Status of the $\bar{\nu}_\mu CC\pi^0$ cross-section measurement in the NOvA ND

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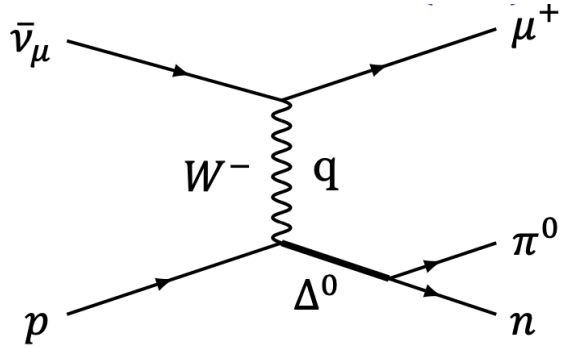
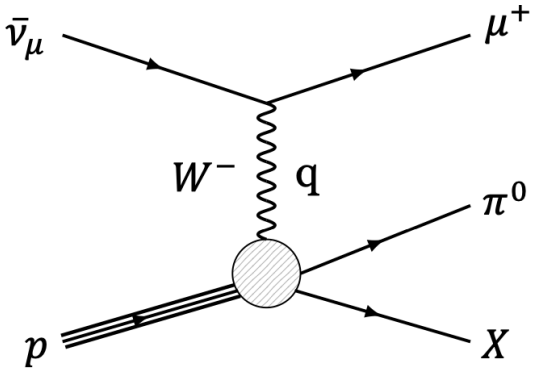
Motivations

- π^0 production measurements provides insight on backgrounds to $\nu_e/\bar{\nu}_e$ appearance
- Measuring $\mathrm{CC}\pi^0$ production probes systematic uncertainties for neutrino interaction models
  - Resonant
  - Deep Inelastic Scattering



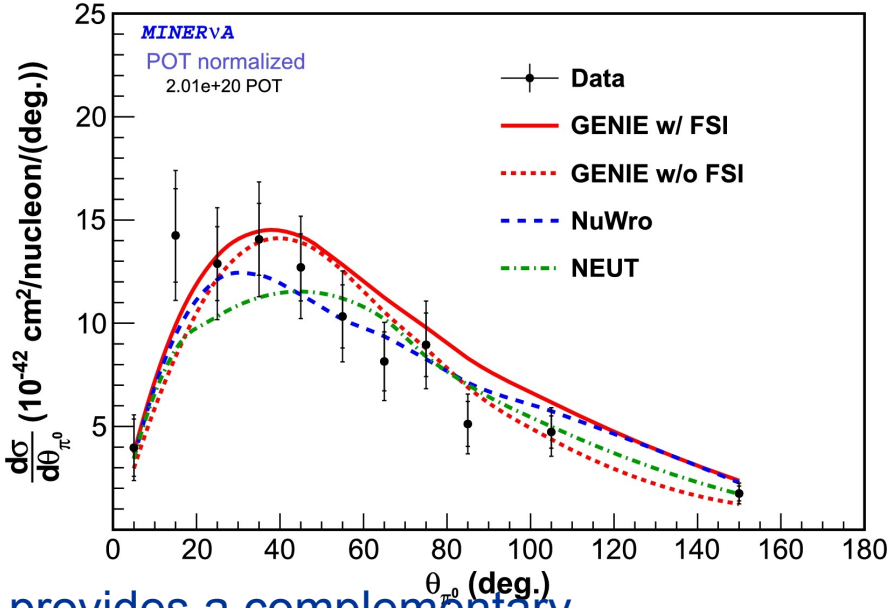
Resonant

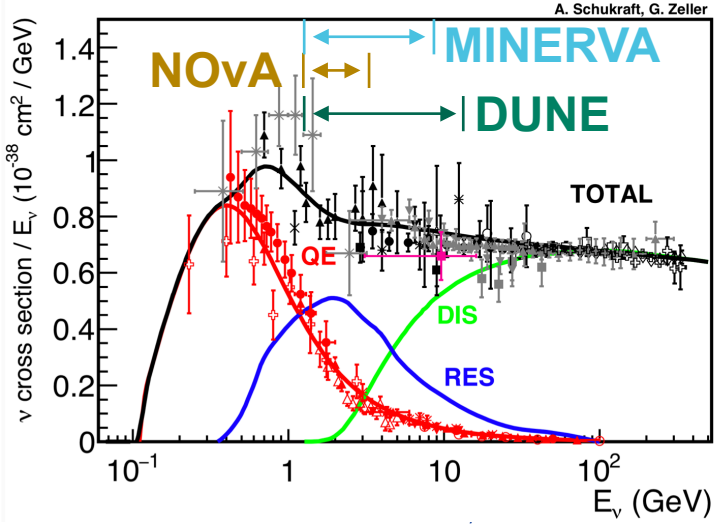


Deep Inelastic Scattering

Motivations

- One previous measurement of $\bar{\nu}_\mu CC1\pi^0$ - MINERvA (Phys. Lett. B749, 130-136 (2015))

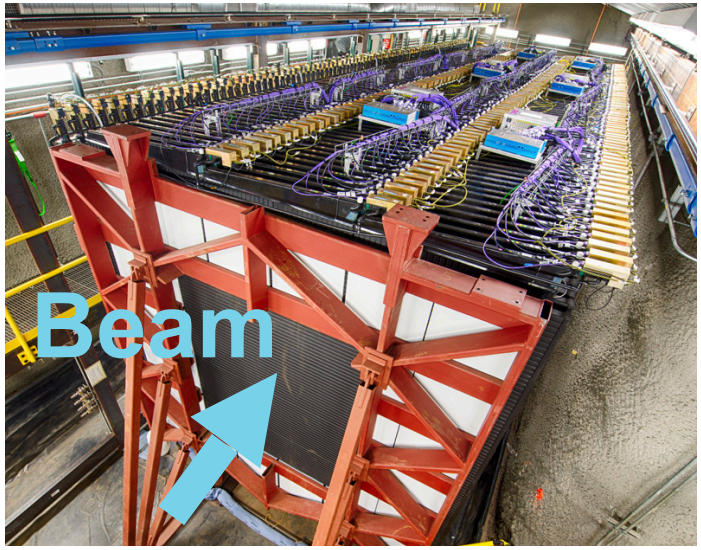




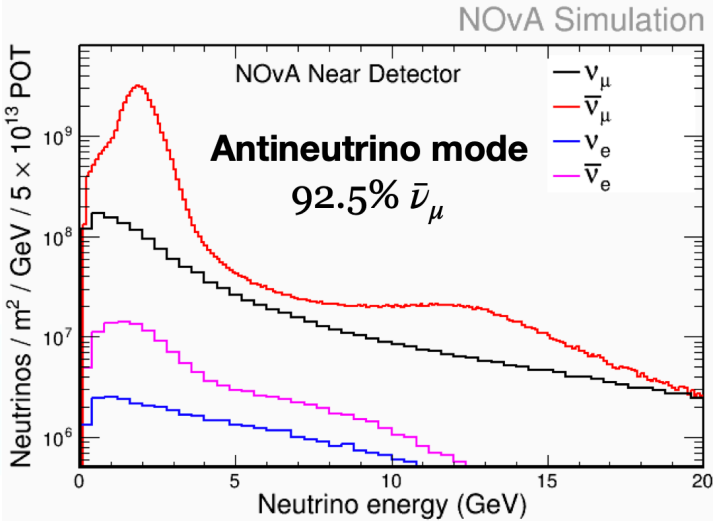
- NOvA provides a complementary measurement:
  - $\bar{\nu}_\mu CC\ N\pi^0$ where $N \geq 1$
  - 6x POT
  - 10x selected signal
- Res and DIS region important as we look towards the future

