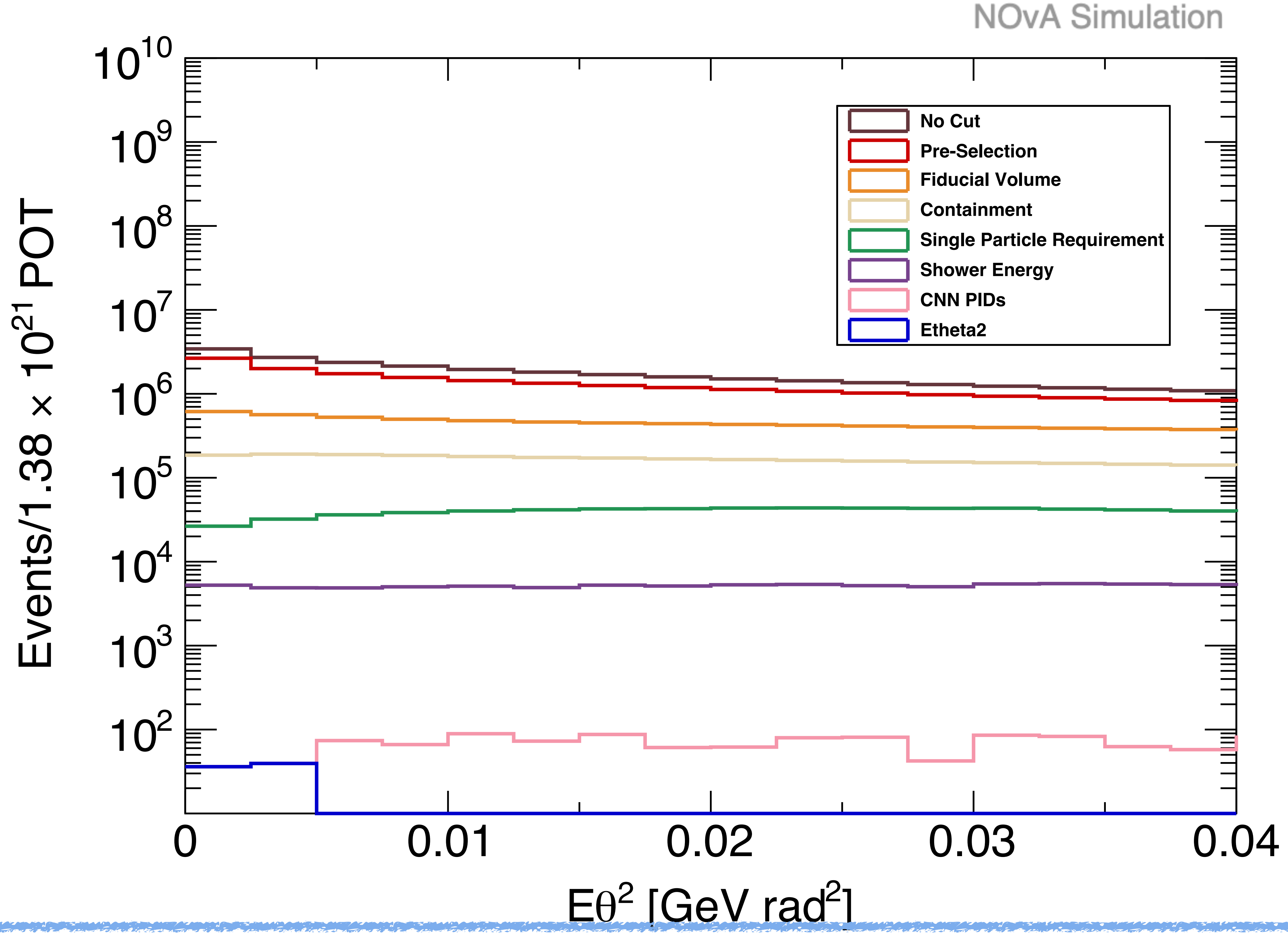
# $\nu - e$ Signal Selection and Optimization

- Monte Carlo (MC) samples were used to study the event selection.

