Measuring Neutral Pion Production in Muon Antineutrino Charged-Current Interactions at the NOvA Near Detector

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On behalf of the NOvA Collaboration

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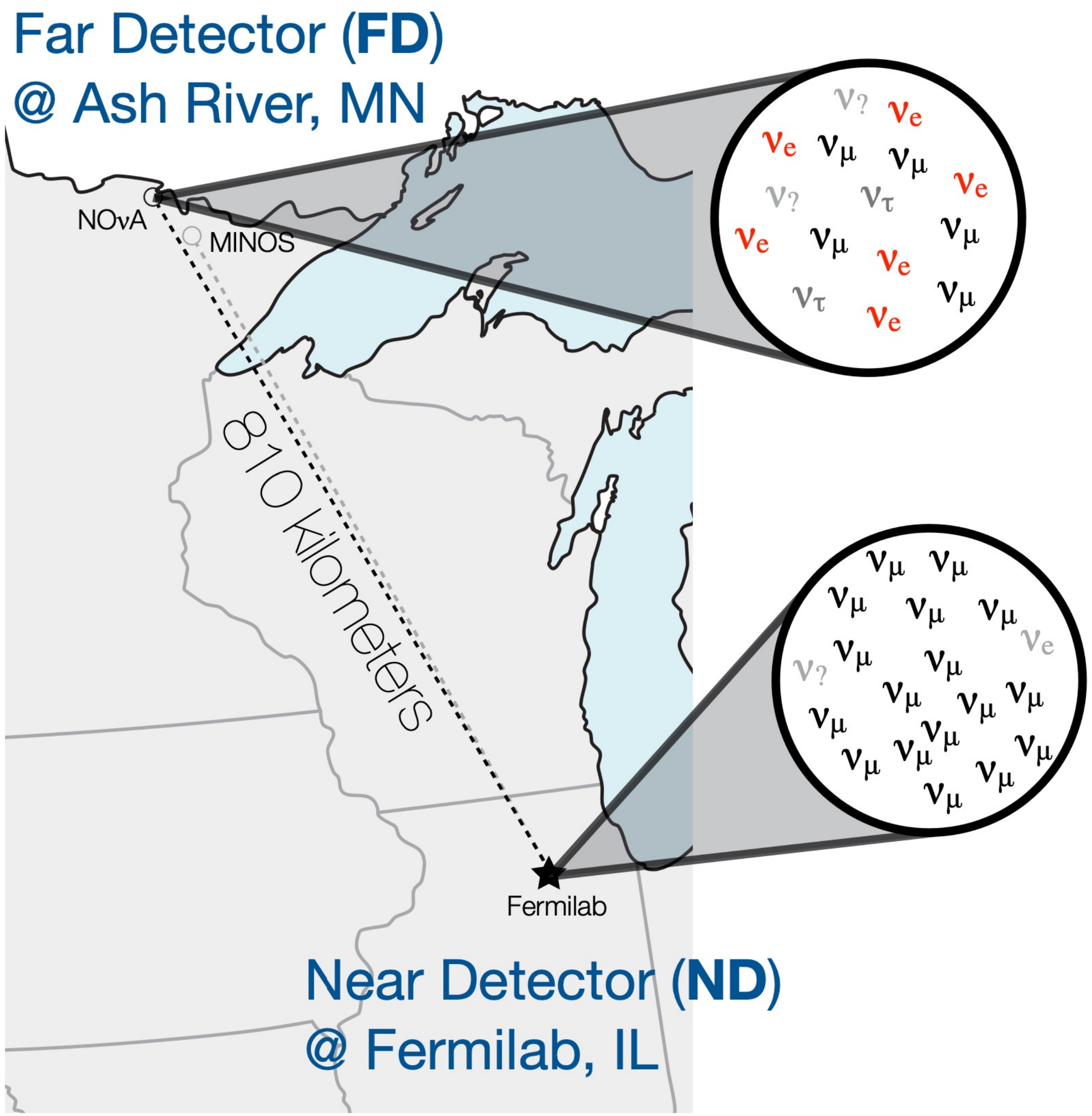


NOvA = NuMI Off-axis ν_e Appearance

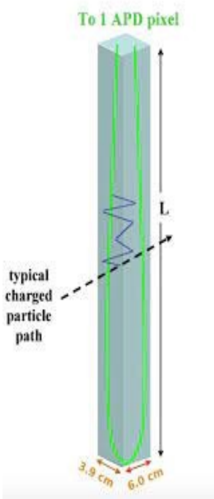
- Long-baseline neutrino oscillation experiment
- NuMI beam at Fermilab
  - Neutrino mode (ν_μ) and antineutrino mode ($\bar{\nu}_\mu$)
  - Power record 954 kW in 2023
- Two functionally-identical tracking calorimeter detectors
  - Separated by ~810 km
  - ~14 mrad off-axis, narrow-band beam around oscillation max
- Oscillation measurements through the $\nu_\mu/\ \bar{\nu}_\mu$ disappearance and the $\nu_e/\ \bar{\nu}_e$ appearance

$\bar{\nu}_\mu$ Charged-Current π^0 @ NOvA Near Detector

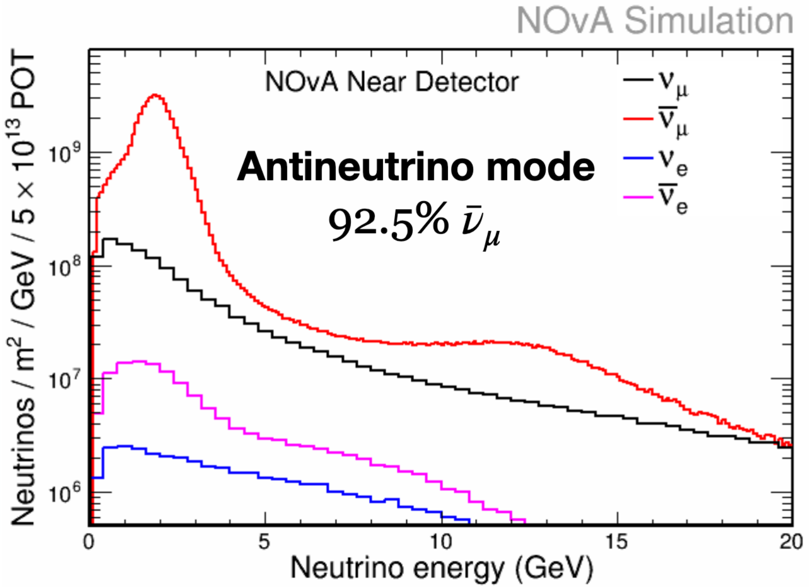
NOvA Near Detector (ND)

- ~300 ton; 100 m underground at Fermilab; ~1 km from beam target
- Highly reflective extruded PVC cells filled with liquid scintillator; alternate in horizontal and vertical orientation for 3D views

C	Cl	H	O	Ti
65.9%	16.1%	10.7%	3.0%	2.4%



- Scintillation light captured and routed to avalanche photodiodes (APDs) via wavelength shifting fibers
- High flux purity (92.5% $\bar{\nu}_\mu$)and large statistics (~1 million $\bar{\nu}_\mu$ CC interactions) in antineutrino mode



$\bar{\nu}_\mu$ Charged-Current (CC) π^0 measurement

$$\left(\frac{d\sigma}{dx_{\pi^0}}\right)_i = \frac{\sum_j U_{ij}^{-1}\left(N_{\text{Sel}}(x_{\pi^0})_j - N_{\text{Bkgd}}(x_{\pi^0})_j\right)}{N_t\,\phi\,\epsilon(x_{\pi^0})_i\,\Delta x_{\pi^0 i}}$$