NOvA Near Detector

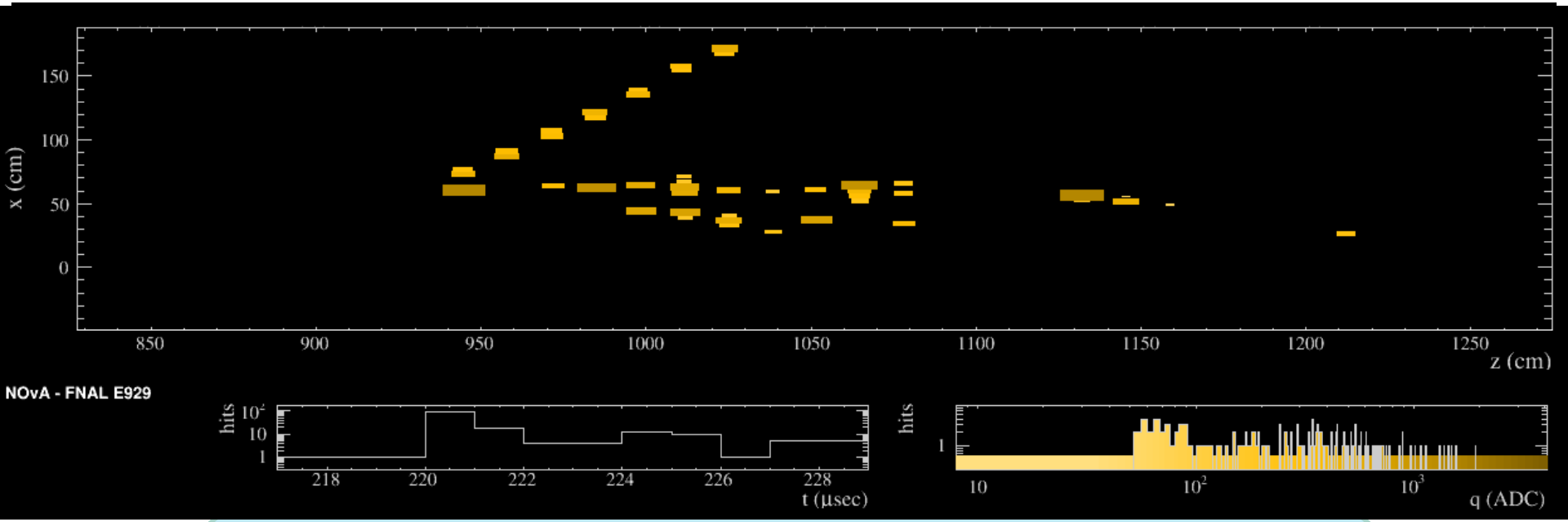
- The near detector (ND) is 1 km from the neutrino beam target and lies 100 m underground at Fermilab.
- 300t tracking calorimeter, constructed from extruded PVC cells filled with liquid scintillator
- 77% CH_2, 16% Cl, 6% TiO_2 by mass
- It is located ~14.6 mrad off-axis from the NuMI beam line



High flux purity and about 1 million $\bar{\nu}_\mu$CC in antineutrino mode dataset



EM Showers in the ND



Cell geometry optimized for electromagnetic shower identification:

~6 samples per X_0

~60% active

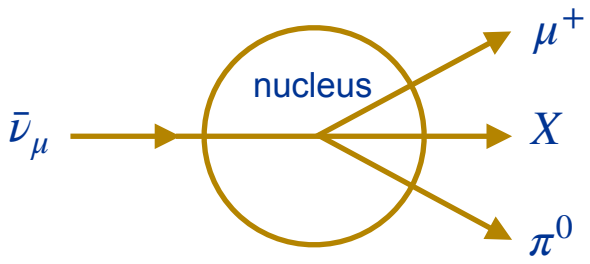
Goal

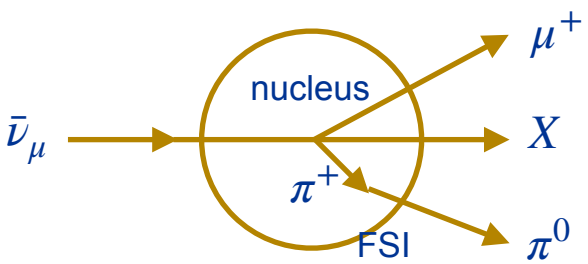
$$\bar{\nu}_\mu + N \rightarrow \mu^+ + N\pi^0 + X$$

Measure charged-current differential cross section with respect to π^0 momentum and angle in antineutrino mode NOvA near detector data

Semi-inclusive measurement: $N \geq 1$

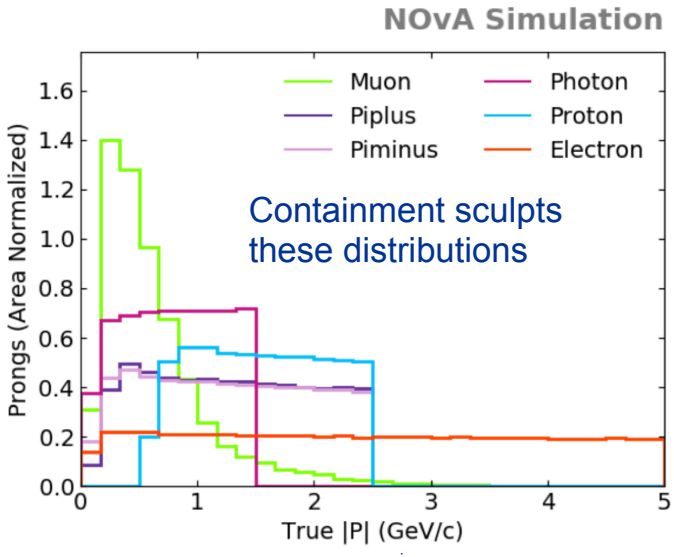
Detection threshold: $E_{\pi^0} > 200$ MeV