$E\theta^2$ **cut-flow for Signal MC**



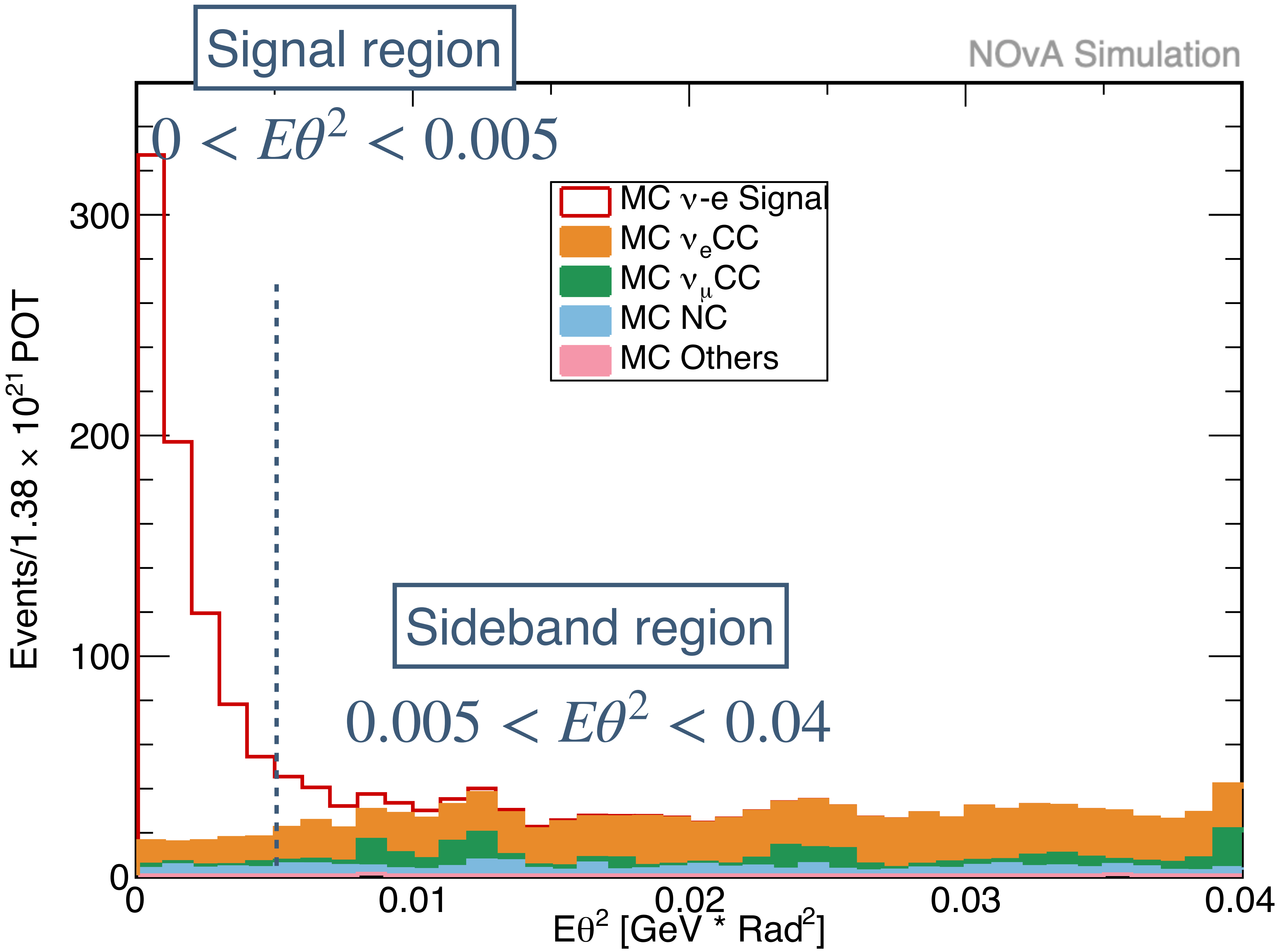

$E\theta^2$ **cut-flow for Background MC**




Optimize selection criteria based on Figure of Merit (FOM). To consider background uncertainty in the measurement, define $FOM = \frac{S}{\sqrt{S + B + \delta B^2}}$, where $\delta B$ is the systematic uncertainty in the background. Assume $\delta B = 0.2B$ according to the $\nu_e$CC cross-section measurement.

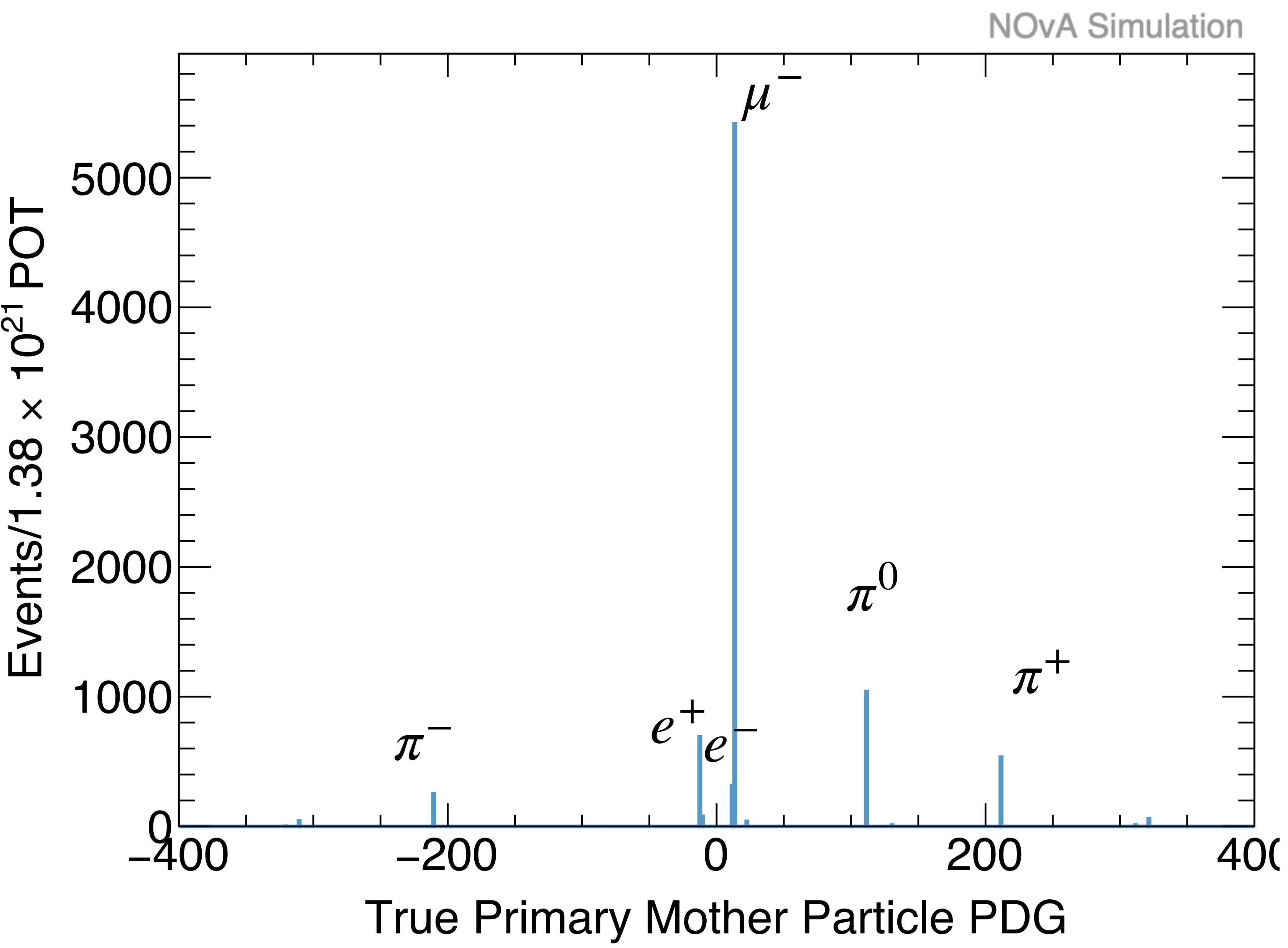
# $\nu - e$ Signal Selection Results and Sideband Constraint

