Constraining neutrino interaction model parameters in NOvA

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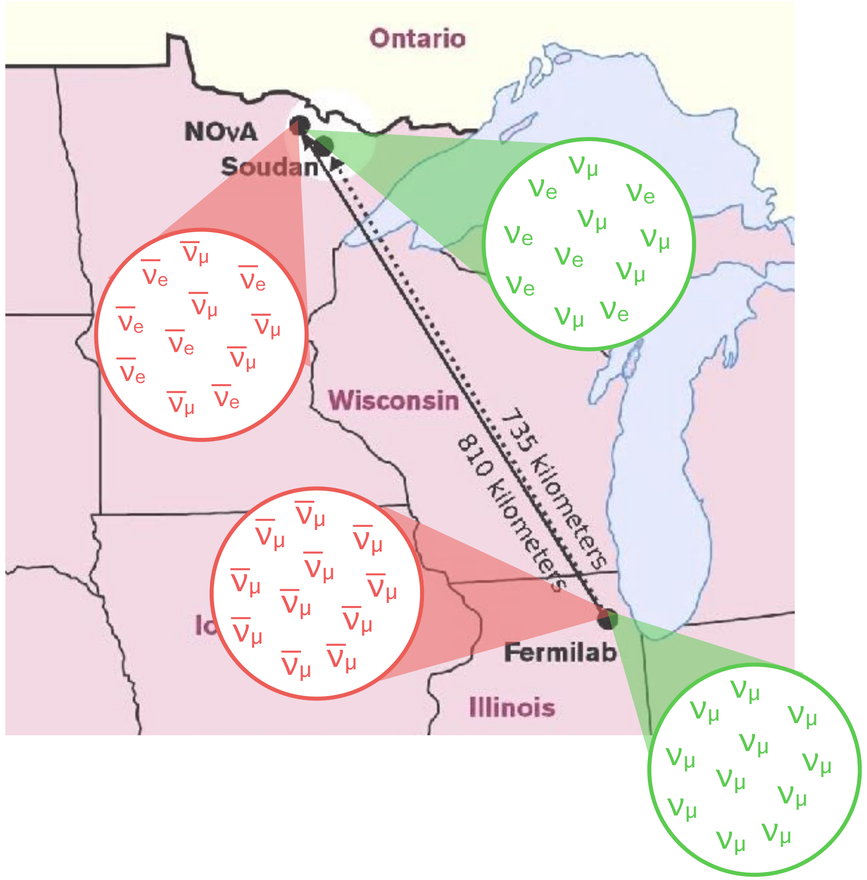
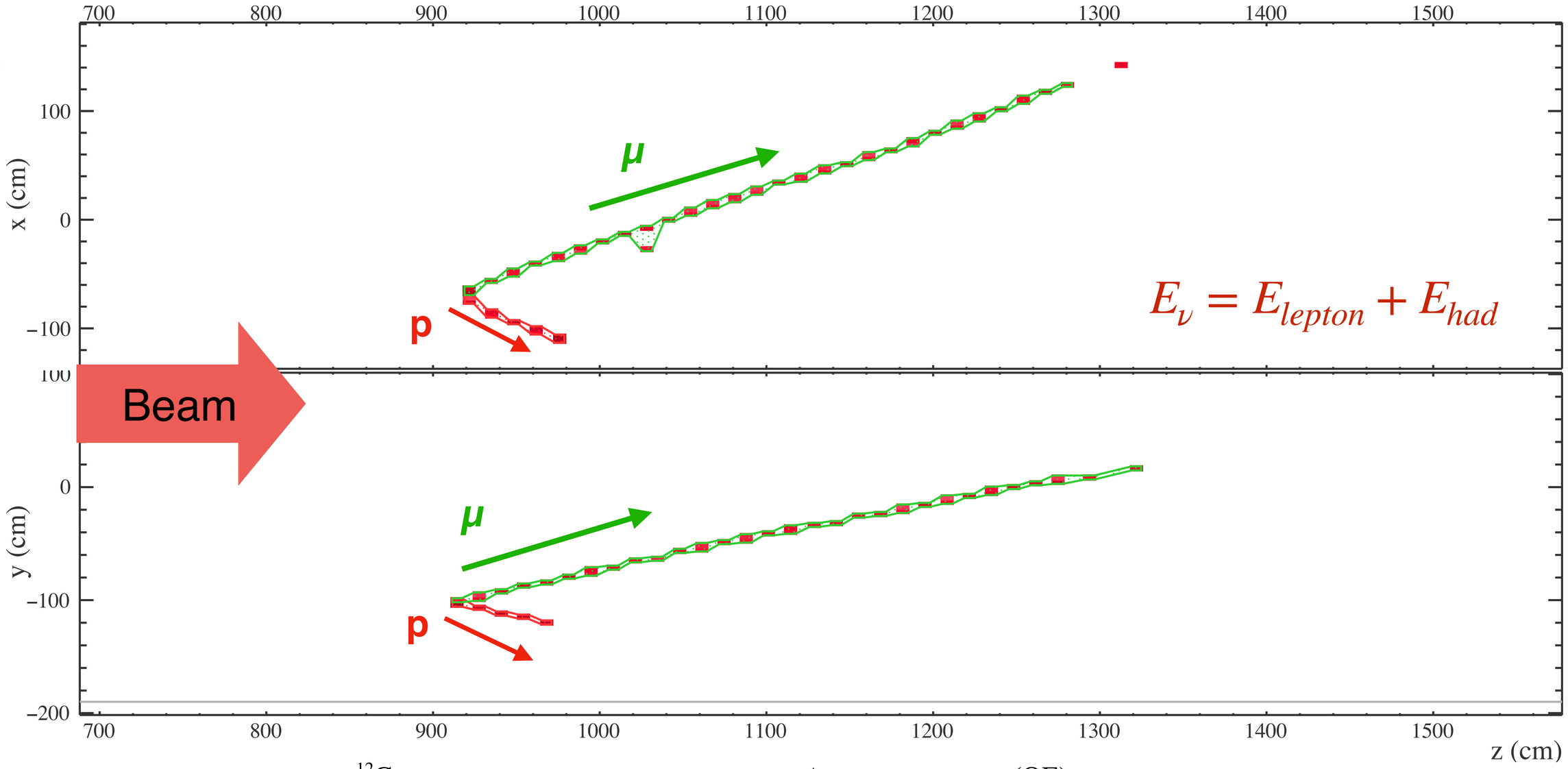
For the NOvA collaboration
DPF21

