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

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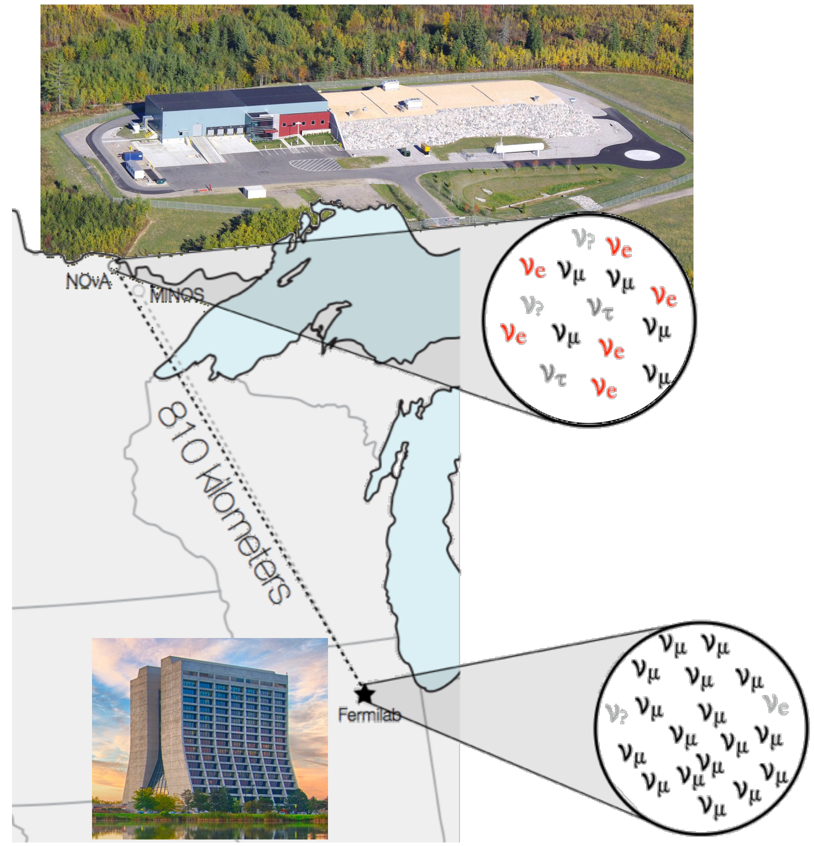
NOvA (NuMI Off-Axis ν_e Appearance)

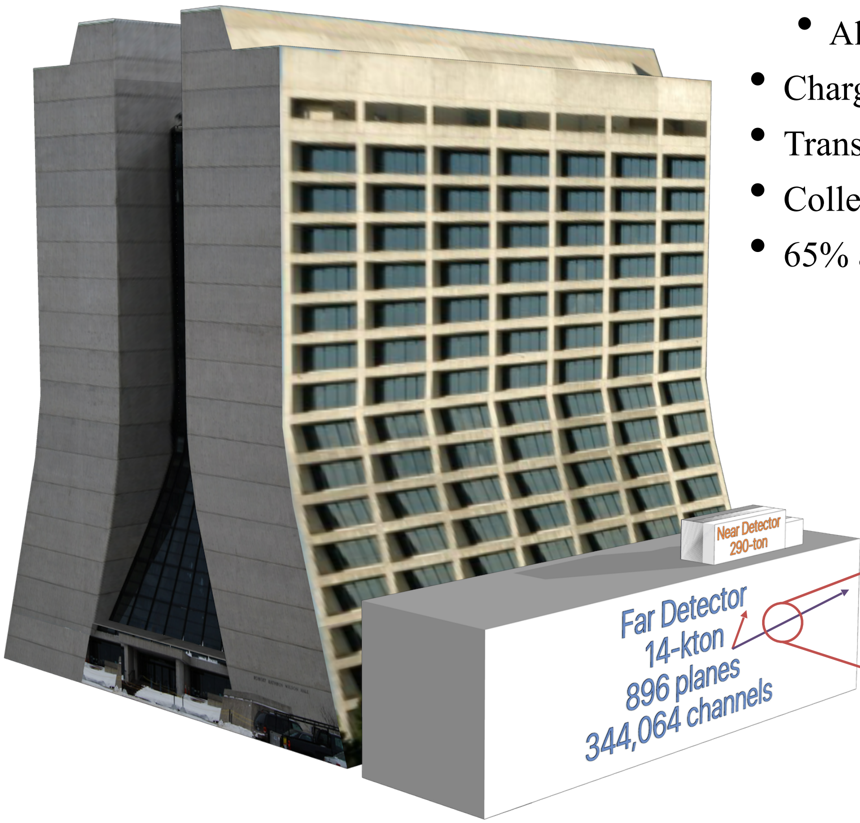
- Long baseline neutrino oscillation experiment, optimized for measuring $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance
- 2 functionally identical tracking calorimeter detectors filled with mineral oil, located 14.6 mrad off-axis from NuMI beamline
  - The near detector (ND) 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

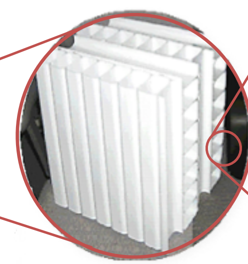
Parallel Talk of NOvA by Alec Habig (#170)

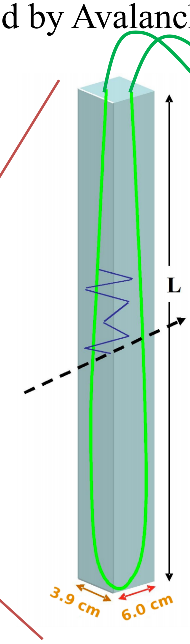


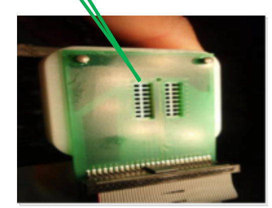
NOvA (NuMI Off-Axis ν_e Appearance)