- $E$ refers to the calorimetric energy of the most energetic shower and $\theta$ is the angle between the direction of the most energetic shower and the beam direction
- With CNN PIDs and cut optimization, based on $1.38 \times 10^{21}$ POT FHC simulation:
  - Sig. 675.09, Bkg. 75.47 for
  - FOM = 24.59
- Sideband Region ($0.005 < E\theta^2 < 0.04$).
  - Large sideband region (7x signal region) to reduce statistical error
  - Sideband region can be used to correct background yield in the signal region

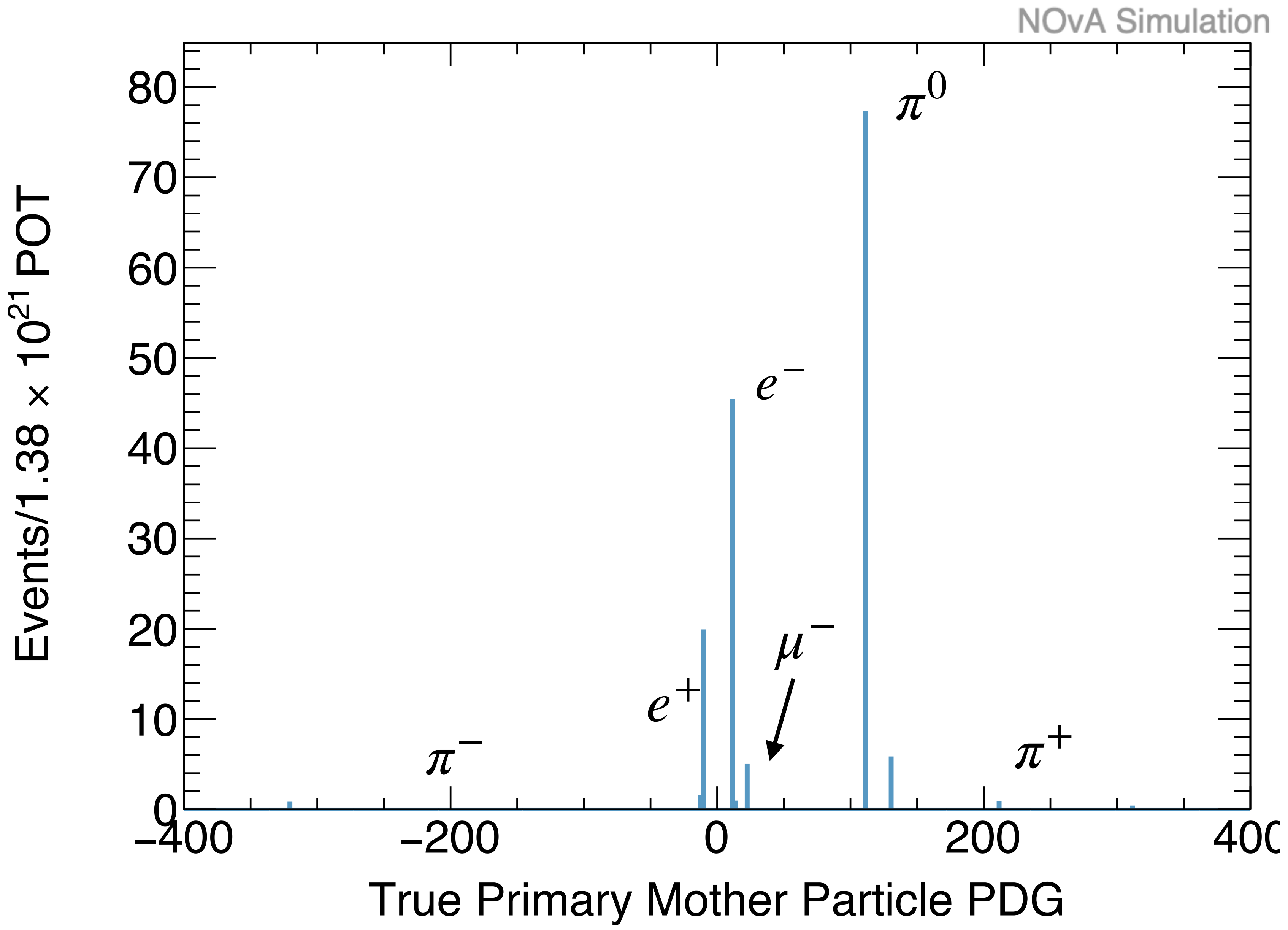


# Performance of CNN PIDs breakdown by Primary Mother Particle

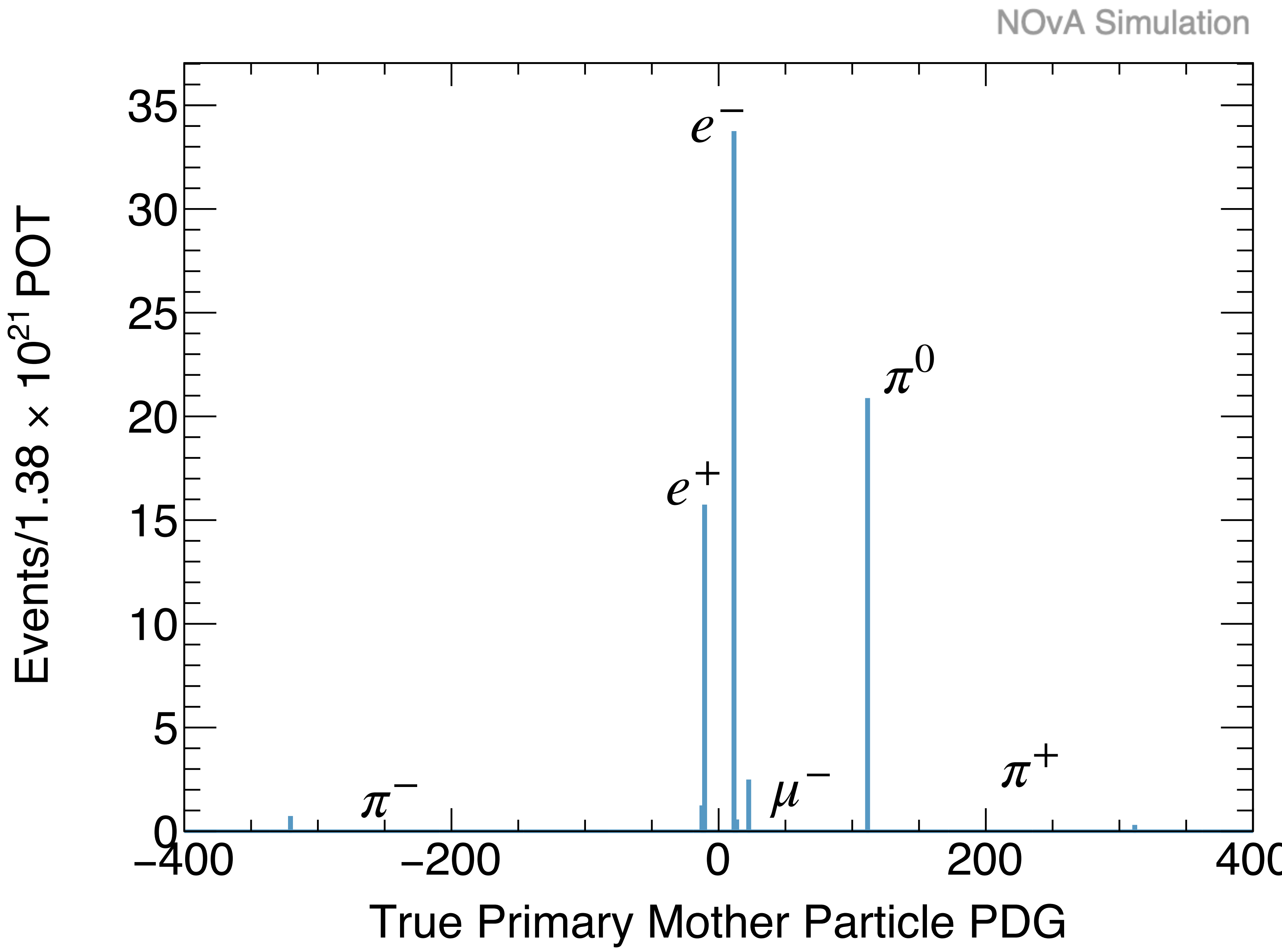
Selected Background before CNN PIDs




Selected Background after $\nu - e$ PID