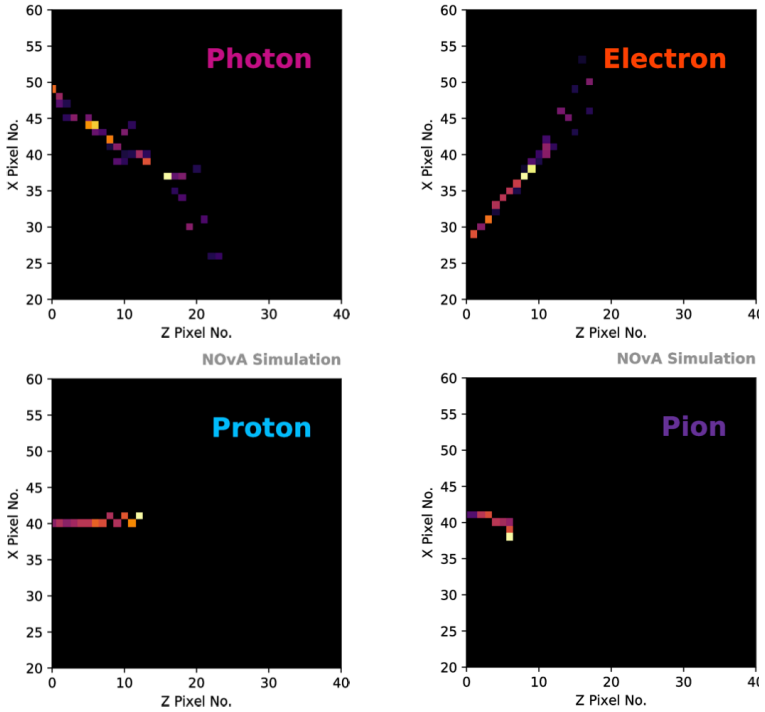




Particle Identification

- Developed CNN algorithms to identify final-state particles associated with reconstructed prongs
- Trained on sample of individually simulated particles (no reliance on Event Generators)
  - $e, \gamma, \pi^{\pm}, \mu, p$
  - Uniform sampling in momentum, angle, position

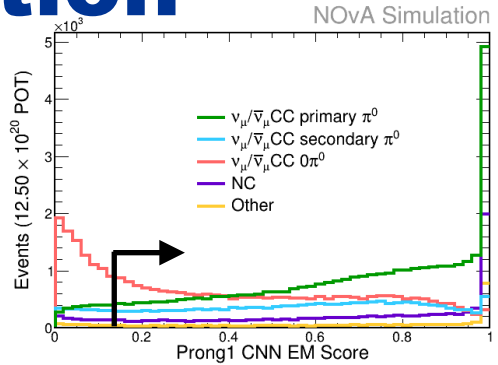


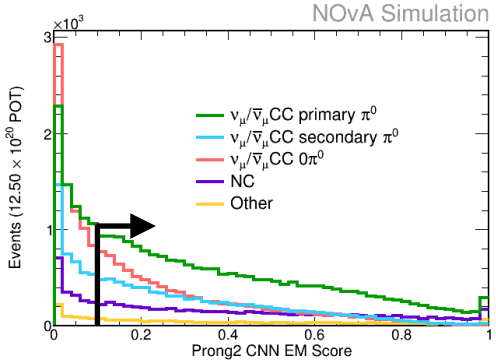


Binary classification for prongs:
- EM-like vs non-EM-like

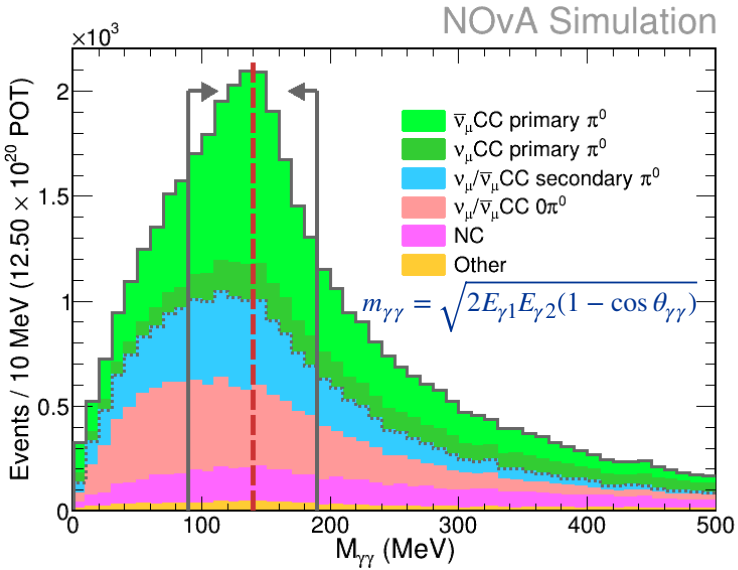
EM Shower Selection

- **Prong 1 & 2:** Two candidate EM-like prongs in $\bar{\nu}_\mu$CC sample
  - Select two candidate EM-like prongs with highest CNN EM scores



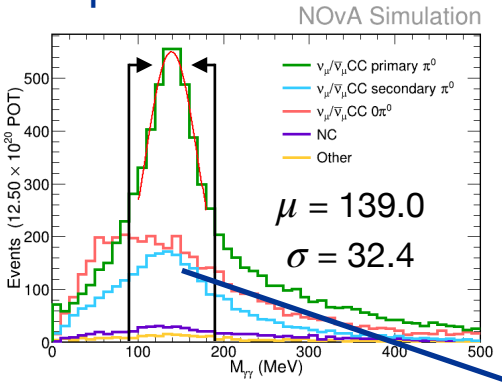


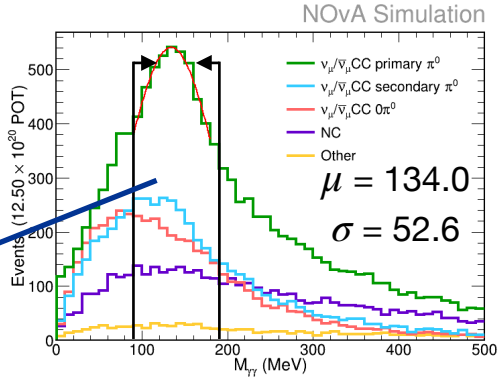
- ~8700 $\bar{\nu}_\mu CC\pi^0$ signal events
- Selection purity 48.5%
- Largest backgrounds:
  - $\bar{\nu}_\mu$CC with Secondary π^0
  - $\bar{\nu}_\mu CC0\pi^0$