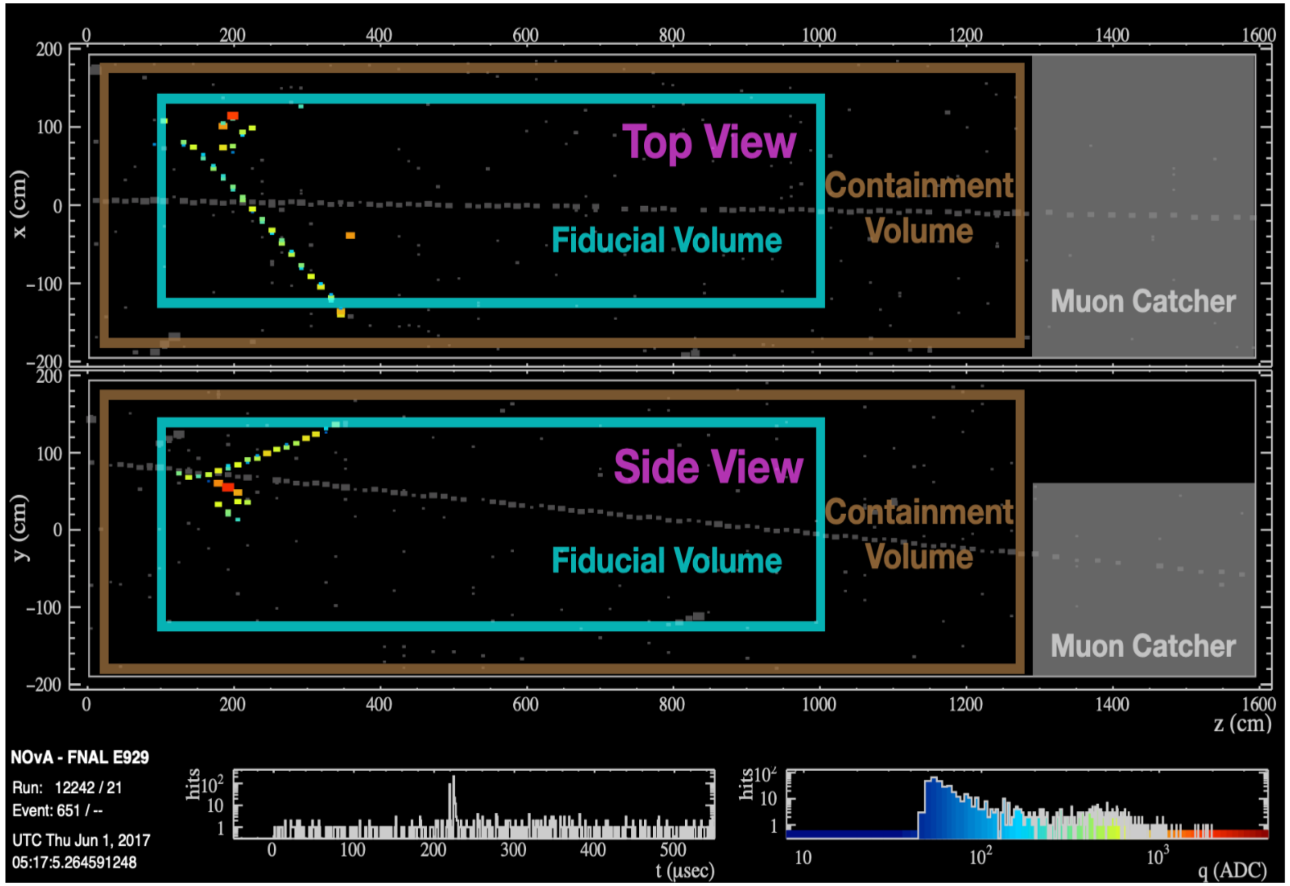
$\bar{\nu}_\mu$ CC π^0 Signal

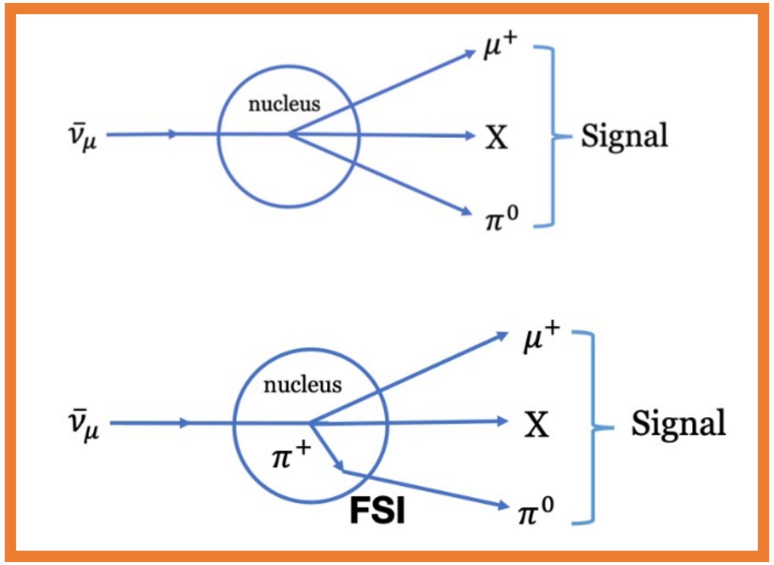
Signal definition

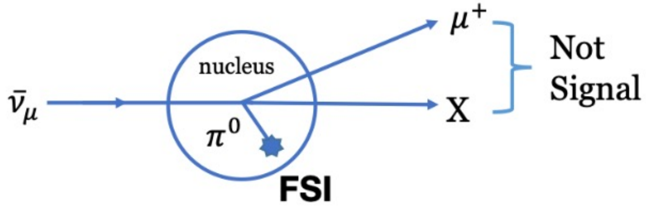
$$\bar{\nu}_\mu + N \to \mu^+ + \pi^0 + X$$

$$\hookrightarrow \pi^0 \to \gamma + \gamma$$

- $\bar{\nu}_\mu$CC interaction in fiducial volume in ND
- At least one π^0 in the final states emerging from the nucleus







Secondary π^0: produced outside the target nucleus is **background**

- Particle decay or inelastic scattering during particle propagation

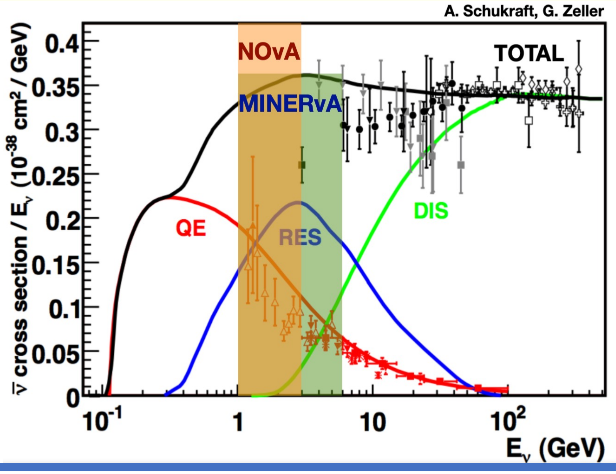
Motivation

- Neutrino oscillations are measured as a function of E_{υ} and accurate estimation of E_{υ} requires knowledge of final states
- $\overline{\upsilon}_{\mu}$ CC π^0 provides insights on backgrounds to υ_e/ $\overline{\upsilon}_e$ appearance
- Measuring $\overline{\upsilon}_{\mu}$ CC π^0 production constrains systematic uncertainties for neutrino interaction models

Experiment	Nuclear Target	E(GeV)	Selected Events	Efficiency	Purity
ANL(1982)(ν_μ)	H_2, D_2 Bubble Chamber	< 1.5	273	-	-
BNL(1986)(ν_μ)	D_2 Bubble Chamber	1.6	853	-	-
MiniBooNE(2011)(ν_μ)	CH_2	0.965	5810	6%	57%
SciBooNE(2014)(ν_μ)	CH	0.8	308	2%	38%
MINERvA(2015)($\bar{\nu}_\mu$)	CH	3.6	1304	6%	55%
MINERvA(2017)(ν_μ)	CH	3.6	6110	8.4%	51%

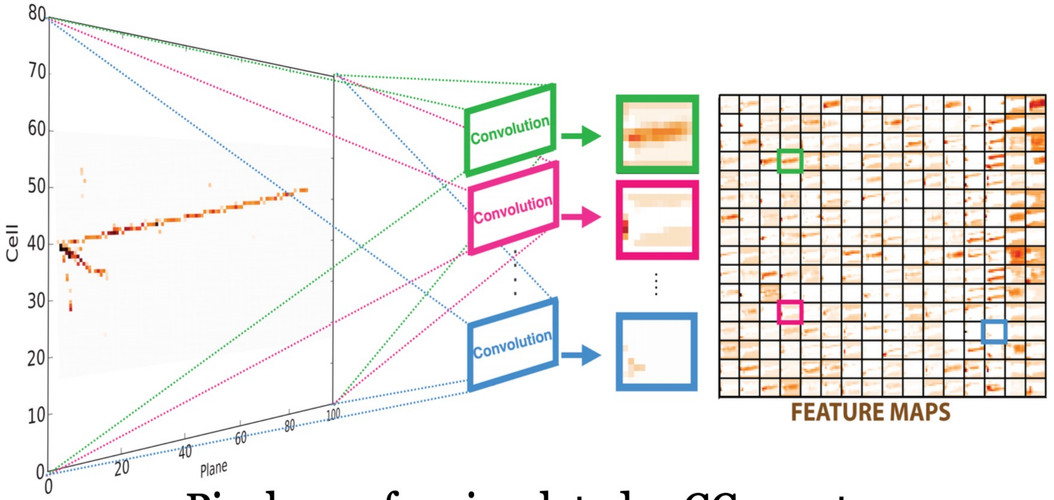
NOvA can provide a complementary measurement

- ~ 6x POT
- E_{υ} (NOvA) has a narrow band peaked at ~2 GeV, while E_{υ} (MINERvA) has a broad band averaged at 3.6 GeV