Selected Background after $e/\pi^0$ PID



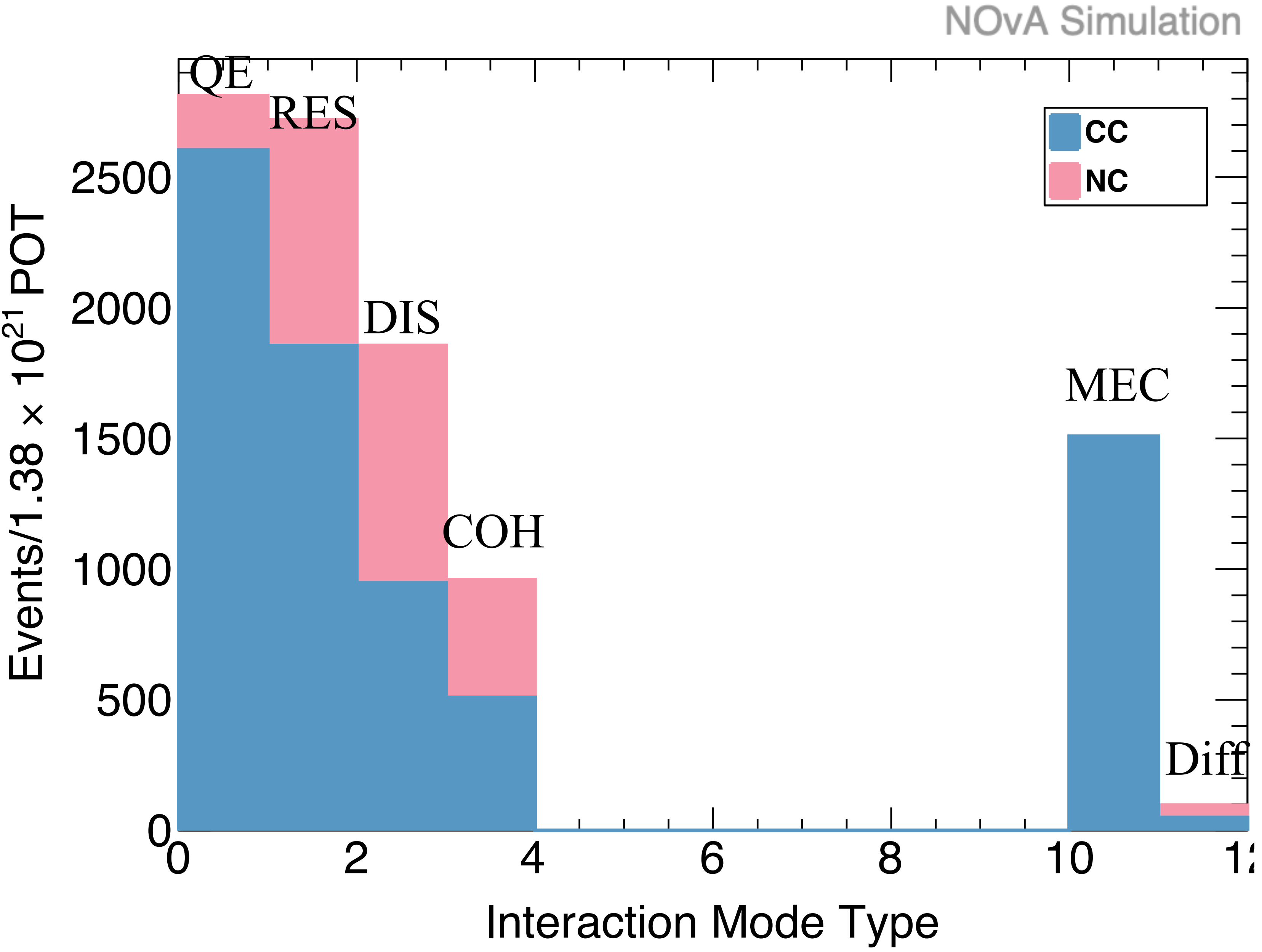

Applying $\nu - e$ PID

Applying $e/\pi^0$ PID

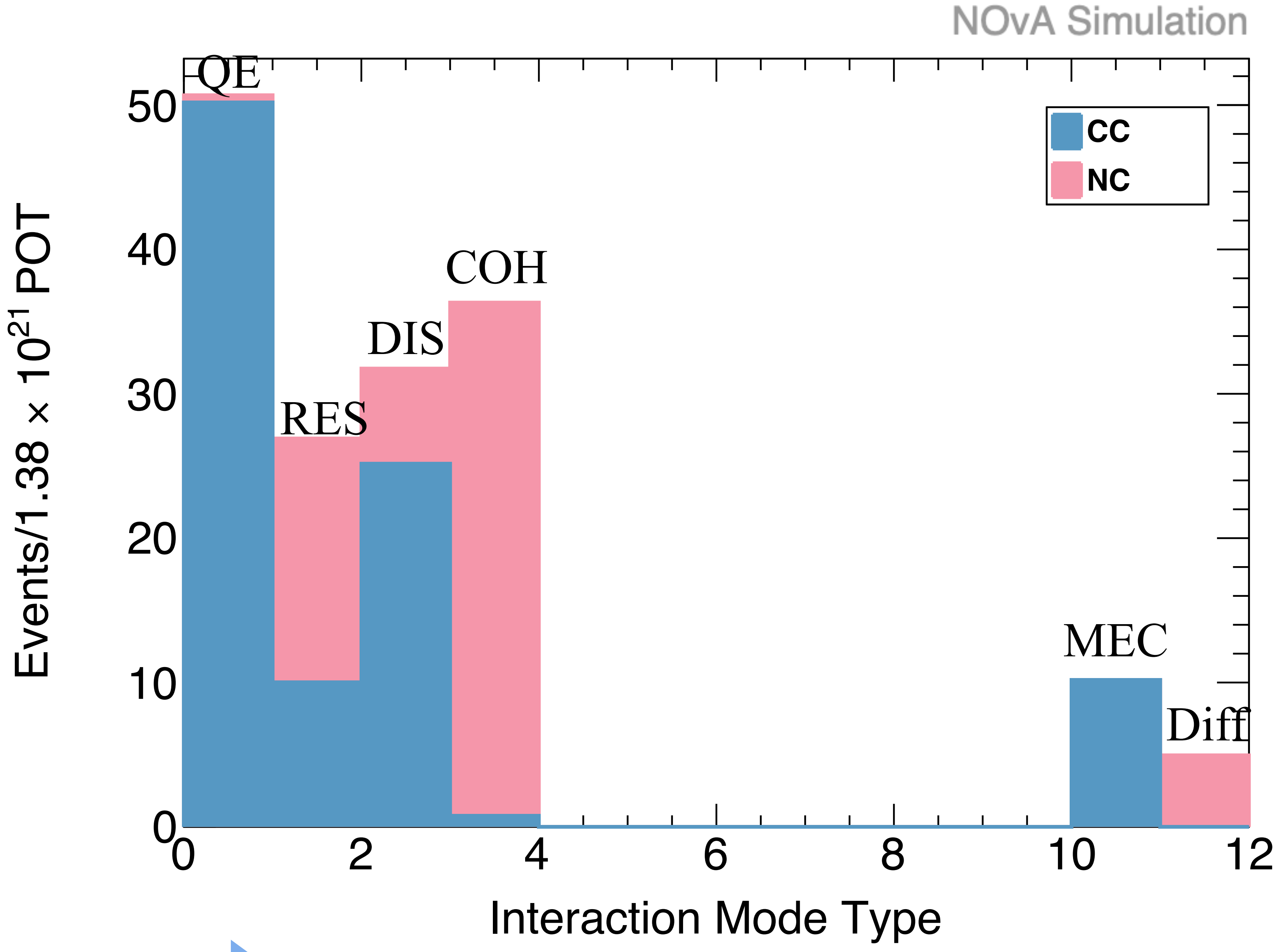
- After all cuts without CNN PID, $\mu^-$ and $\pi^0$ play major roles;
- $\nu - e$ PID helps to remove $\mu^-$ events;
- $e/\pi^0$ PID helps to further reject $\pi^0$ events.