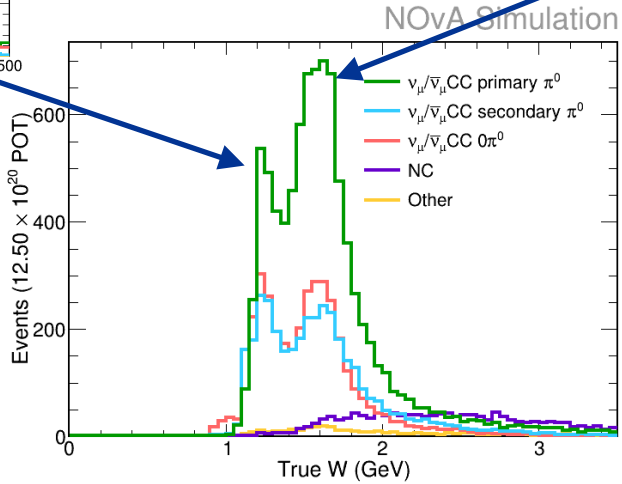


Extracting More Physics

- Number of prong cut splits selected sample into two samples
- Corresponds to two different average W values





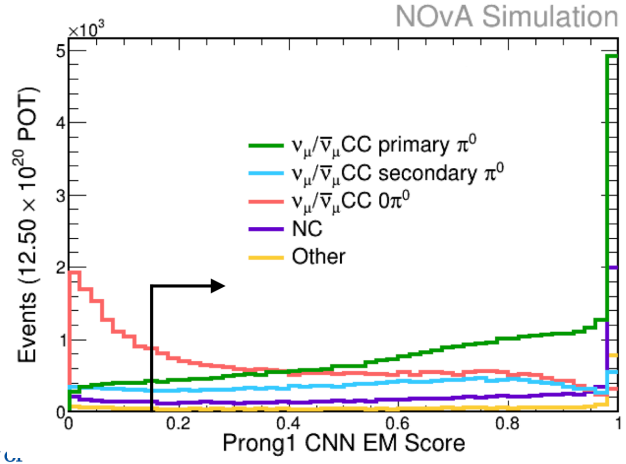


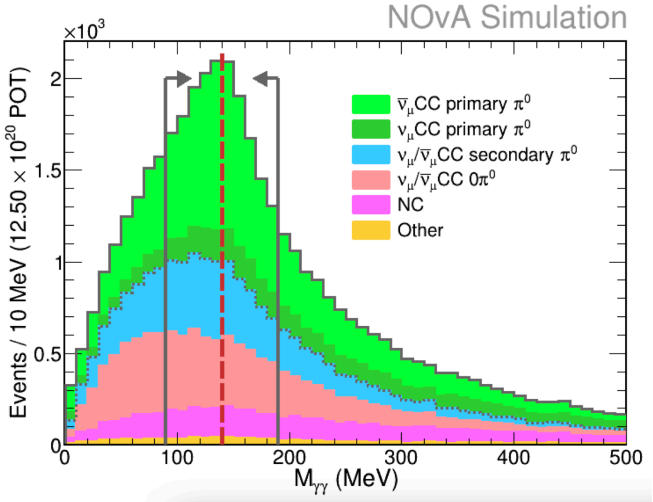
	Signal Sample Size	Purity
nProng = 3	46%	53.1%
nProng > 3	54%	45.2%

Background Constraints

Analysis uses a data-driven **template fit** to constrain $\bar{\nu}_\mu/\nu_\mu \mathrm{CC}\mathbf{0}\pi^{\mathbf{0}}$ and **NC** backgrounds

- Utilizes 4 sidebands:
  - nProngs = 3: $\bar{\nu}_\mu/\nu_\mu \mathrm{CC}0\pi^0$-1 Sideband, $\bar{\nu}_\mu/\nu_\mu \mathrm{CC}0\pi^0$-2 Sideband
  - nProngs > 3: $\bar{\nu}_\mu/\nu_\mu \mathrm{CC}0\pi^0$-1 Sideband, NC sideband





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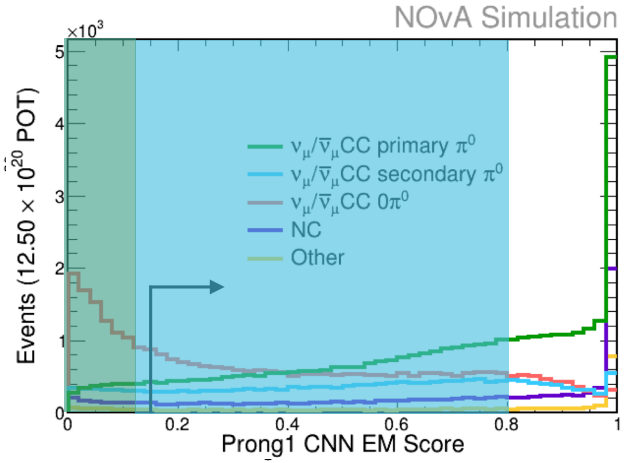