- 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



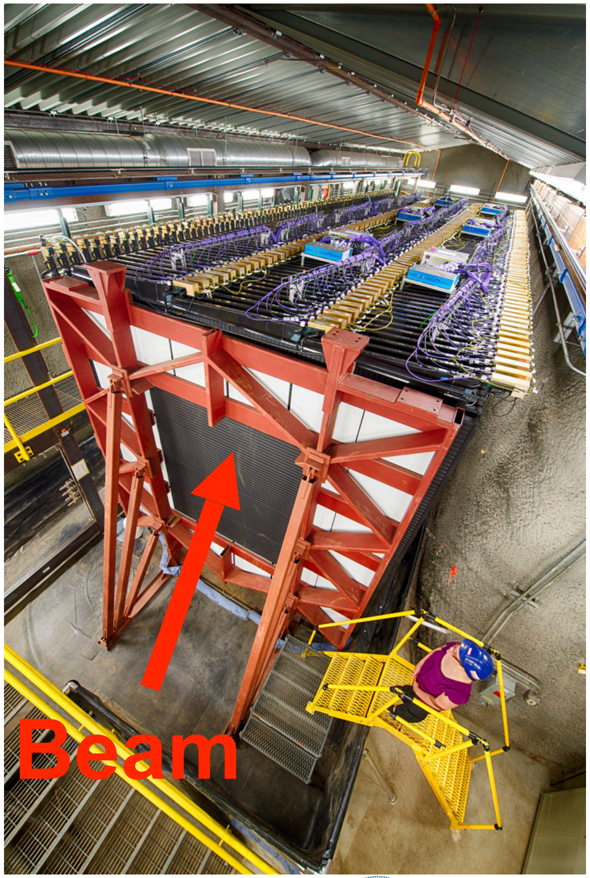






The NOvA Near Detector

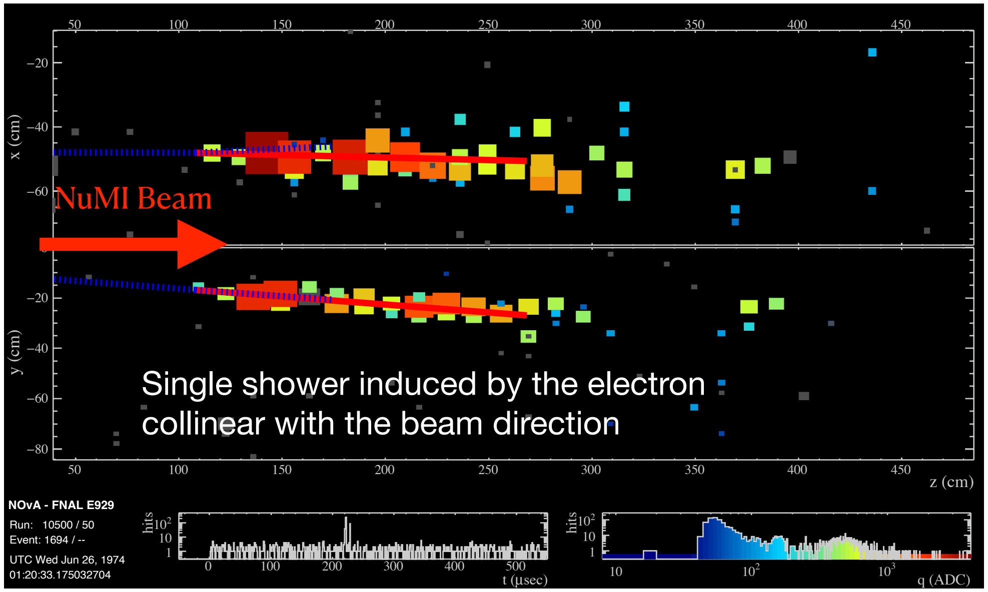
- The near detector (ND) is 1 km away from the neutrino beam target and lies 100 m underground at Fermilab.
- It is located 14.6 mrad off-axis from the NuMI beam line, results in a narrow-band neutrino flux peaked at ~2 GeV with ~1 GeV FWHM.
- 300t tracking calorimeter, constructed from extruded PVC 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.