# Performance of CNN PIDs breakdown by interaction mode

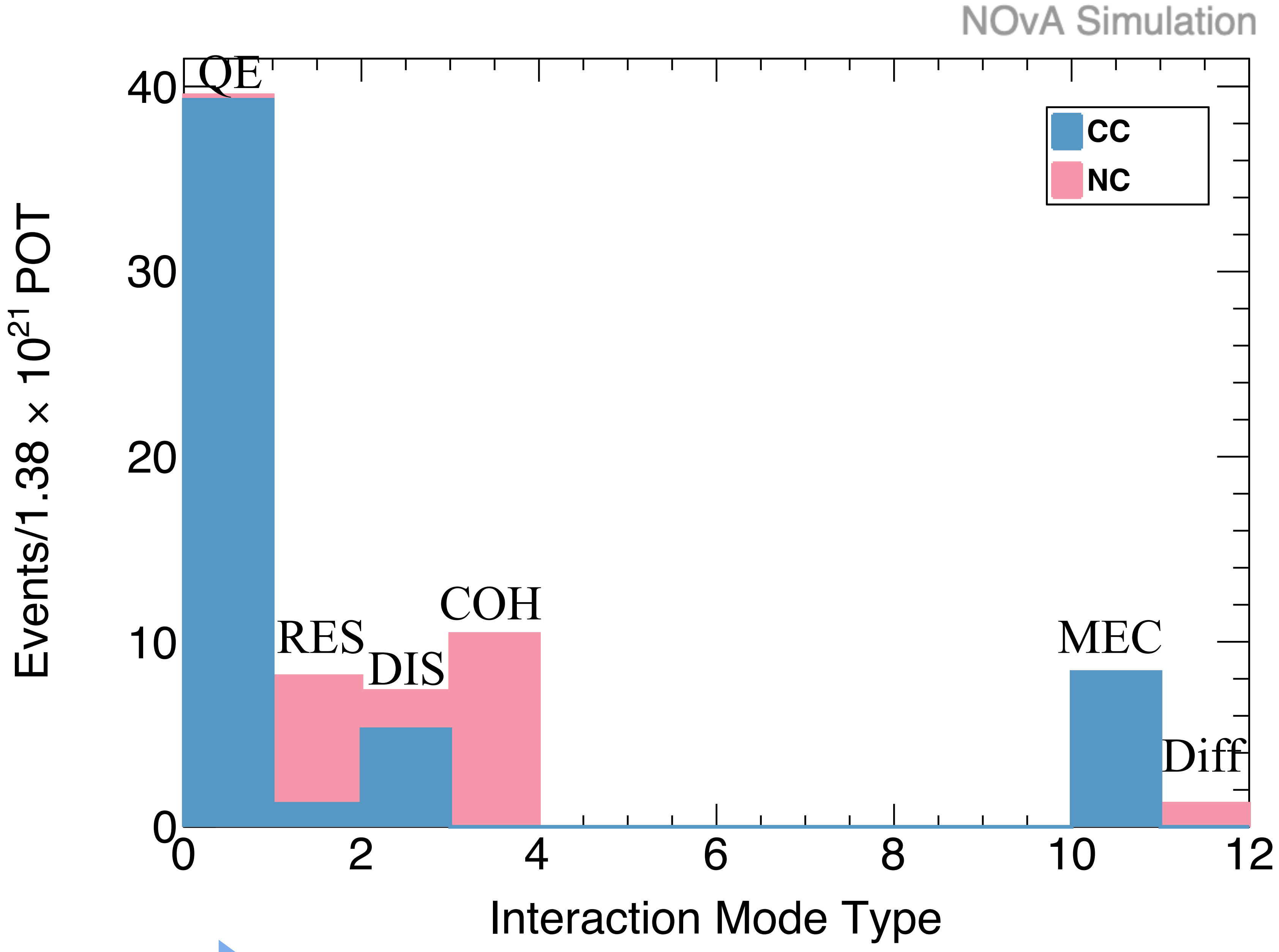
Selected Background before CNN PIDs




Selected Background after $\nu - e$ PID




Selected Background after $e/\pi^0$ PID




Applying $\nu - e$ PID

Applying $e/\pi^0$ PID

- $\nu - e$ PID and $e/\pi^0$ PID helps to remove QE, RES, DIS, COH, MEC and Diff events in the background

# Nu-E Signal Correction — One-Loop Radiative Correction

- To improve the precision of the simulated $\nu - e$ elastic scattering cross-section, radiative corrections were calculated by tuning $C_{LL}$ and $C_{LR}$ to one-loop values obtained from global fits to electroweak data. (Ref: arXiv:1512.07699 and arXiv: 1906.00111 (MINERvA)

| | $C_{LL}^{\nu_e e}$ | $C_{LL}^{\nu_\mu e}$ | $C_{LR}^{\nu e}$ |
|---|---|---|---|
| GENIE 3 | 0.7313 | -0.2687 | 0.2313 |
| This analysis | 0.7276 | -0.2730 | 0.2334 |

$$w(\nu_\mu e) = \frac{\sigma^{radcor}(\nu_\mu e^-)}{\sigma^{nom}(\nu_\mu e^-)}$$


y ≡ (Te + Eγ )/Eν

# Systematic Uncertainty Study — background

- The integrated neutrino flux in the data can be determined as follows:

$$\Phi(Data) = \Phi(MC) \times \frac{N^{Data}_{\nu-e}}{N^{MC}_{\nu-e}}$$

- The background in the signal region needs to be estimated and subtracted to obtain the $\nu - e$ signal yield in data ($N^{Data}_{\nu-e}$)