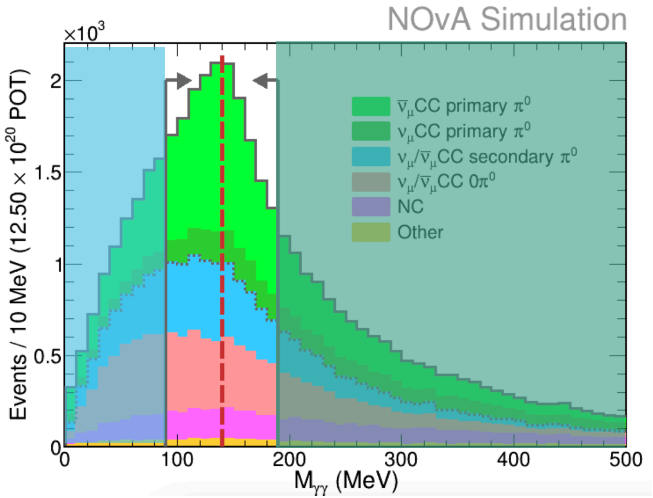

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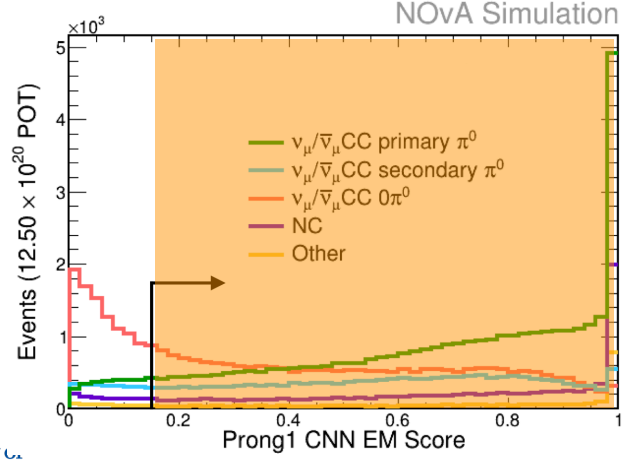
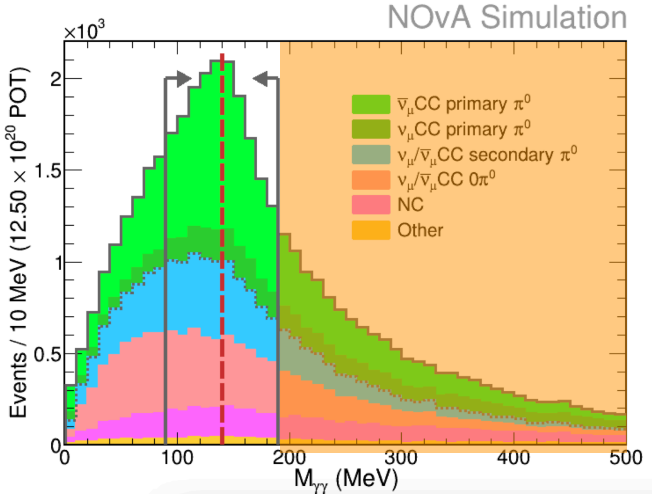
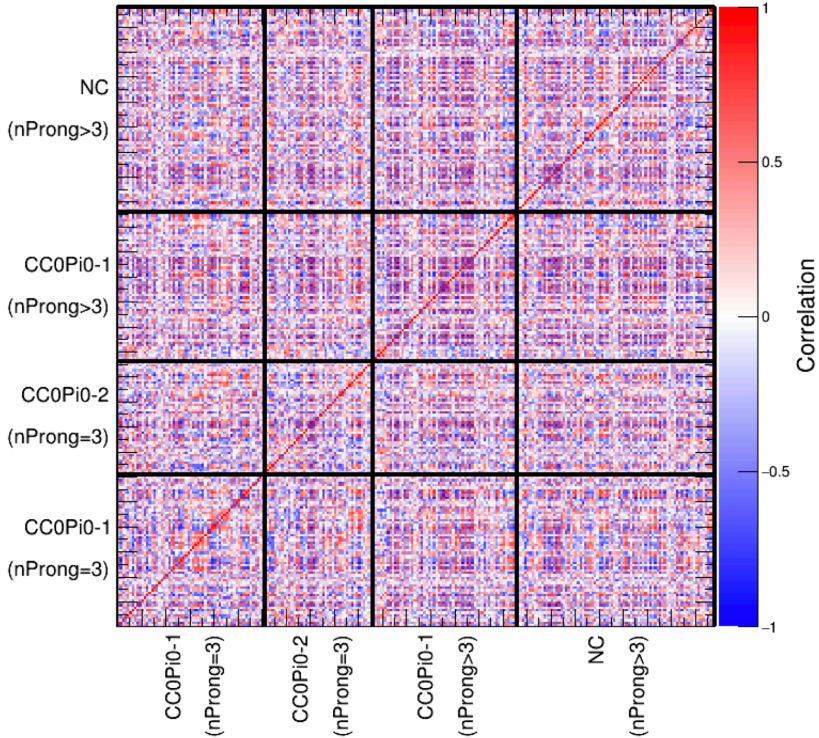




Background Constraints

Analysis uses a data-driven **template fit** to constrain $\bar{\nu}_\mu/\nu_\mu \mathrm{CC}\mathbf{0}\pi^{\mathbf{0}}$ and **NC** backgrounds

- Project each kinematic bin $\left(\theta_{\pi^0}, P_{\pi^0}\right)$ down to the template distributions broken down by signal and background components across all sidebands
- Construct covariance matrix V, where $V = V_{stat} + V_{syst}$
  - Systematics include: nu-A modeling, detector calibration and modeling, and flux
- Fit for background template normalization parameters using all bins simultaneously to minimize:
  - $\chi^2 = \left(x-\mu\right)^T V^{-1} \left(x-\mu\right)$



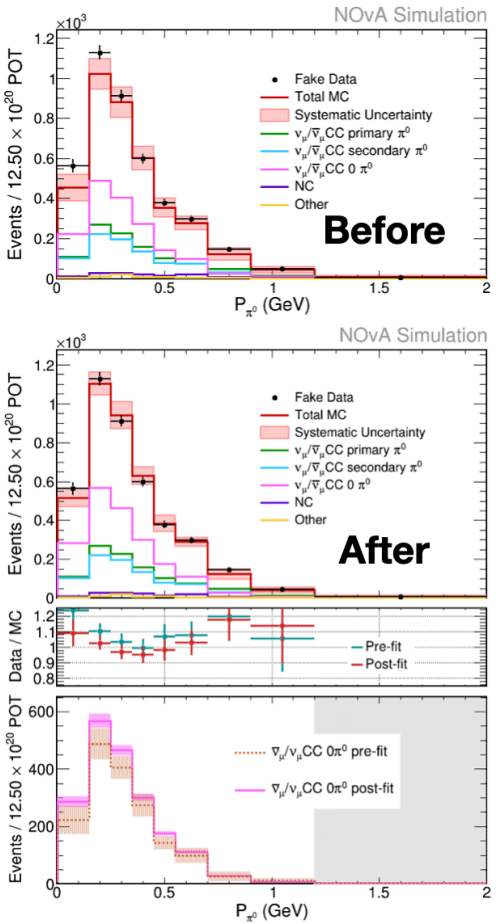
Fit Results - Fake Data

nProngs = 3

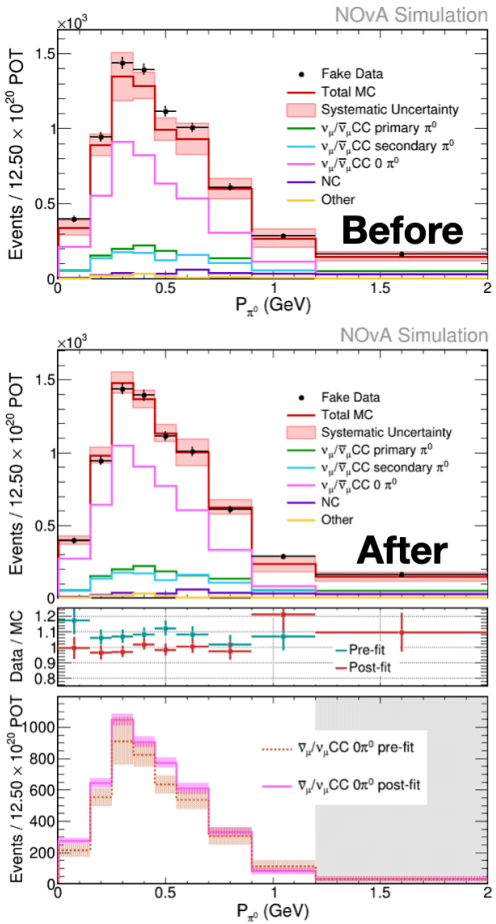
Fake Data:
Adjust $\bar{\nu}_\mu/\nu_\mu \mathrm{CC}\mathbf{0\pi^0}$ and **NC** shifted up 10% in statistically independent sample