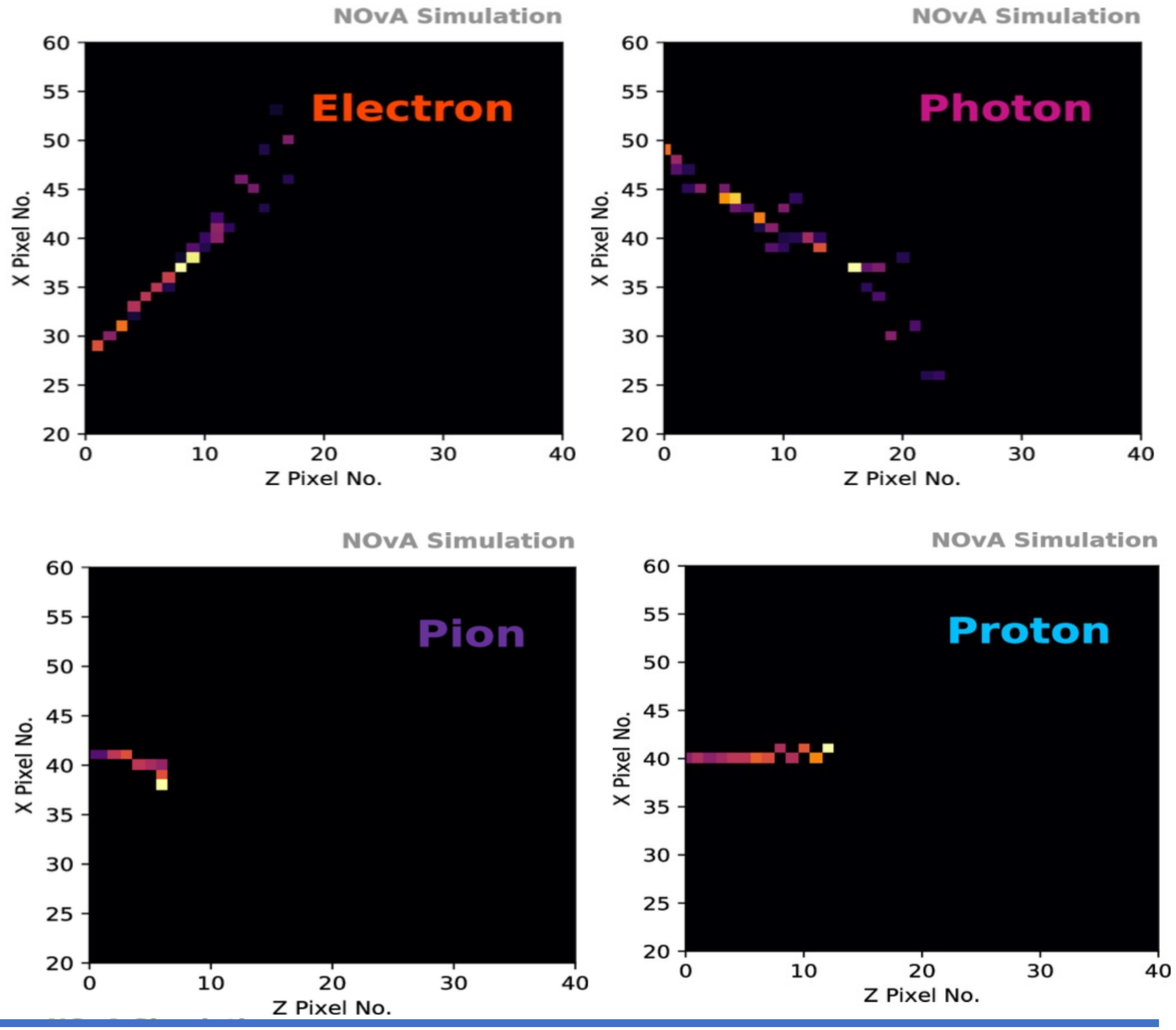


Event and Particle Identification

- NOvA implemented Convolutional Neural Networks (CNNs) to identify neutrino event and particle.
  - Convolutions are applied to pixel maps to extract features such as showers, tracks, vertex, etc.



Pixel map for simulated ν_μCC event.

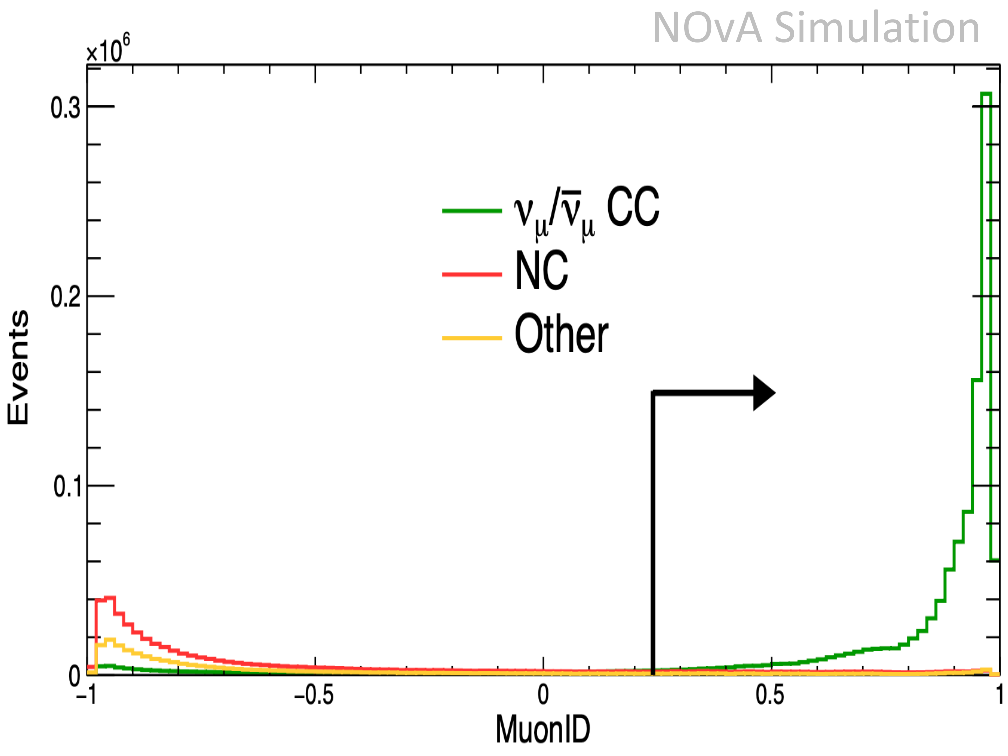


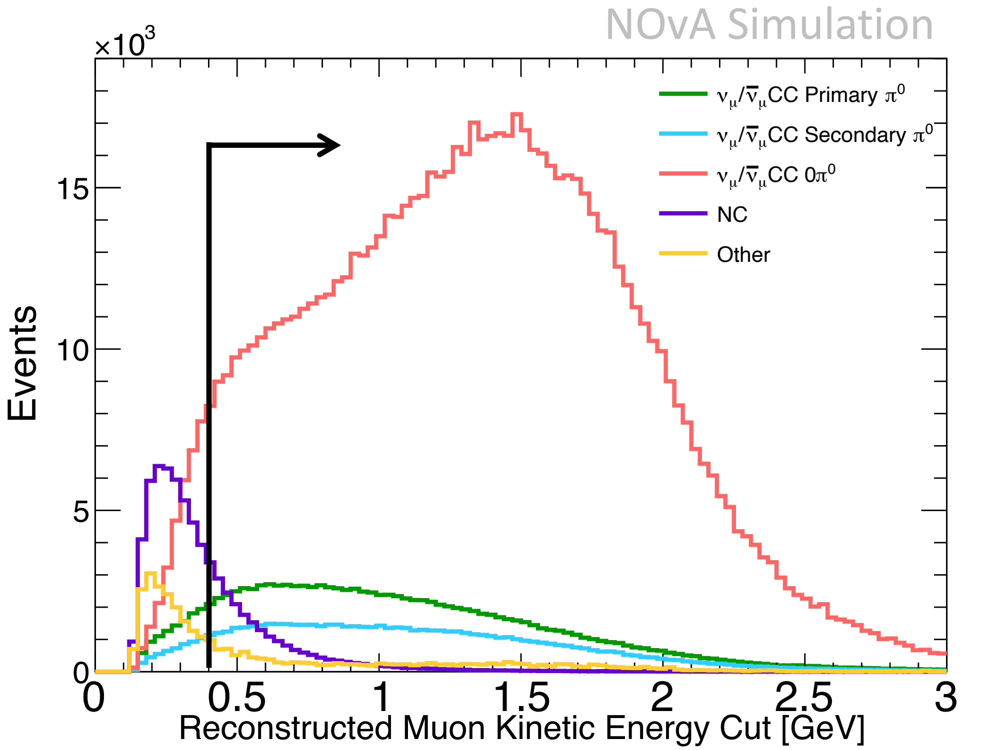
A CNN is trained using single particle samples, rather than neutrino interaction samples, to identify electromagnetic showers.

- Binary classification for prongs:
  - Electromagnetic-like (EM-like) vs. non-EM-like

$\bar{\nu}_\mu$ CC π^0 Event Selection

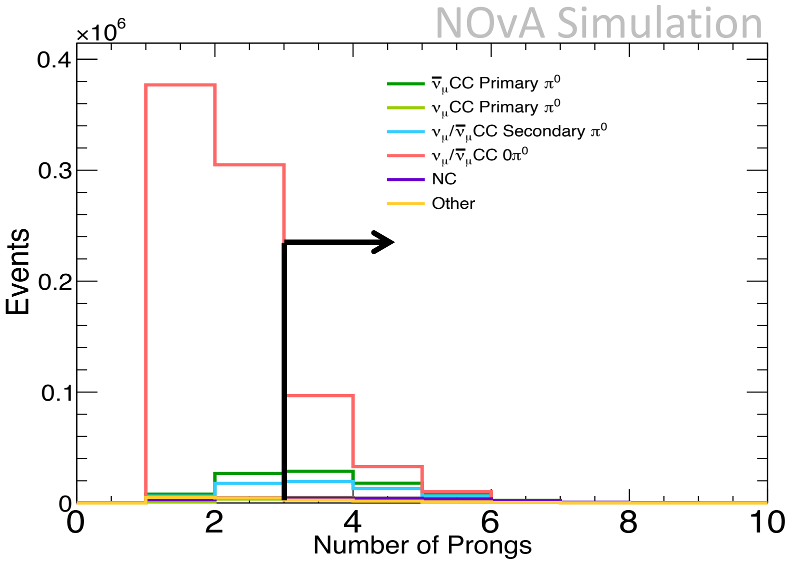
- **Track-based cuts:** $\nu_\mu/\bar{\nu}_\mu$ CC inclusive events
  - Preseletion: event quality, fiducial volume, containment
  - **Muon likelihood score (MuonID)**
  - **Reconstructed muon kinetic energy**