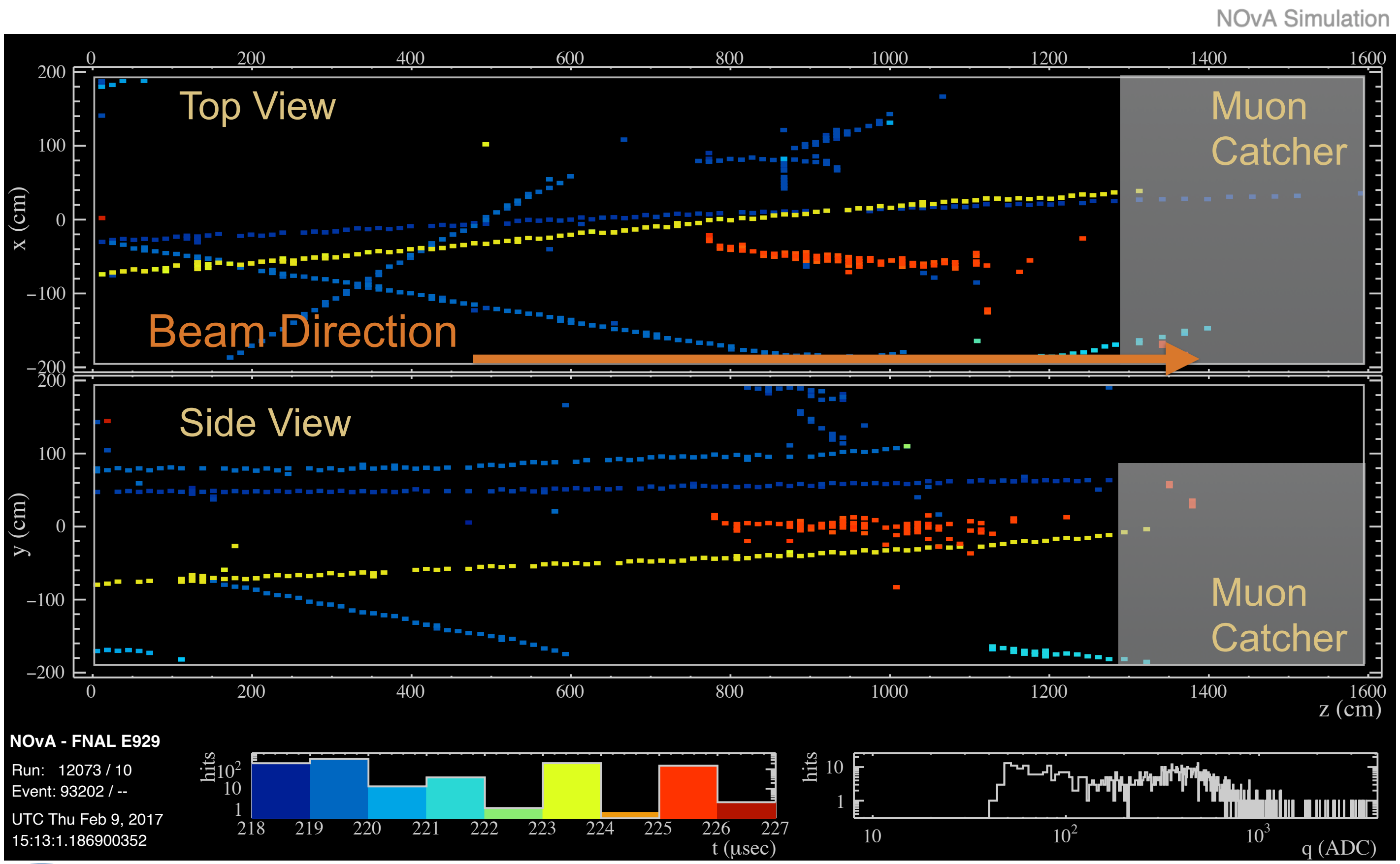
The NOvA Near Detector

- 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 Simulation



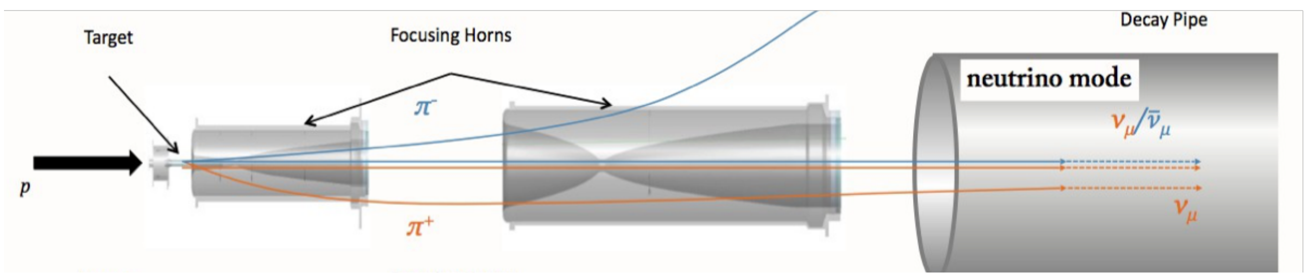
NOvA Reconstruction

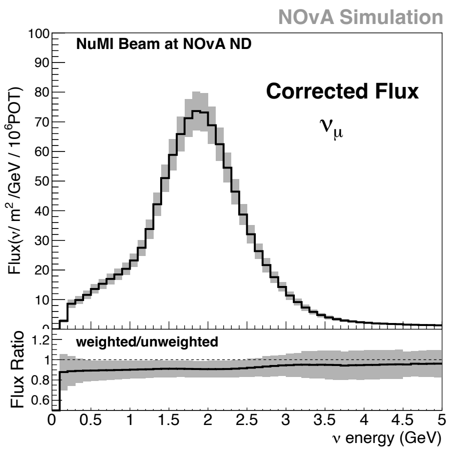


- Hits associated in time and space are used to form a candidate interaction.
- Tracks and showers are reconstructed from these hits.