χ^2: 388 (Pre-fit) → 264 (Post)

$\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$ - 1 Sideband



$\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$ - 2 Sideband



Fit Results - Fake Data

nProngs > 3

Fake Data:
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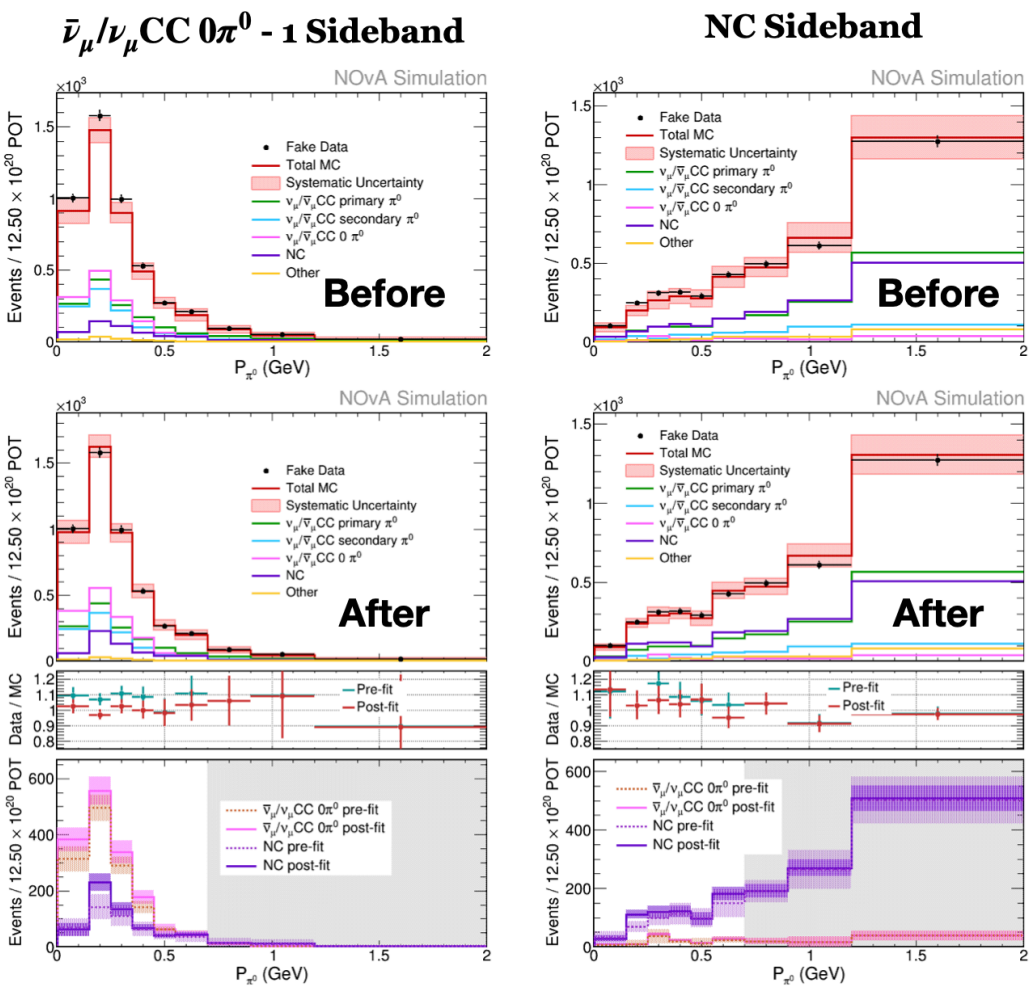
χ^2: 388 (Pre-fit) → 264 (Post)

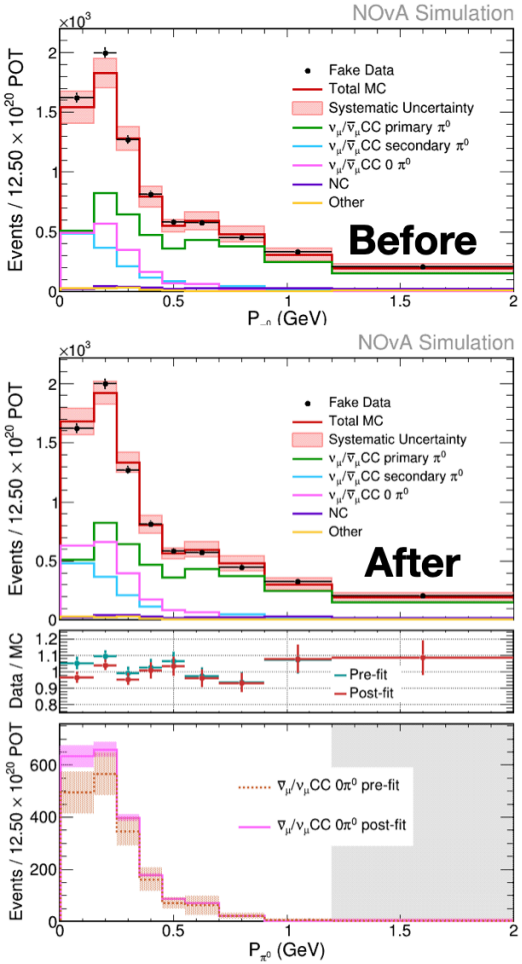


Fit Results - Fake Data

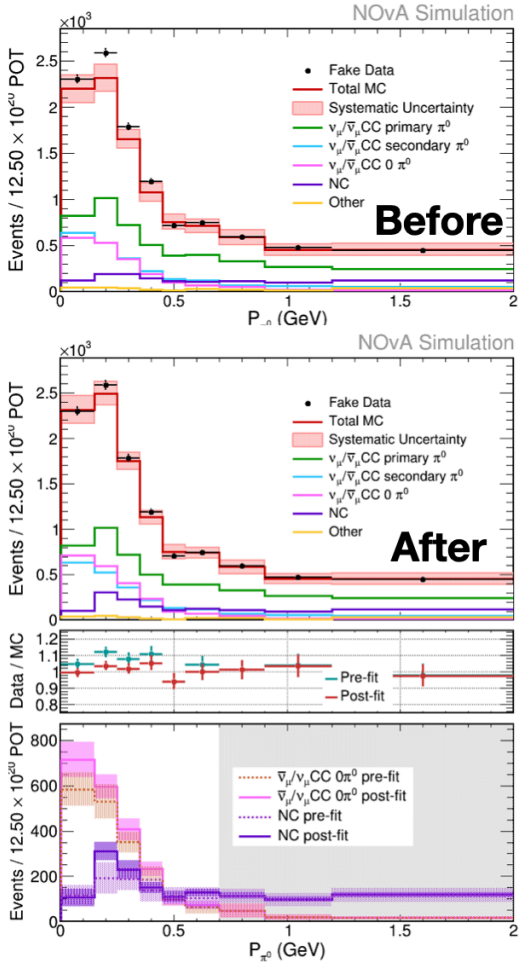
Fit results applied to signal region to constraint $\bar{\nu}_\mu/\nu_\mu \mathrm{CC}\mathbf{0}\pi^{\mathbf{0}}$ and **NC** predictions