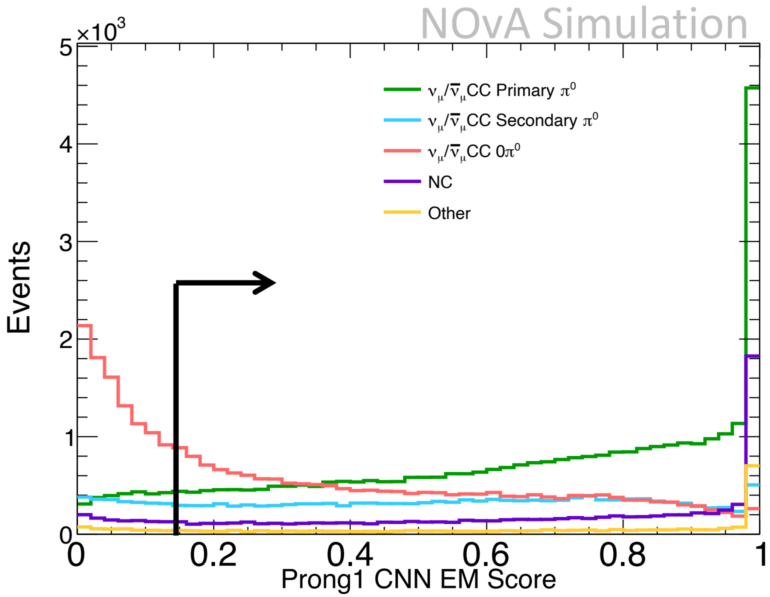


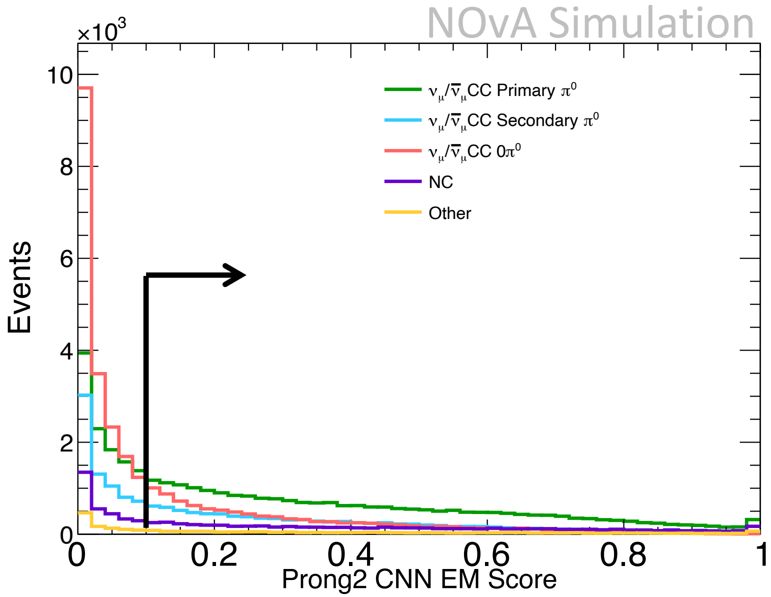


$\bar{\nu}_\mu$ CC π^0 Event Selection

- **Shower-based cuts:**
  - **Number of prongs (NProngs)**
  - Number of hits in the prong
  - **Prong CNN EM scores**



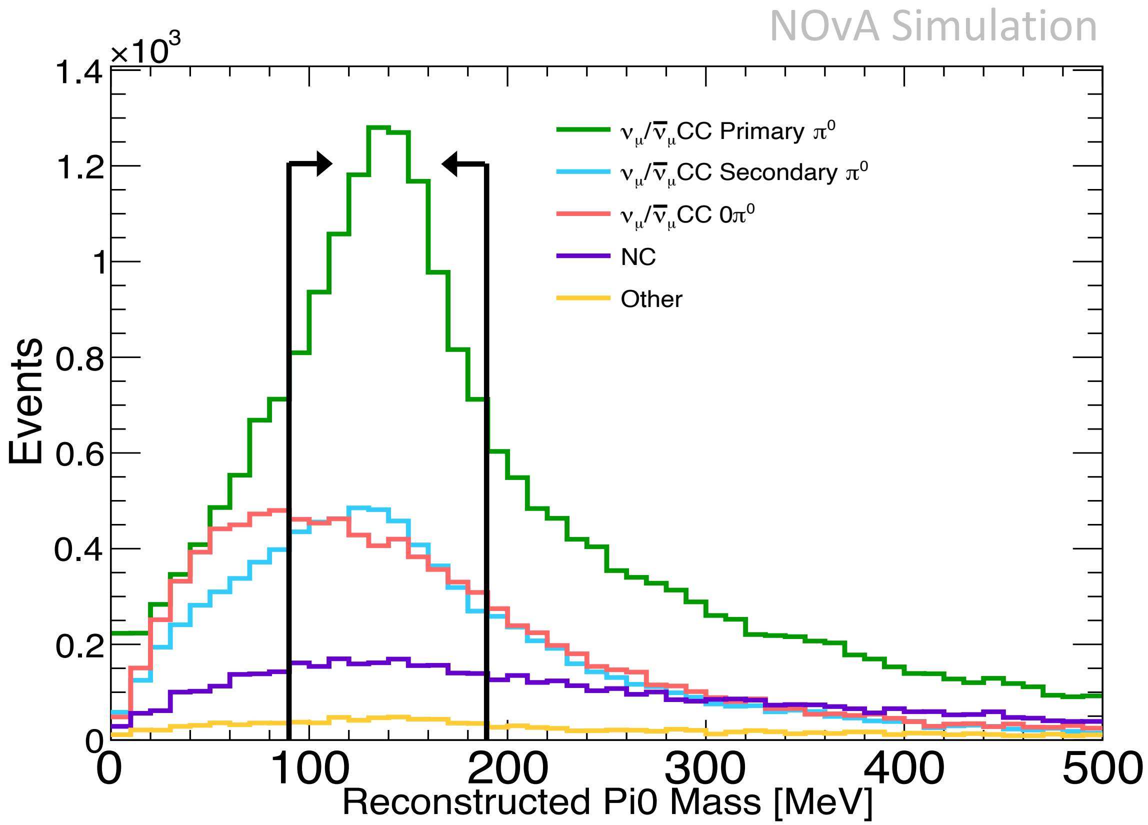




$\overline{\nu}_\mu$ CC π^0 Event Selection

- **Final state π^0 invariance mass cut:**

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1 - \cos\theta_{\gamma\gamma})}$$



Template Fit

- A **data-driven template fit** has been developed to more accurately constrain background contributions and estimate signal events, which is performed in all π^0 kinematic bins **using templates from sidebands and signal region simultaneously.**
  - Create templates across the sidebands and signal region
    - Two signal templates and four sideband templates for $\nu_\mu / \bar{\nu}_\mu$CC $0\pi^0$ and NC
  - Construct the covariance matrix

$$V = V_{stat} + V_{syst}$$

  - Adjust the normalization of the templates through a fit to data by minimizing

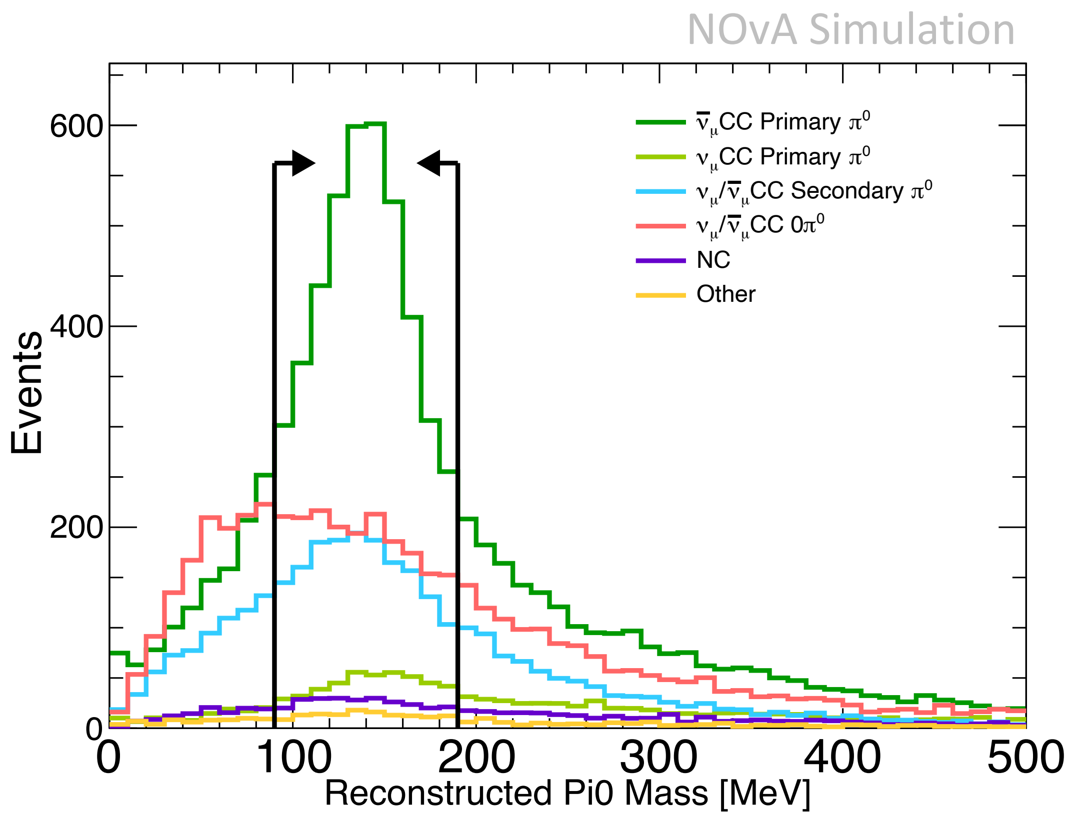
$$\chi^2 = (x_i - \mu_i)^T V_{ij}^{-1} (x_j - \mu_j)$$