Numi Off-axis ν_e Appearance

- NOvA is a long-baseline neutrino experiment with Near Detector (ND) at Fermilab and a baseline of 810km with the main physics goals:
  - Determine neutrino mass hierarchy
  - Probe δ_{CP} violating phase
  - Resolve the octant of θ_{23} mixing angle
- These parameters are extracted from the observed charged current (CC) interactions of neutrinos in the oscillation channels:
  - $(\nu_\mu \rightarrow \nu_\mu), (\nu_\mu \rightarrow \nu_e), (\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu), (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- NOvA uses simulations based on the GENIE neutrino event generator to predict the neutrino spectrum observed.



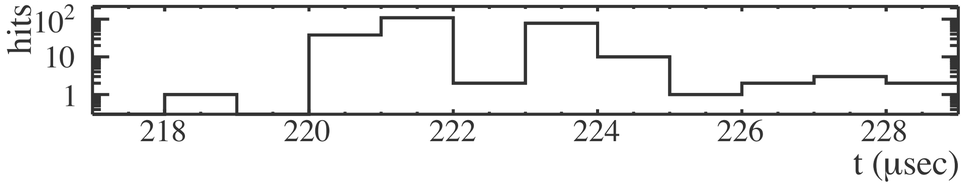


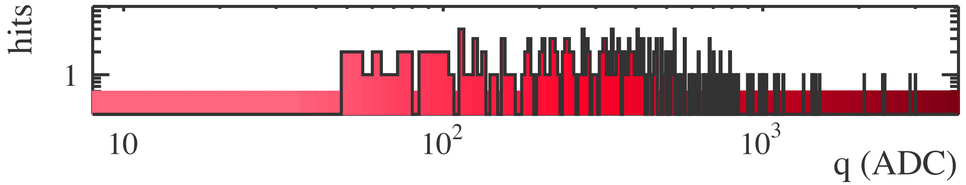
NOvA - FNAL E929

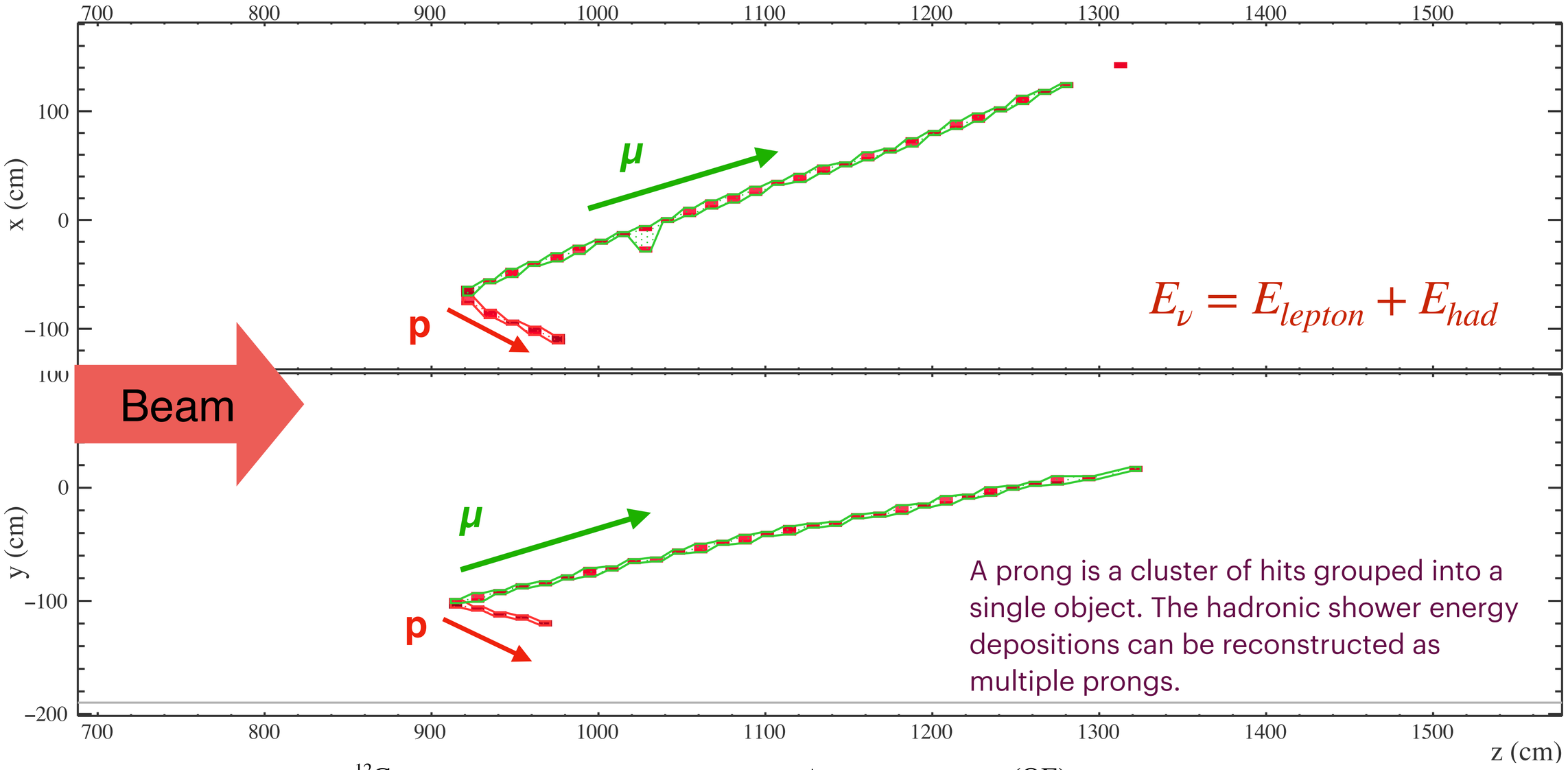
Run: 10743 / 7
Event: 880 / --

UTC Mon Feb 9, 2015
06:54:56.590908992

ν_μ [2.0GeV/c] + $^{12}C \rightarrow \mu$ [1.3GeV/c] + p [1.0GeV/c] + p [0.5GeV/c] + π^+ [0.1GeV/c] + n [0.1GeV/c] (QE)







$$E_\nu = E_{lepton} + E_{had}$$

A prong is a cluster of hits grouped into a single object. The hadronic shower energy depositions can be reconstructed as multiple prongs.