χ^2: 388 (Pre-fit) → 264 (Post)

nProngs = 3



nProngs > 3



Summary

- High statistics antineutrino mode data in the NOvA near detector can be used to measure the $\bar{\nu}_\mu \mathrm{CC}\pi^0$ differential cross section w.r.t π^0 momentum and angle
  - Planning measurement to be made in 2 bins of different average W
- CNN has been developed for EM shower selection
- Developed data-driven template fit to estimate $\bar{\nu}_\mu/\nu_\mu \mathrm{CC0}\pi^0$ and NC backgrounds using correlated sidebands
- Currently finalizing unfolding and systematic uncertainty estimation
  - Expecting uncertainties in the 15-20% range

Expect results soon!

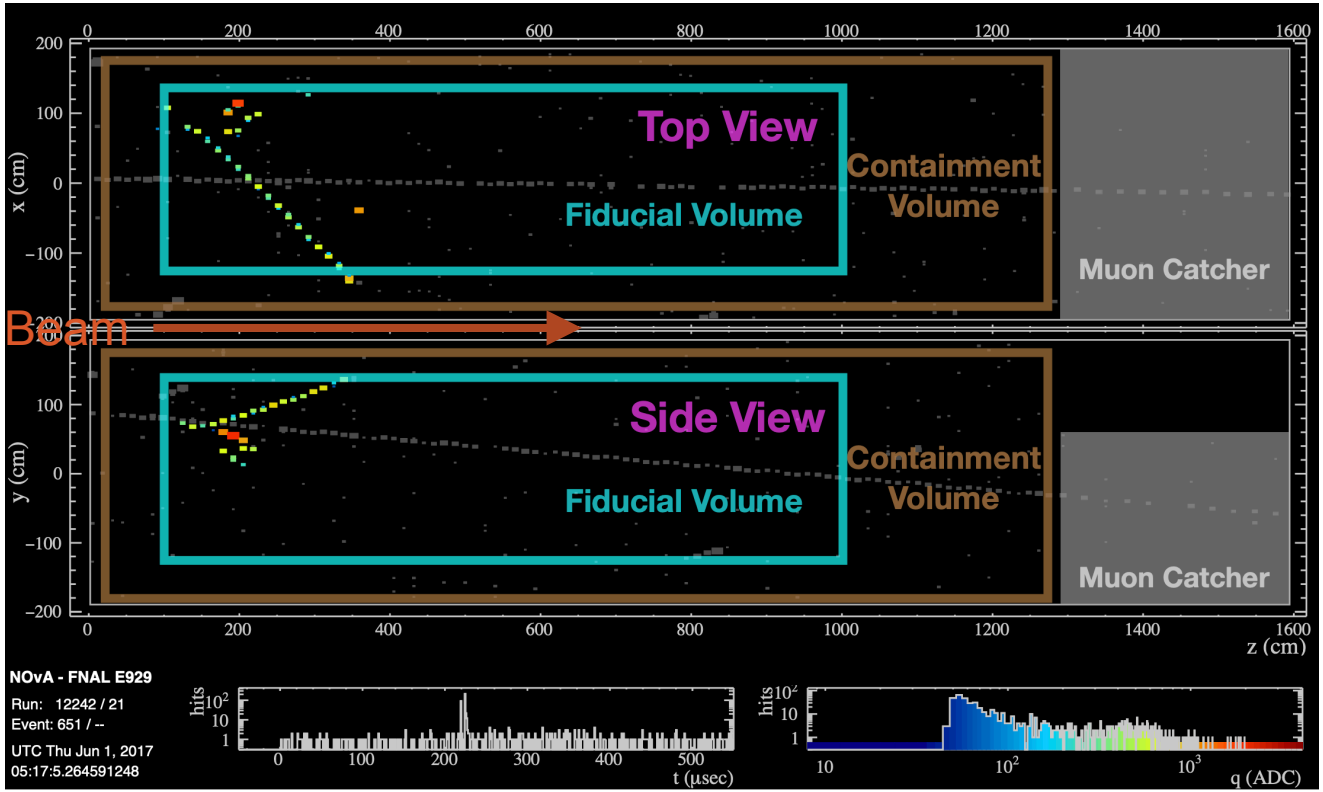
Looking Forward

- NOvA's high rate of neutrino interactions in the ND, off-axis narrow-band beam, and excellent tracking capabilities provide a great platform to make precision measurements of nu-A interactions
- High statistics datasets:
  - $\approx 20 \times 10^{20}$ POT in neutrino mode
  - $\approx 12 \times 10^{20}$ POT in antineutrino mode
- Antineutrino inclusive measurements are a high priority in NOvA
- Both $\mathrm{CC}\pi$ and $\mathrm{CC0}\pi$ measurements are in progress for neutrino and antineutrino mode data

Stay tuned for exciting results from NOvA!