    - x_i: data observable
    - μ_i: prediction according to the variation of three normalization parameters (***a***, ***b***, ***c***) for each template π^0 kinematic bin

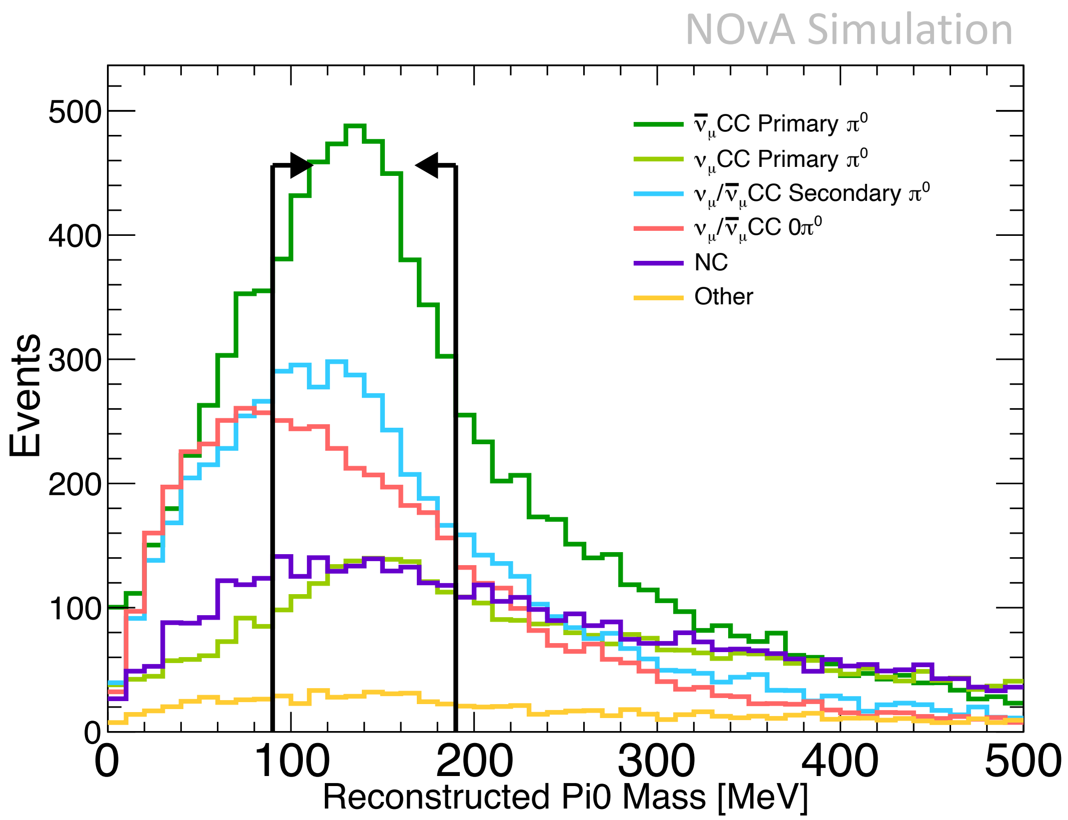
$$\mu_i = \boldsymbol{a_i} \times \left(N_{\mathrm{CC\,Prim}\,\pi^0,\,i} + N_{\mathrm{CC\,Seco}\,\pi^0,\,i}\right) + \boldsymbol{b_i} \times N_{\mathrm{CC}\,0\pi^0,\,i} + \boldsymbol{c_i} \times N_{\mathrm{NC},\,i} + N_{\mathrm{Other},\,i}$$

Templates

Signal Template (NProngs = 3)



Signal Template (NProngs > 3)



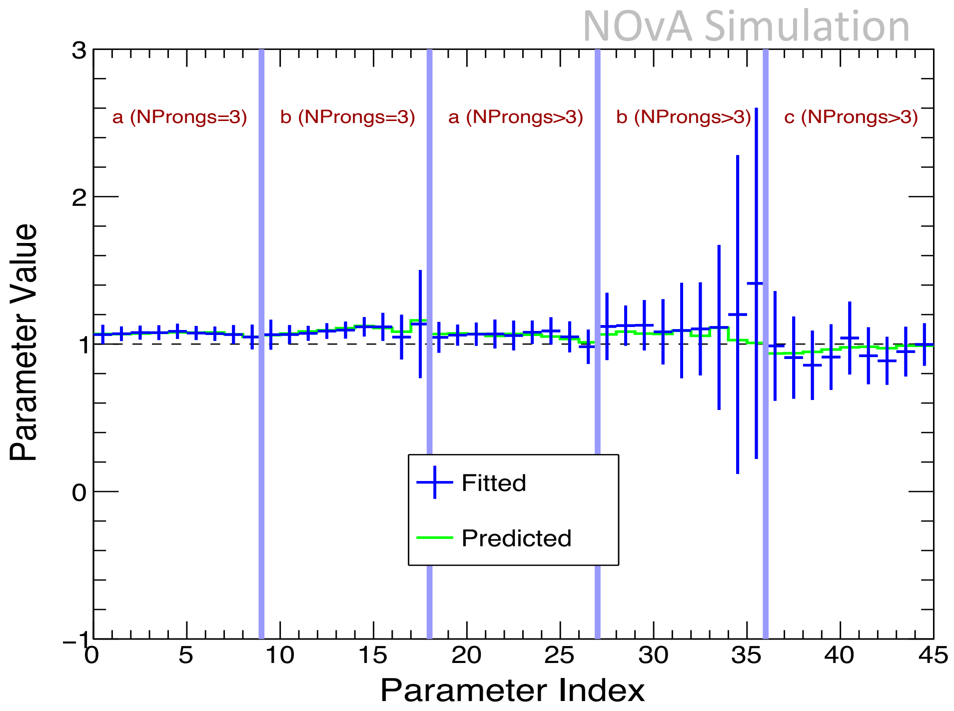
Template Fit

$$\mu_i = \boldsymbol{a_i} \times (N_{\mathrm{CC\,Prim}\,\pi^0,\,i} + N_{\mathrm{CC\,Seco}\,\pi^0,\,i}) + \boldsymbol{b_i} \times N_{\mathrm{CC}\,0\pi^0,\,i} + \boldsymbol{c_i} \times N_{\mathrm{NC},\,i} + N_{\mathrm{Other},\,i}$$

- **Closure test example from fake data**

  (+1σ MaCCRES and -1σ MaNCRES)

  - Predicted parameter values is calculated from the ratio of fake data to mc nominal using corresponding components in the template samples



- **We conducted a series of validations using various fake data sets, and all indicate that the template fit performs as expected.**

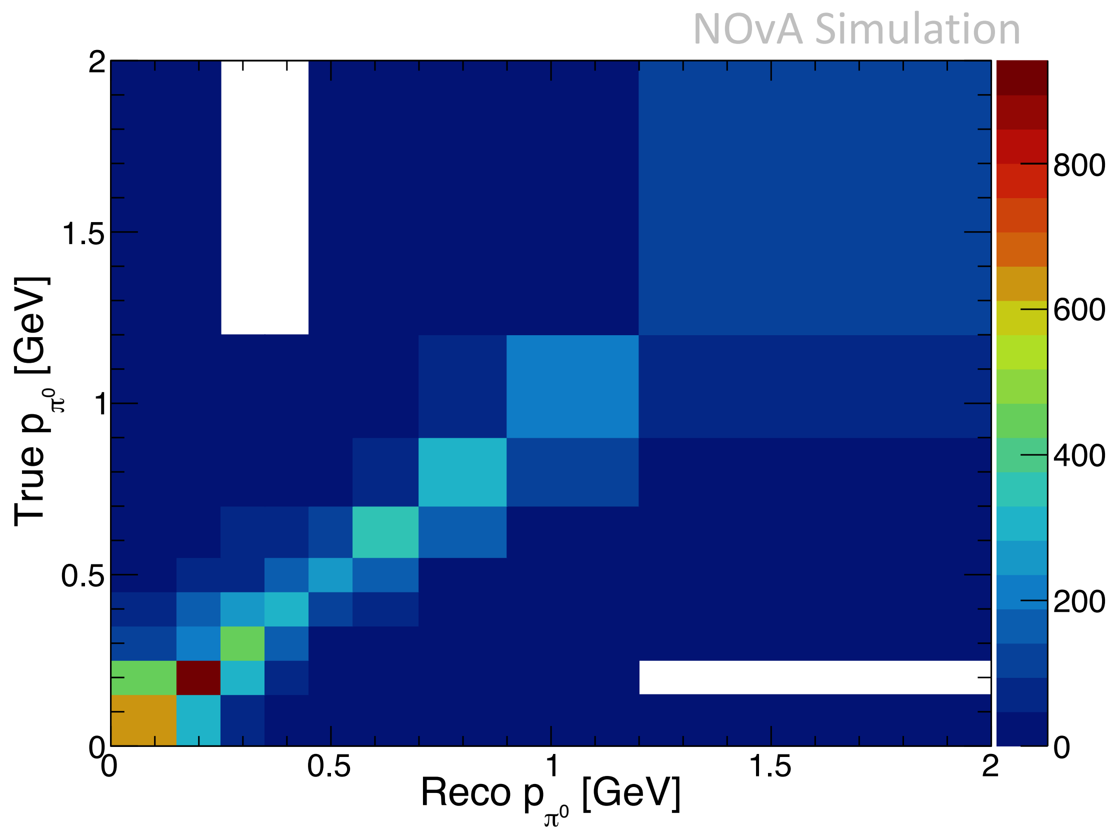
Cross Section Extraction

- The single differential cross section calculation is expressed as

$$\left(\frac{d\sigma}{dx_{\pi^0}}\right)_i = \frac{\sum_j U_{ij}^{-1}\left(N_{\mathrm{Sel}}(x_{\pi^0})_j - N_{\mathrm{Bkgd}}(x_{\pi^0})_j\right)}{N_t\,\phi\,\epsilon(x_{\pi^0})_i\,\Delta x_{\pi^0 i}}$$