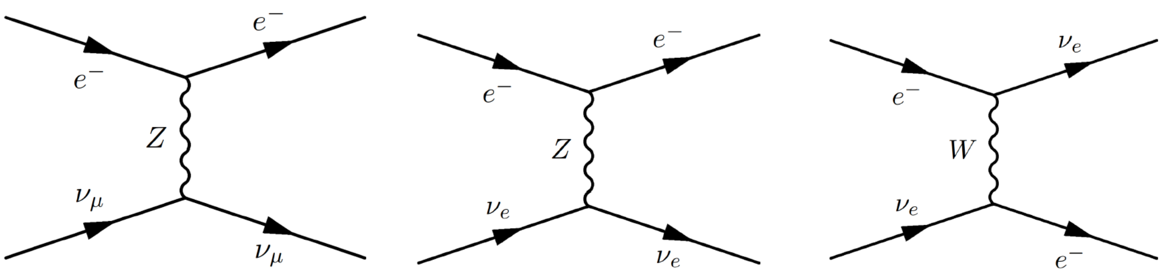
Neutrino Source

- NuMI beam: ν_μ 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



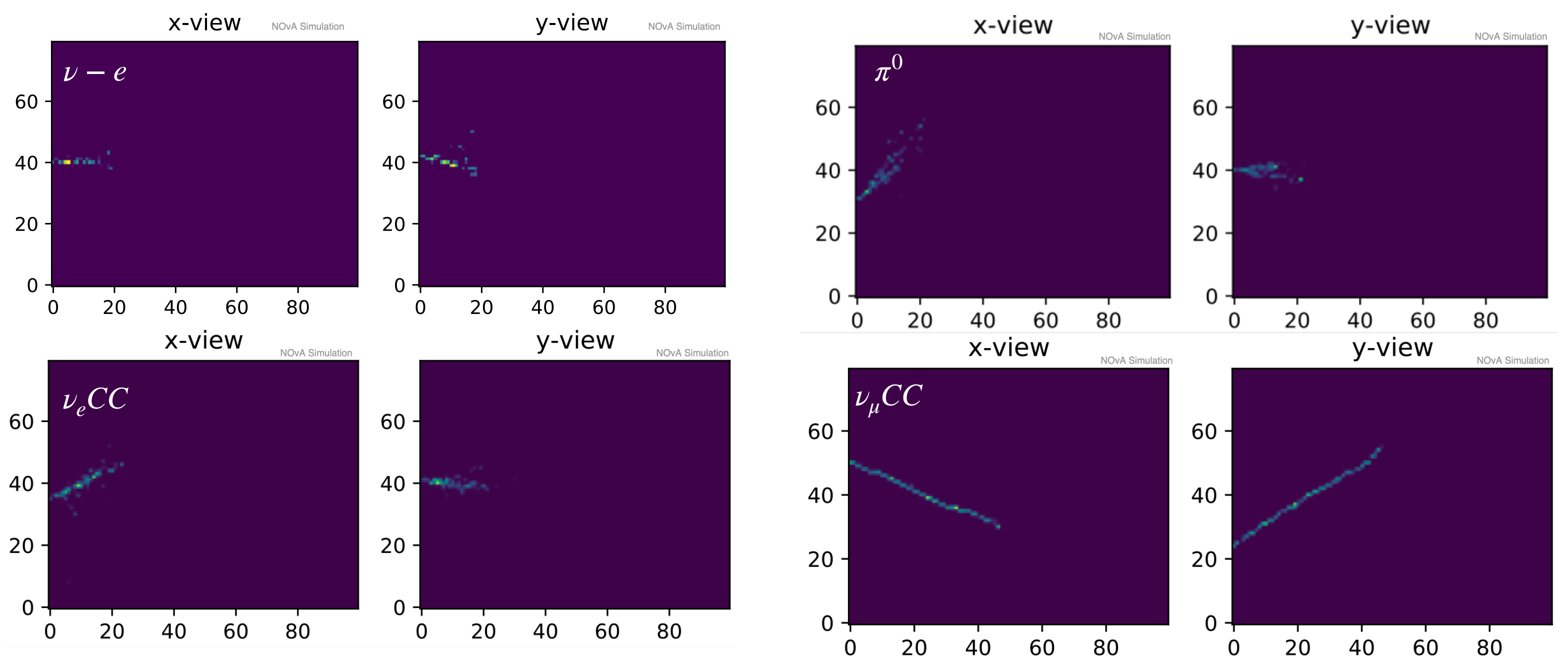
$$N_\nu^{\mathrm{obs}} \propto \int \Phi_{\mathrm{flux}}\left(E_\nu\right) \cdot \sigma\left(E_\nu\right) dE_\nu$$

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

- 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

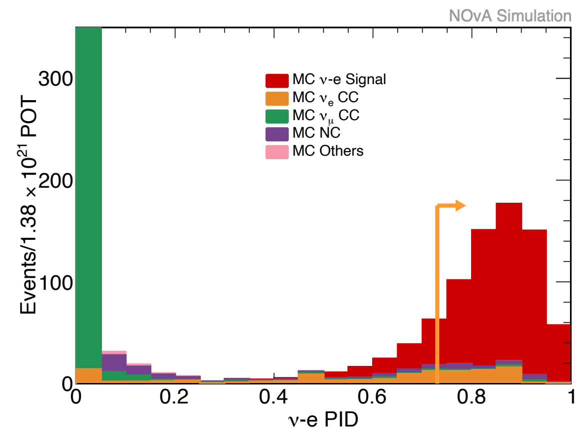
- The topology of signal event requires one EM shower with no other particles in the final state.
- Event identifications are important for separating signals from substantial backgrounds.
- NOvA has developed a convolutional neural network (called CVN) to classify events (ν_e CC, ν_μ CC, ν NC, Cosmics).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

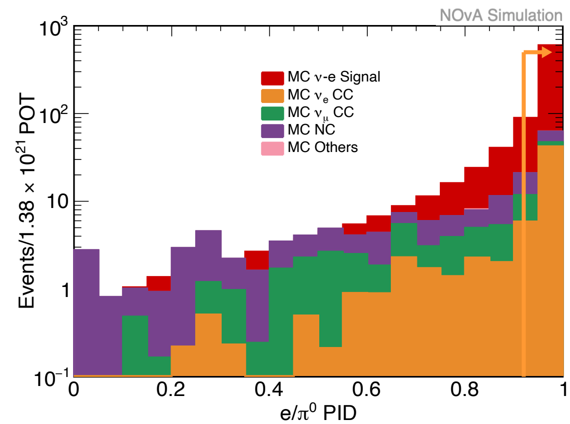


(Ref: arXiv:1604.01444)

CNN-Based Classifiers for event selection

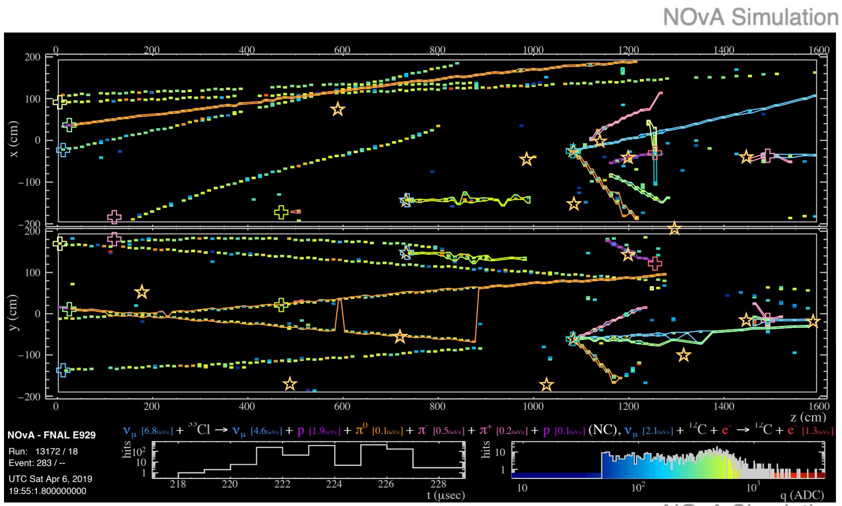
- Training Sample:
  - Signal: Simulation of single electrons in the detector
  - Background: Inclusive MC of an enriched ν_e sample
  - Preselection was applied to remove events from the peripheral region
- Two event classifiers based on the same architecture were trained.
  - $\nu - e$ PID:
    - trained with four categories ($\nu - e$, ν induced π^0, $\nu_e CC$, Others)
    - to separate $\nu - e$ scattering events from backgrounds.
  - e/π^0PID:
    - trained with only two categories ($\nu - e$, ν induced π^0)
    - to further rejects backgrounds with ν induced π^0 in the final state.