$$N^{Data}_{\nu-e} = N^{Data} - N^{MC}_{Background}$$

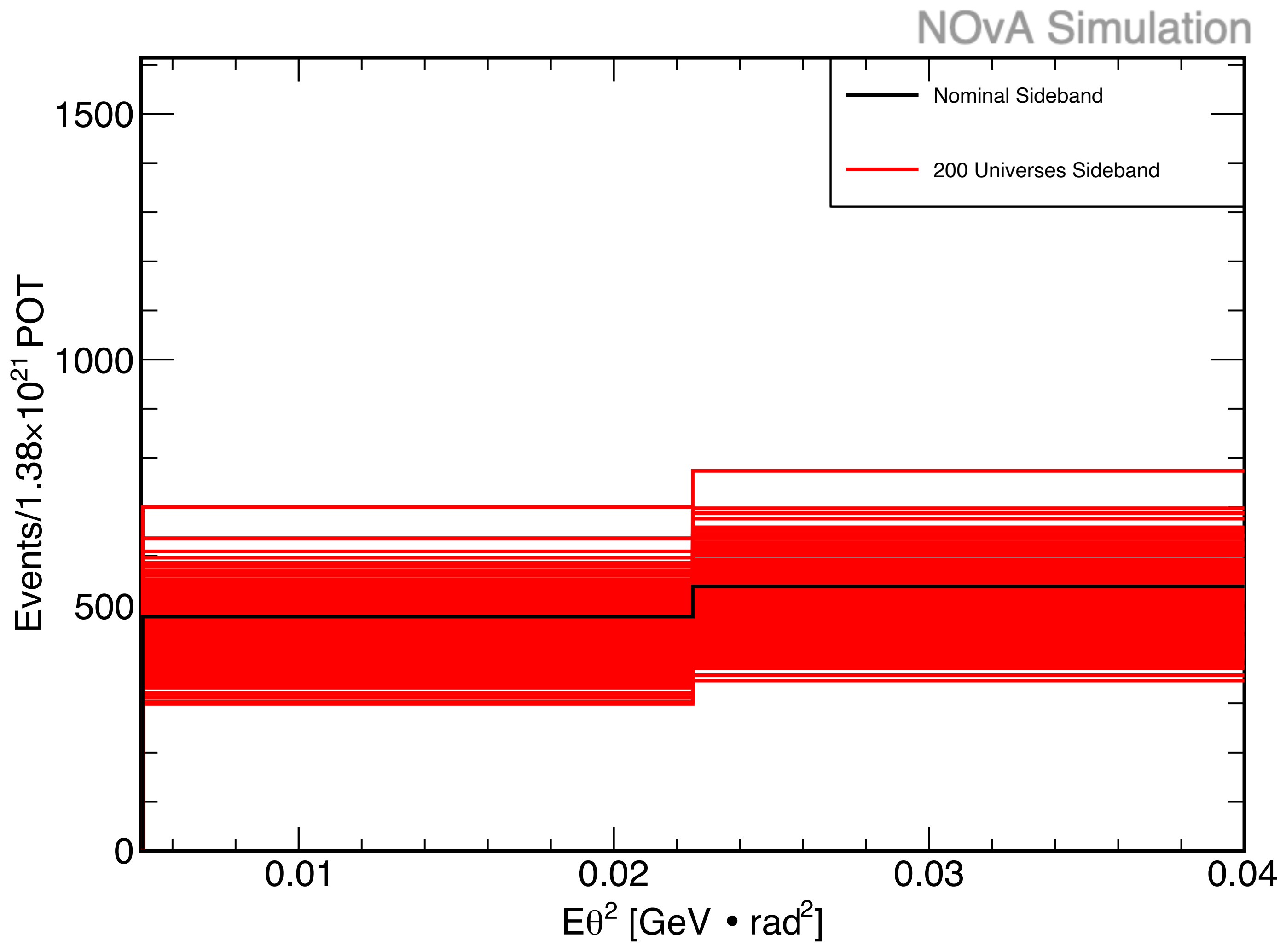
- The background subtraction procedure is subject to systematic uncertainties because the mis-modeling of the background and neutrino flux can bias the signal measurement.
- To improve background subtraction, the Data/MC ratio in the $E\theta^2$ sideband region (dominated by background events) is used to correct the MC background yield in the signal region.

$$N^{MC}_{Background,\ corrected} = N^{MC}_{Background} * C_{bkg}$$

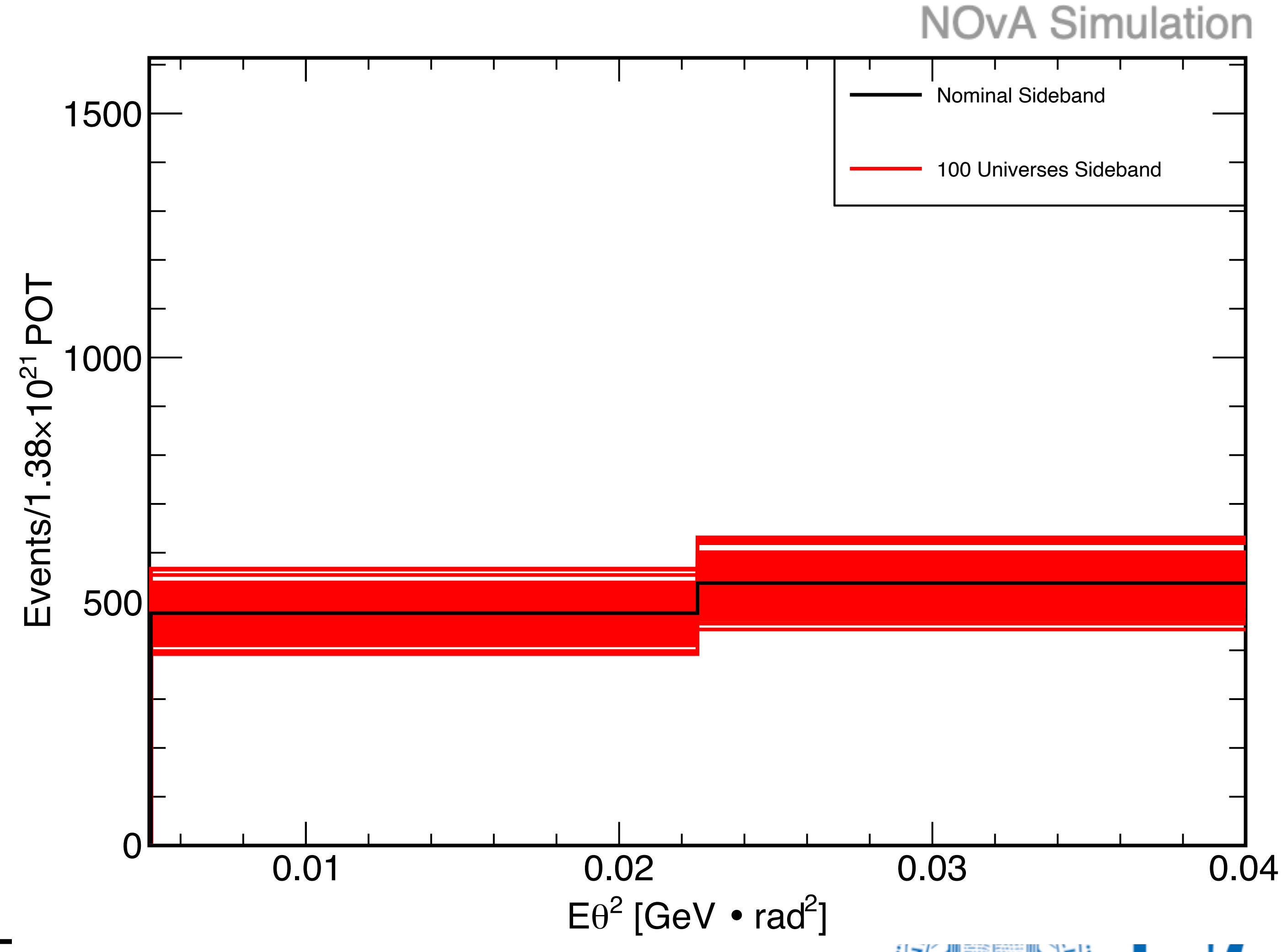
$$N^{Data}_{\nu-e} = N^{Data} - N^{MC}_{Background,\ corrected}$$