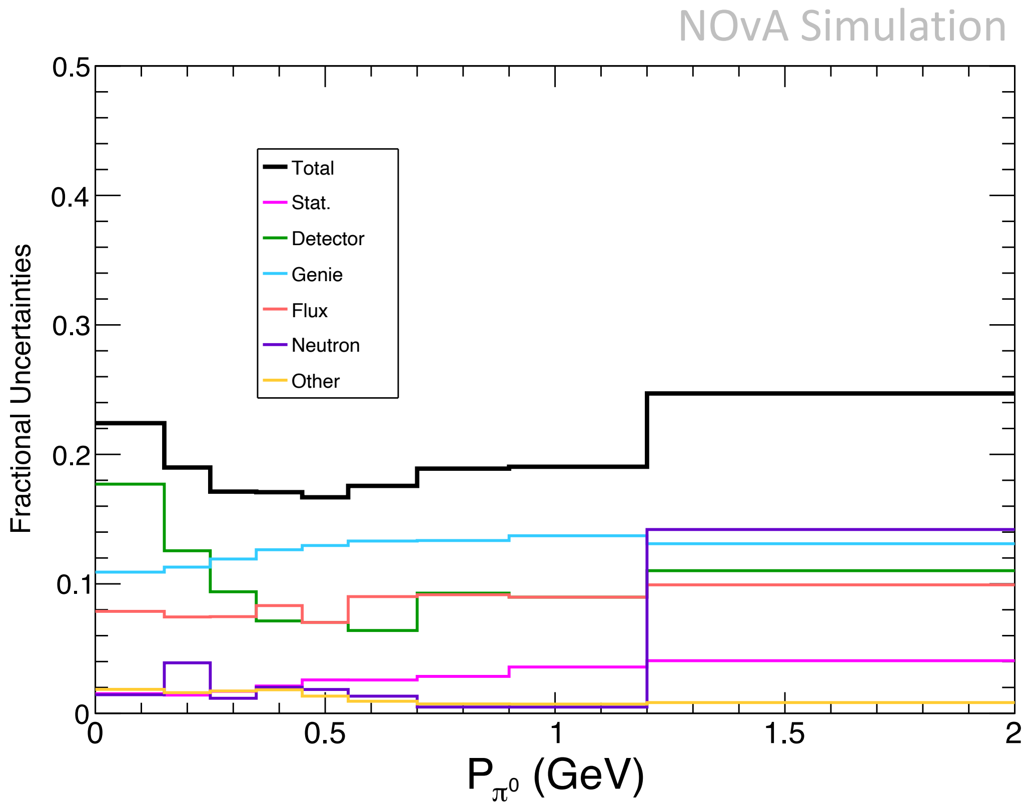
- x_{π^0}: π^0 momentum or angle
- N_{Sel}: number of selected events
- N_{Bkgd}: number of estimated background events
- U: unfolding matrix
- N_t: number of nucleons in the target
- ϕ: integrated flux
- ϵ: efficiency
- i,j: bin index

Unfolding matrix (reconstructed to true migration)



Systematic Uncertainties

- The rich statistics of data at the NOvA Near Detector enables the $\bar{\nu}_\mu$ CC π^0 measurement to be a systematic-limited measurement.
- Major systematic sources come from the **detector response (mainly from detector calibration)**, **Neutrino-nucleus interaction modeling**, **flux**, etc.



Conclusion

- The rich statistics of data at the NOvA Near Detector can be used to perform a measurement of $\bar{\nu}_\mu$ CC π^0 production in the resonance regime.
    - Differential cross-section measurement as a function of π^0 momentum and angle
- A CNN trained on single particle samples is used to identify the EM showers.
- A data-driven template fit has been developed to better constrain the background contributions and estimate the signal events.
- We're finalizing the systematics and preparing for the signal box opening.

Stay tuned. Thank you!

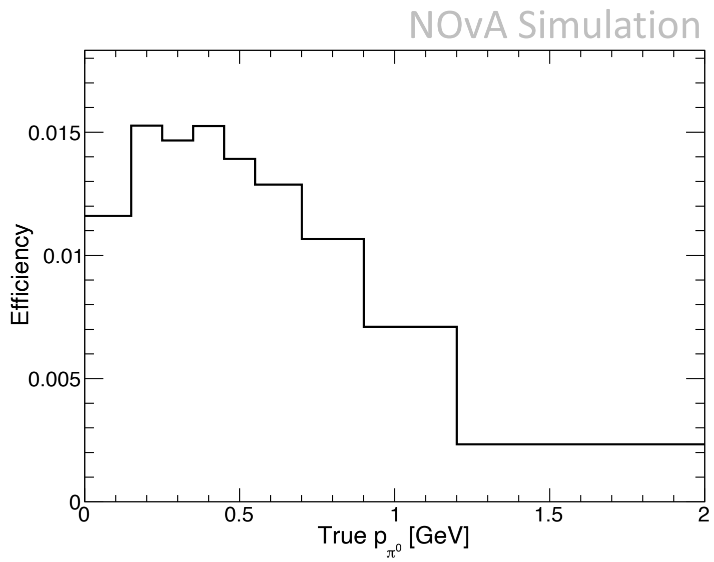
Backup

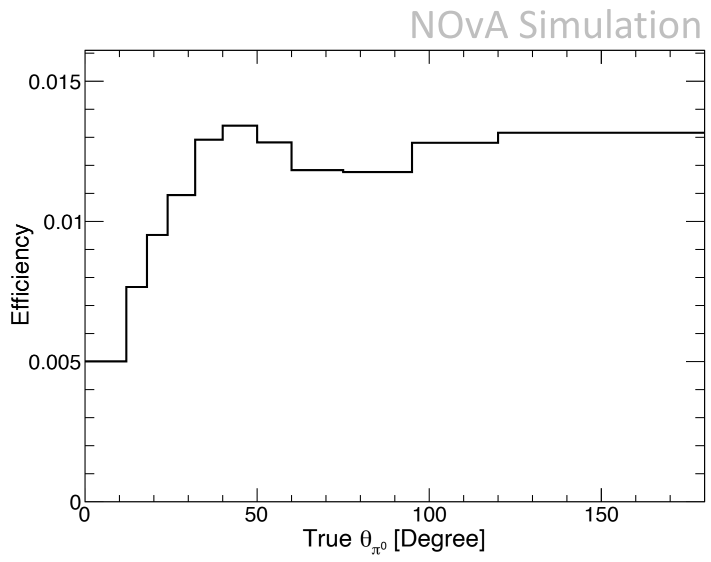
Event Selection

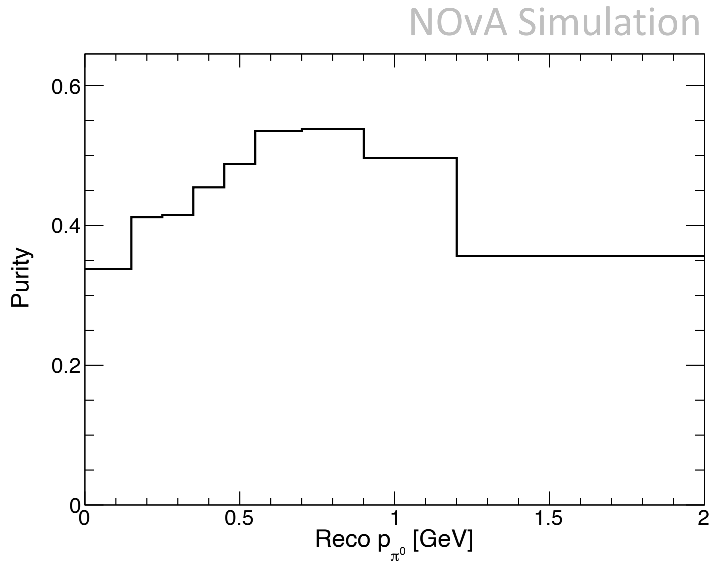
The following cuts are applied for event selection