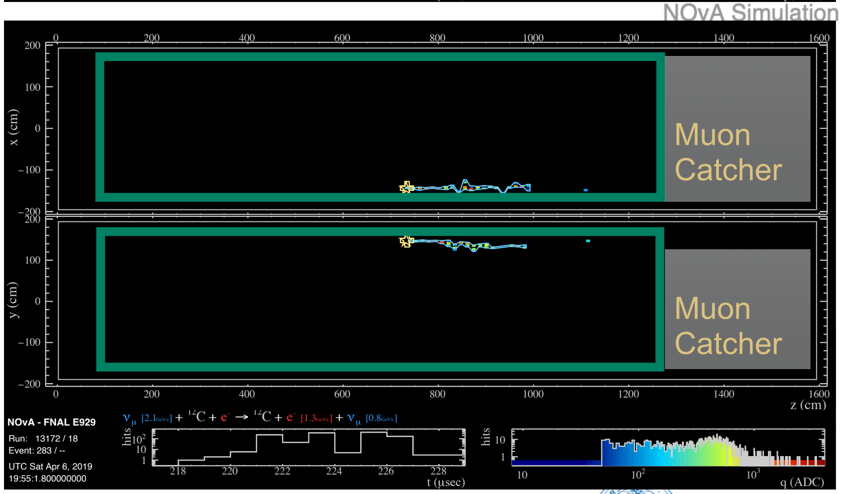




$\nu - e$ Signal Selection

- Monte Carlo (MC) samples were used to study the event selection.
- Event Selection:
  - Pre-selection: remove obvious ν_μ 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.

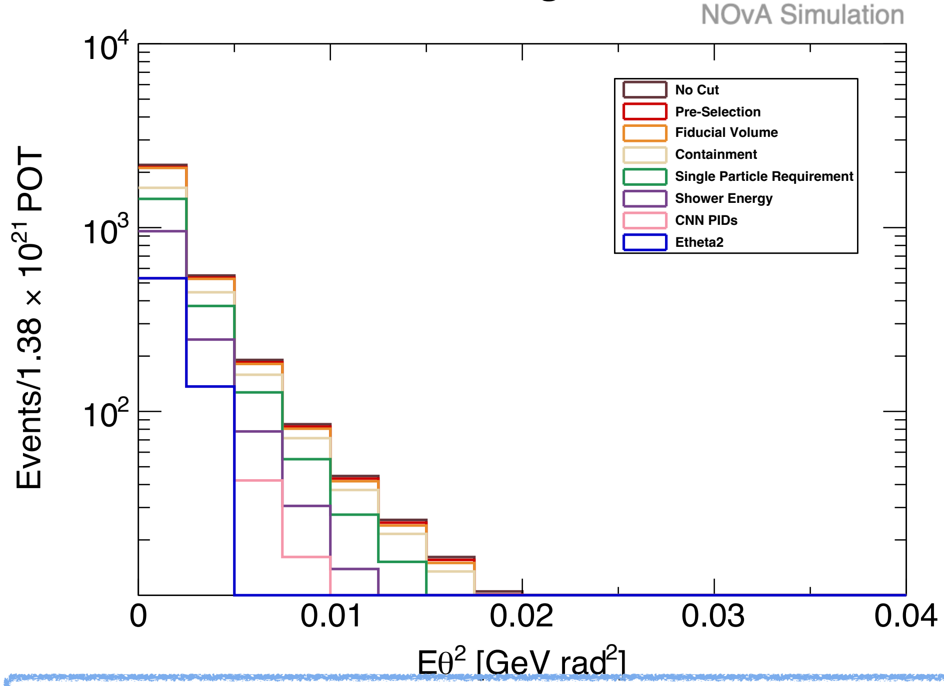




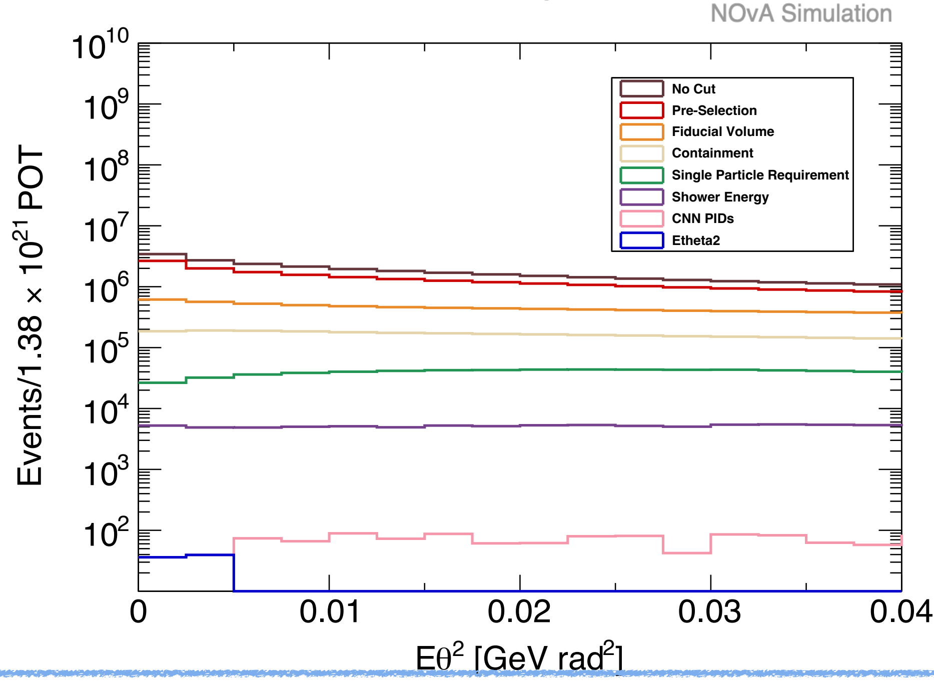
$\nu - e$ Signal Selection and Optimization