- Genie modeling, neutrino flux, beam focusing, and detector response uncertainties are included in the total uncertainty calculation

**Genie Shifts (200 Universes) Sideband**




**Flux Weights (100 Universes) Sideband**



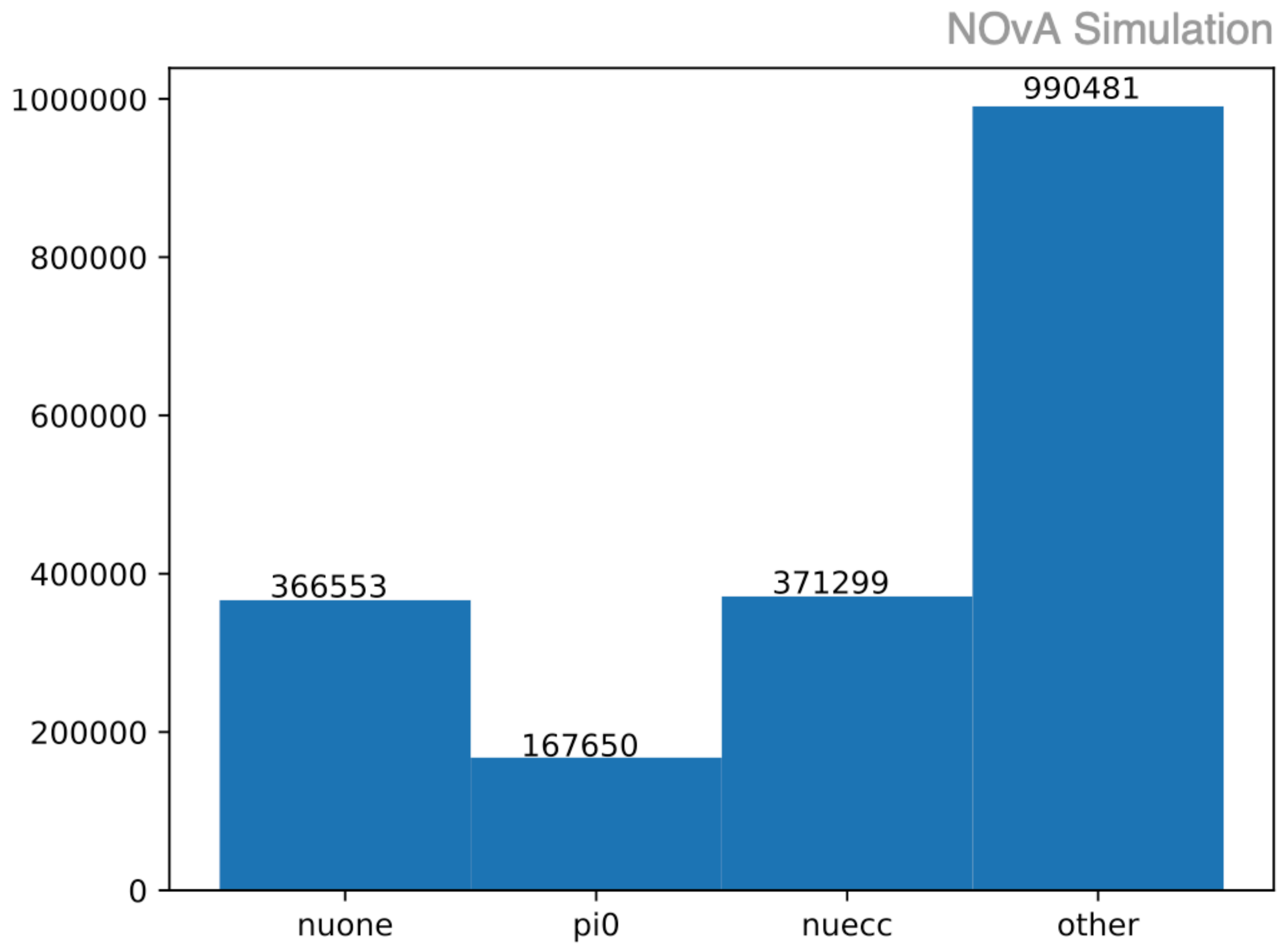
# Summary and Prospect

- FOM-based cut optimization gives a promising result.
  - CNN-based classifiers could achieve better performance for separating $\nu - e$ events from backgrounds.
- The radiative correction in the $\nu - e$ elastic scattering covered the next-leading order effect of the amplitude
- Expect to see ~700 $\nu - e$ events in a 1.38E21 POT FHC sample, with a 8:1 signal/background ratio
- We are working on systematic studies to estimate the uncertainties of our measurement.
- ν − e scattering is promising to constrain the flux uncertainty to ~ 6%. (Current, by the external hadron production measurement ~10%)
- Stay tuned!

Thanks!

# Backup

# Training Sample




**Training Sample Breakdown by interaction type**