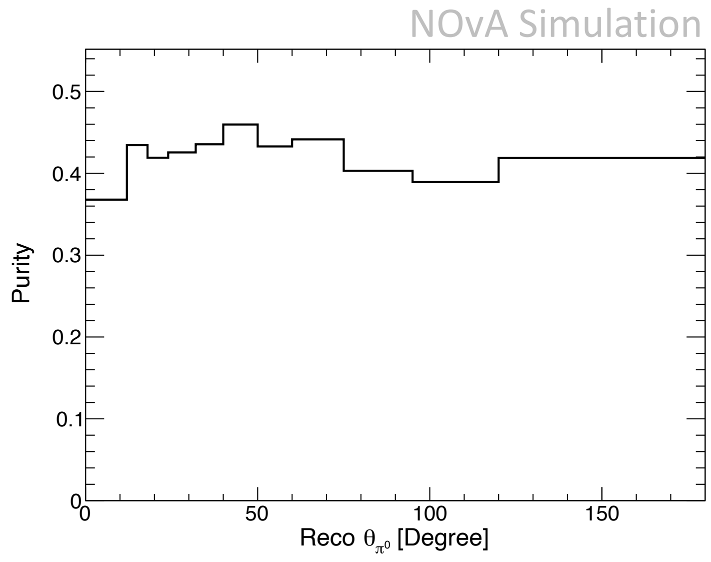
- **Preselection**
  - **Event quality**: NHits in slice > 20 & NKalmanTracks in slice > 0 & NContiguousPlanes in slice > 4
  - **Fiducial volume**: Primary muon track start position/reconstructed event vertex satisfies (in [cm]) $-130 < x < 140$, $-130 < y < 140$, and $100 < z < 1000$
  - **Containment**: all reconstructed showers within the detector active region except for the primary muon track
  - **Muon likelihood score (MuonID)** (≥ 0.24)
- **Reconstructed muon kinematic energy (ReconMuonKE)** (≥ 0.4 GeV)
- **Number of Prongs (Nprongs)** (≥ 3)
- **Prong Number of Hits (NHits)**: Prong 1 NHits ≥ 6 & Prong 2 NHits ≥ 4
- **Prong CNN EM Scores**: Prong 1 CNN EM score ≥ 0.15 & Prong 2 CNN EM score ≥ 0.10
- **Reconstructed π^0 Mass (Pi0Mass):** 90 MeV ≤ Pi0Mass < 190 MeV

$\bar{\nu}_\mu$ CC π^0 Event Selection



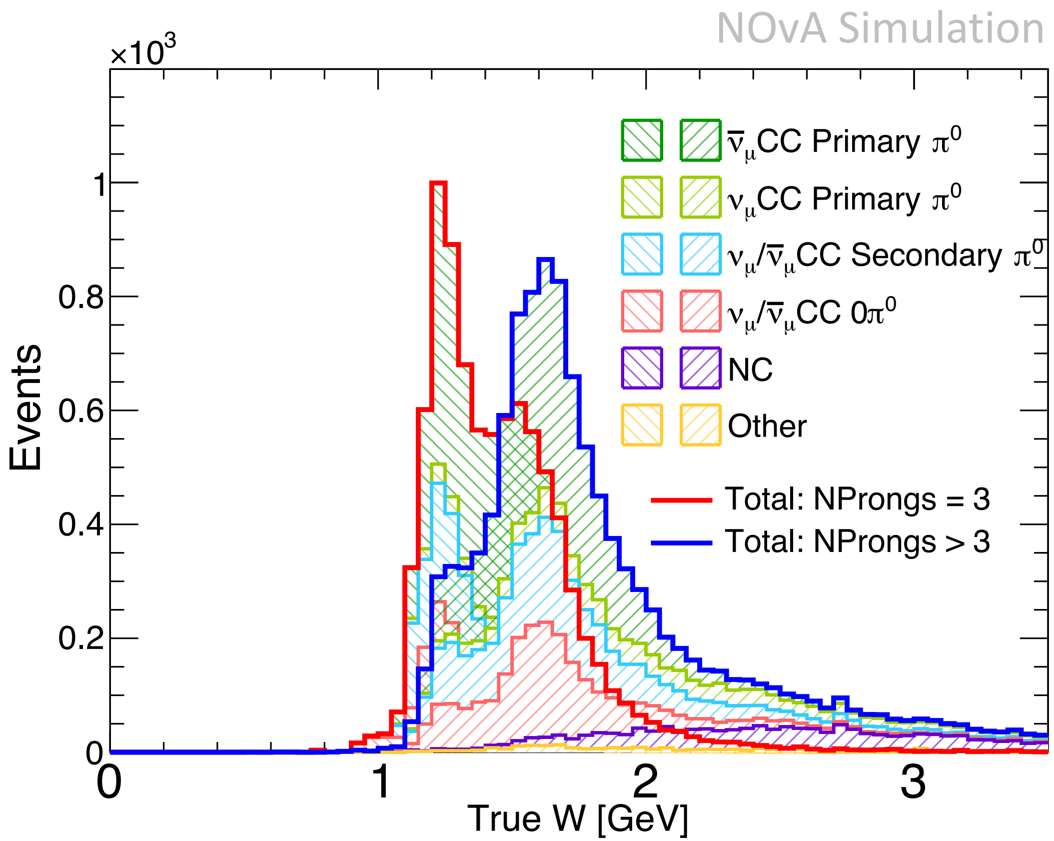






Templates

- Motivated by the true W (invariant mass of hadronic system) distributions, the selected signal sample and sideband samples are split in two orthogonal subsamples with Number of Prongs (NProngs) = 3 and NProngs >3.

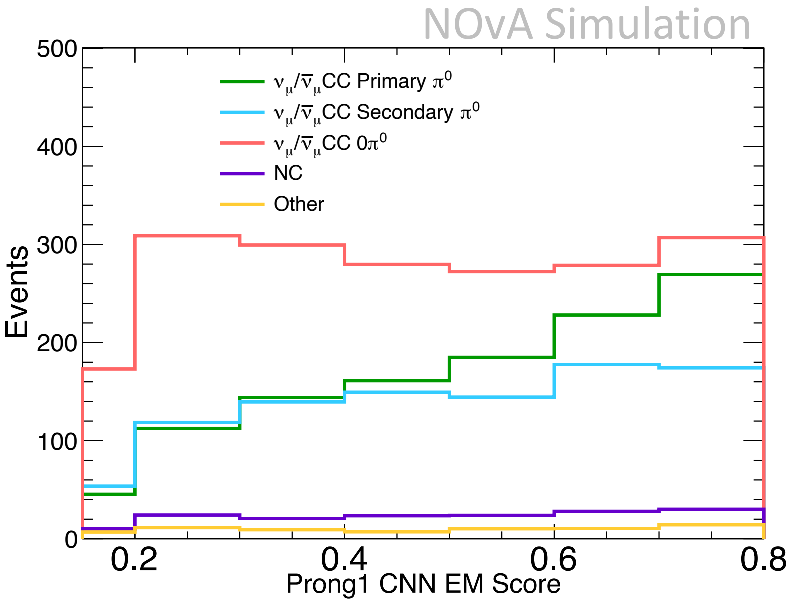


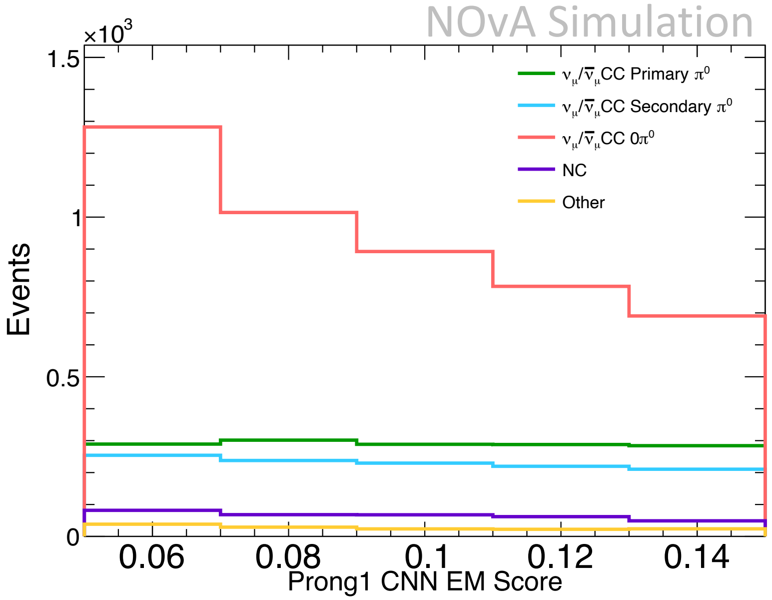
Templates

CC $0\pi^0$ Sideband

(NProngs = 3)

Prong 1 EM-Like





CC $0\pi^0$ Sidband

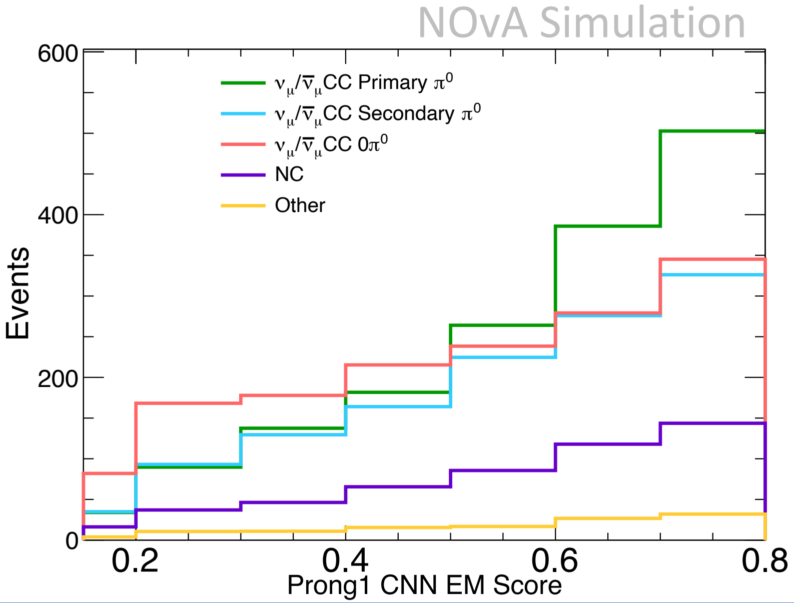
(NProngs = 3)