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

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



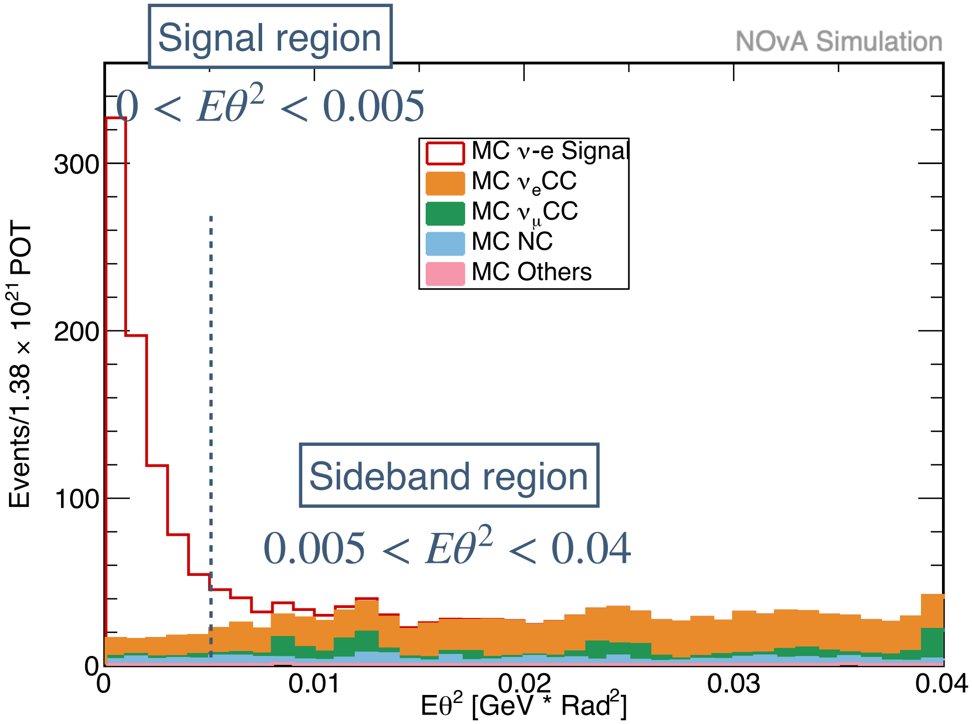
$E\theta^2$ cut-flow for Background MC



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 δB is the systematic uncertainty in the background. Assume $\delta B = 0.2B$ according to the ν_eCC cross-section measurement.

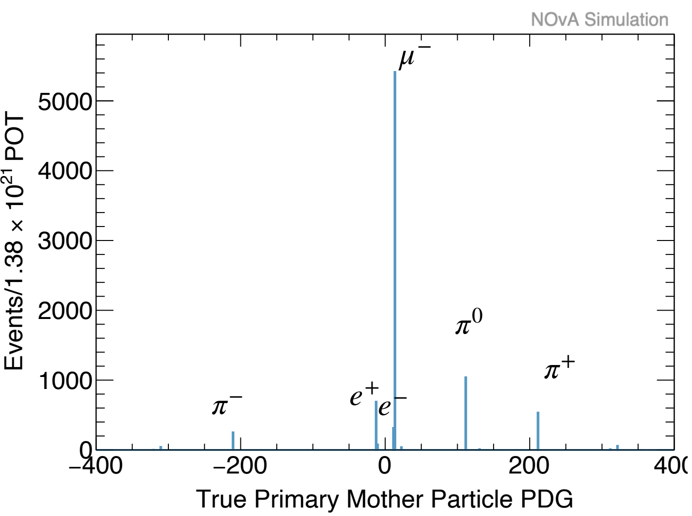
$\nu - e$ Signal Selection Results and Sideband Constraint

- E refers to the calorimetric energy of the most energetic shower and θ is the angle between the direction of the most energetic shower and the beam direction
- With CNN PIDs and cut optimization,
  - Sig. 675.09, Bkg. 75.47
  - 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