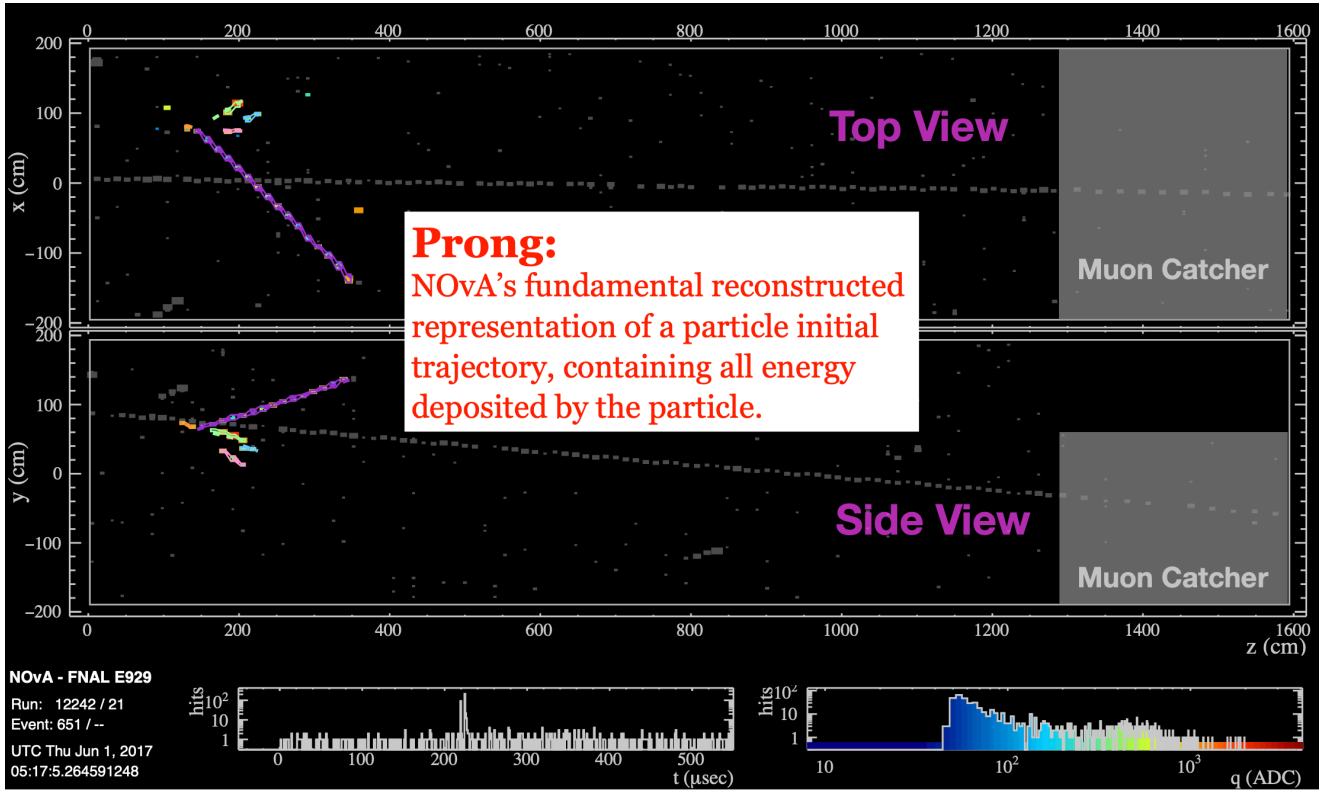
Backups

Selecting Candidate Interactions



- Interaction vertex reconstructed in the fiducial volume
- Tracks/showers contained
- ν_μCC interaction - a long muon track
  - Identify muon-like prong: PID based on dE/dx and scattering variables
- π^0 in the final state
  - 2 distinct EM showers

Selecting Candidate Interactions



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Neutral Pion Selection

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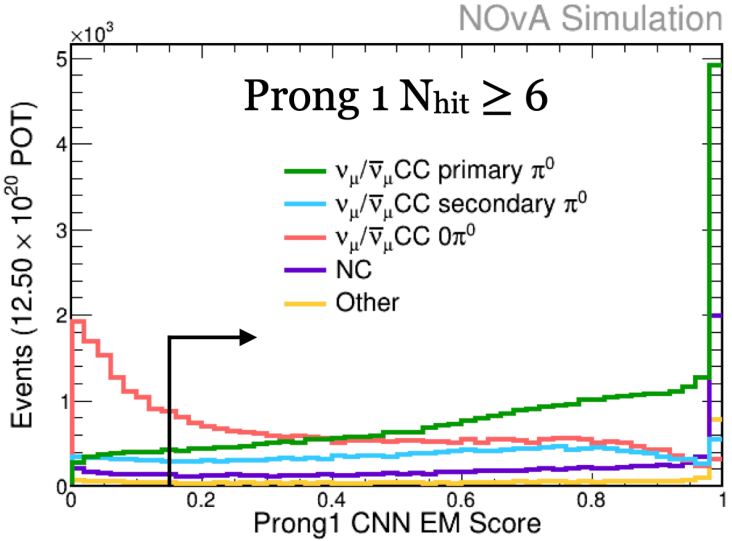
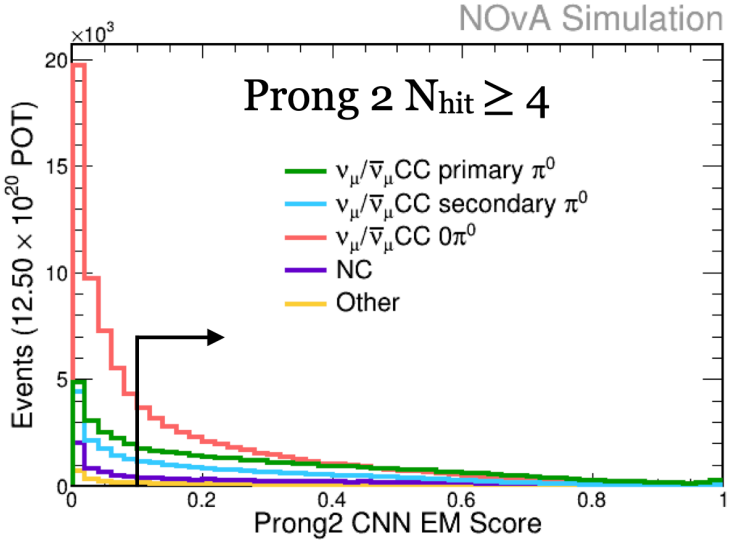
  - Select two candidate EM-like prongs with highest CNN EM scores





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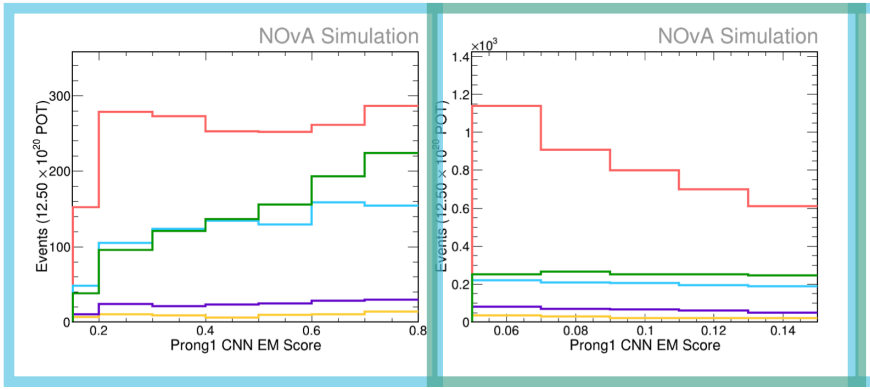
$\nu_\mu/\bar{\nu}_\mu$CC primary π^0
$\nu_\mu/\bar{\nu}_\mu$CC secondary π^0
$\nu_\mu/\bar{\nu}_\mu$CC $0\pi^0$
NC
Other

nProngs = 3 sample sidebands



nProngs > 3 sample sidebands