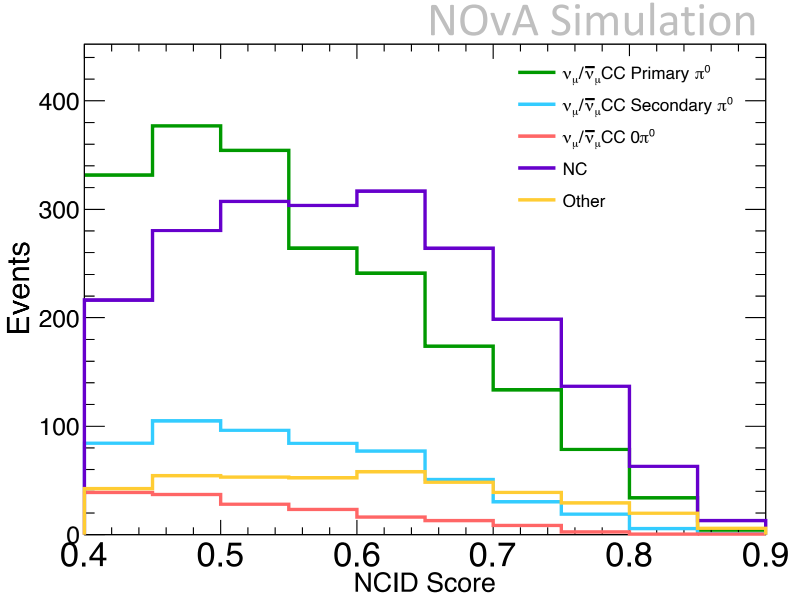
Prong 1 Low-Score

CC $0\pi^0$ Sideband

(NProngs = 3)

Prong 1 EM-Like





ND Sideband

(NProngs > 3)

Templates

Fraction of signal and each background in the template sidebands and selected samples

	$\bar{\nu}_\mu$CC Primary π^0	ν_μCC Primary π^0	$\bar{\nu}_\mu/\nu_\mu$CC Secondary π^0	$\bar{\nu}_\mu/\nu_\mu$CC $0\pi^0$	NC	Other	Total
CC0Pi0 EMLike NProngs = 3	25.6%	3.1%	22.7%	43.5%	3.5%	1.6%	100%
CC0Pi0 EMLike NProngs > 3	24.9%	7.2%	24.3%	30.8%	10.4%	2.3%	100%
CC0Pi0 LowScore NProngs = 3	14.7%	3.6%	15.1%	60.6%	4.1%	1.9%	100%
NC NProngs > 3	11.6%	27.8%	10.1%	2.9%	39.4%	8.1%	100%
Selected NProngs = 3	49.7%	5.3%	18.2%	21.8%	3.2%	1.8%	100%
Selected NProngs > 3	36.7%	10.7%	21.1%	18.2%	10.9%	2.4%	100%

Fake Data Fitting Results

NProngs = 3

CC $0\pi^0$ Prong 1

EM-Like Sideband

NProngs = 3

CC $0\pi^0$ Prong 1

Low-Score Sideband

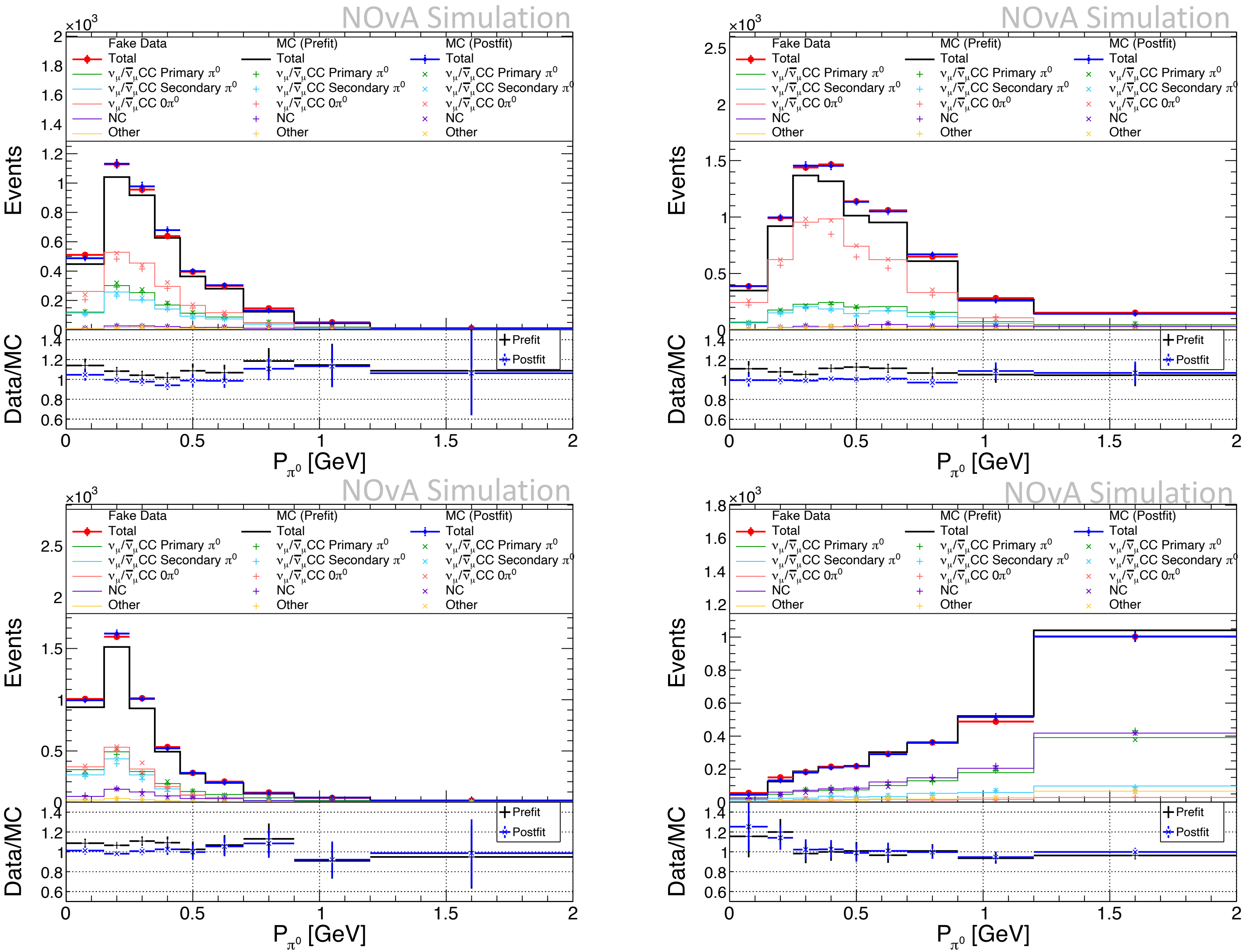
NProngs > 3

CC $0\pi^0$ Prong 1

EM-Like Sideband

NProngs > 3

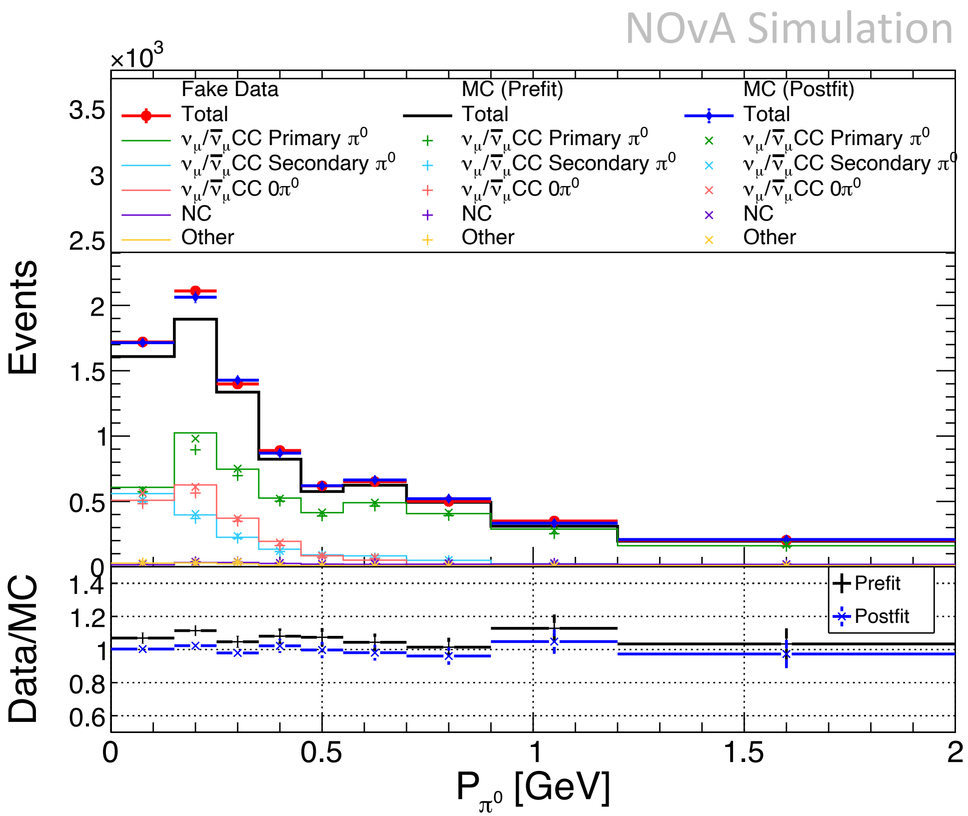
NC Sideband



Fake Data Fitting Results

NProngs = 3

Signal Region



NProngs > 3

Signal Region