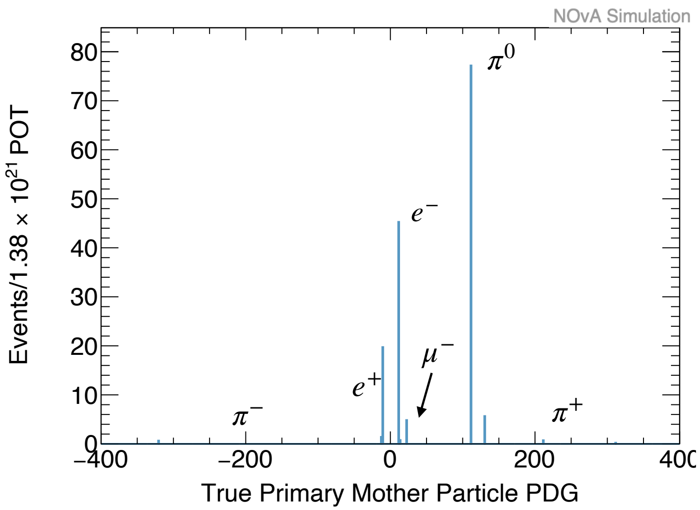


Performance of CNN PIDs breakdown by Primary Mother Particle

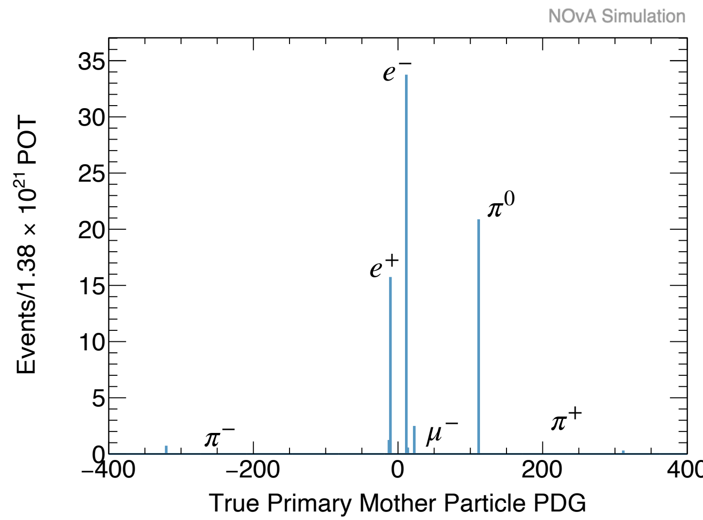
Selected Background before CNN PIDs



Selected Background after $\nu - e$ PID



Selected Background after e/π^0 PID

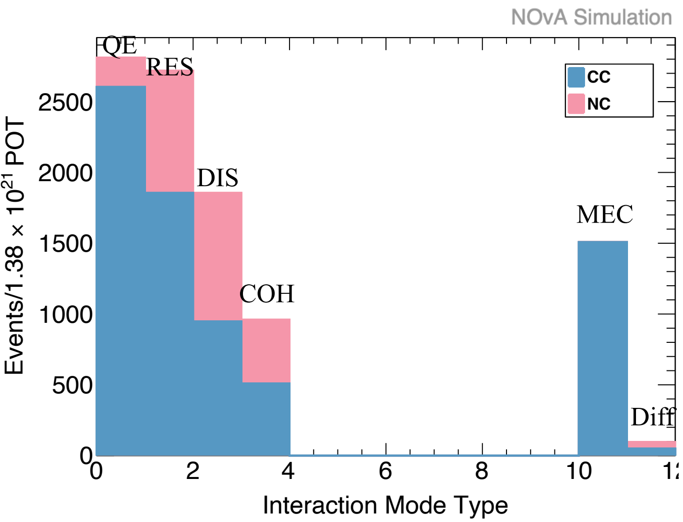


Applying $\nu - e$ PID → Applying e/π^0 PID

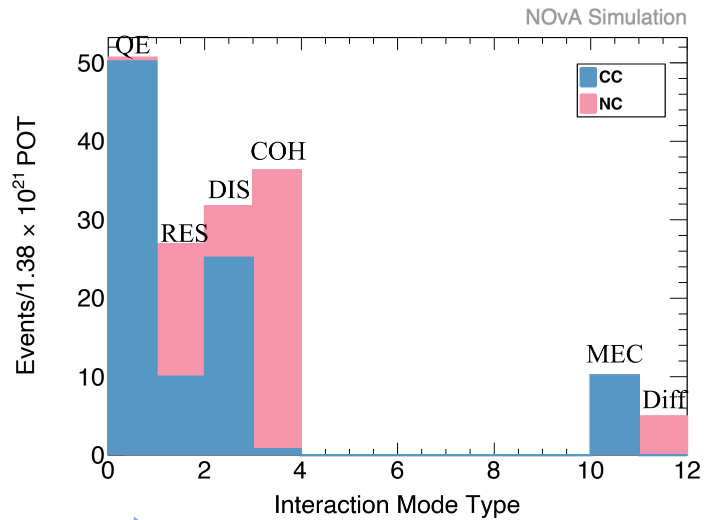
- After all cuts without CNN PID, μ^- and π^0 play major roles;
- $\nu - e$ PID helps to remove μ^- events;
- e/π^0 PID helps to further reject π^0 events.

Performance of CNN PIDs breakdown by interaction mode

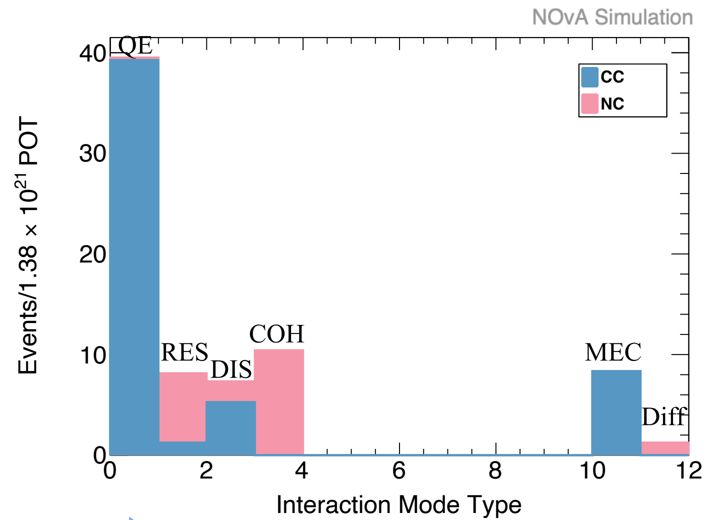
Selected Background before CNN PIDs



Selected Background after $\nu - e$ PID



Selected Background after e/π^0 PID



Applying $\nu - e$ PID

Applying e/π^0 PID

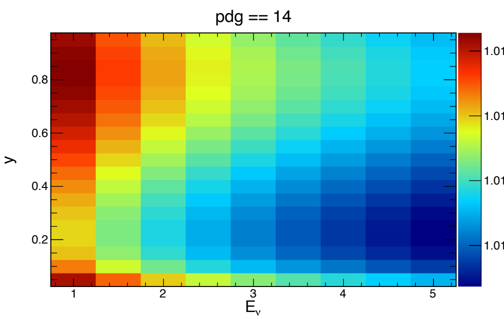
- $\nu - e$ PID and e/π^0 PID helps to remove QE, RES, DIS, COH, MEC and Diff events in the background

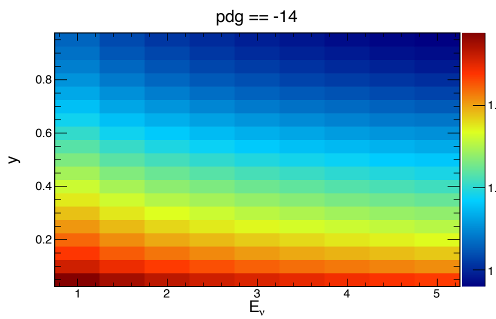
Nu-E Signal Correction — One-Loop Radiative Correction

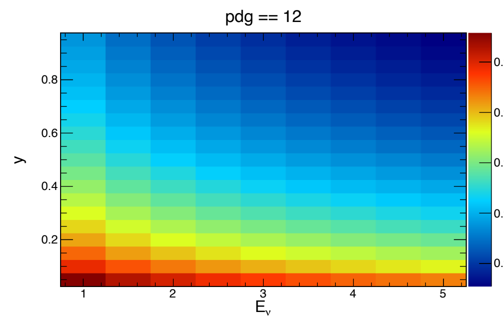
- To improve the precision of the simulated $\nu - e$ elastic scattering cross-section, radiative corrections were calculated by tuning C_{LL} and C_{LR} to one-loop values obtained from global fits to electroweak data. (Ref: arXiv:1512.07699 and arXiv: 1906.00111)

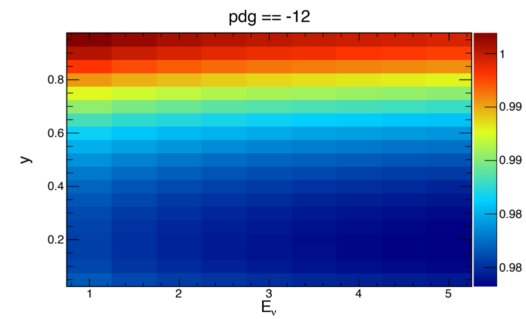
	$C_{LL}^{\nu_e e}$	$C_{LL}^{\nu_\mu e}$	$C_{LR}^{\nu e}$
GENIE 3	0.7313	-0.2687	0.2313
This analysis	0.7276	-0.2730	0.2334

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









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.

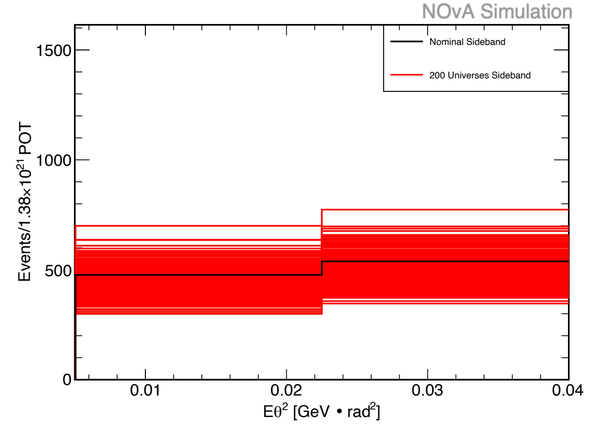
- To improve background subtraction, the Data/MC ratio in the $E\theta^2$ sideband region (dominated by background events) is used to correct the MC background yield in the signal region.

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

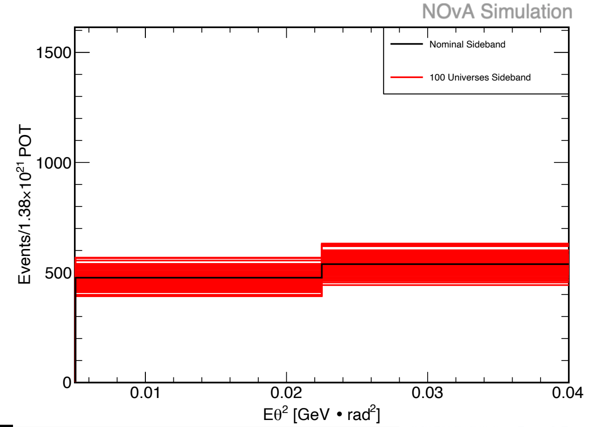
$$N^{Data}_{\nu-e} = N^{Data} - N^{MC}_{Background,\ corrected}$$

- 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



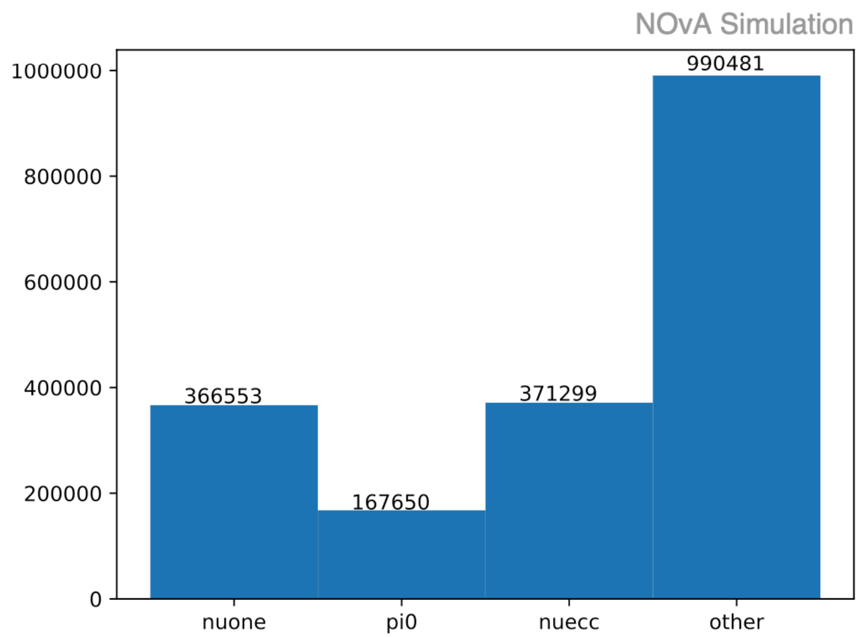
Summary and Prospect

- 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
- We produced an enhanced $\nu - e$ sample to overlay one $\nu - e$ interaction on one spill on the inclusive sample to increase the statistic for $\nu - e$ events → anticipate a small statistical uncertainty (~0.1%).
- 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