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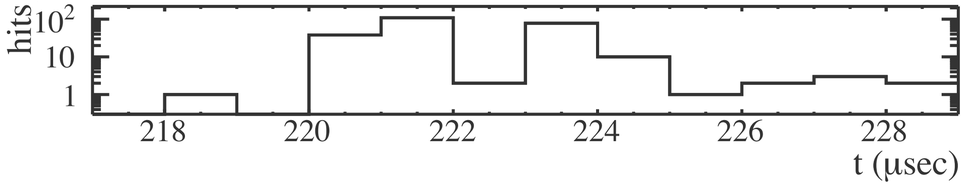
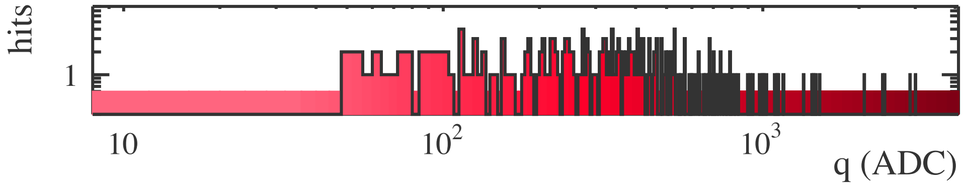
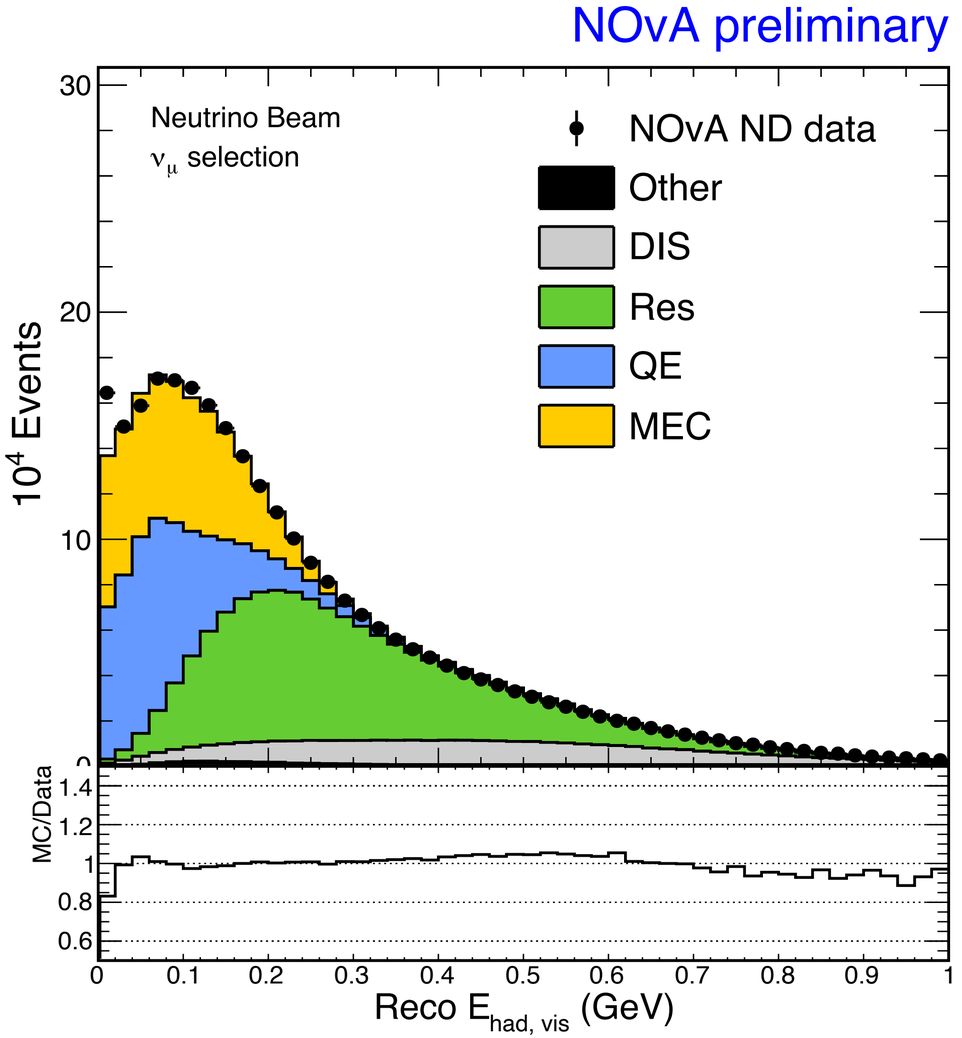




Obtaining more information from Near Detector data

- The ND neutrino and antineutrino selection is a high statistics dataset that is rich in information potentially useful to further constrain model uncertainties prior to the oscillation analysis .
- The muon neutrino/antineutrino selection in NOvA contains a variety of interaction types and final states that can probe different aspects of the simulation.



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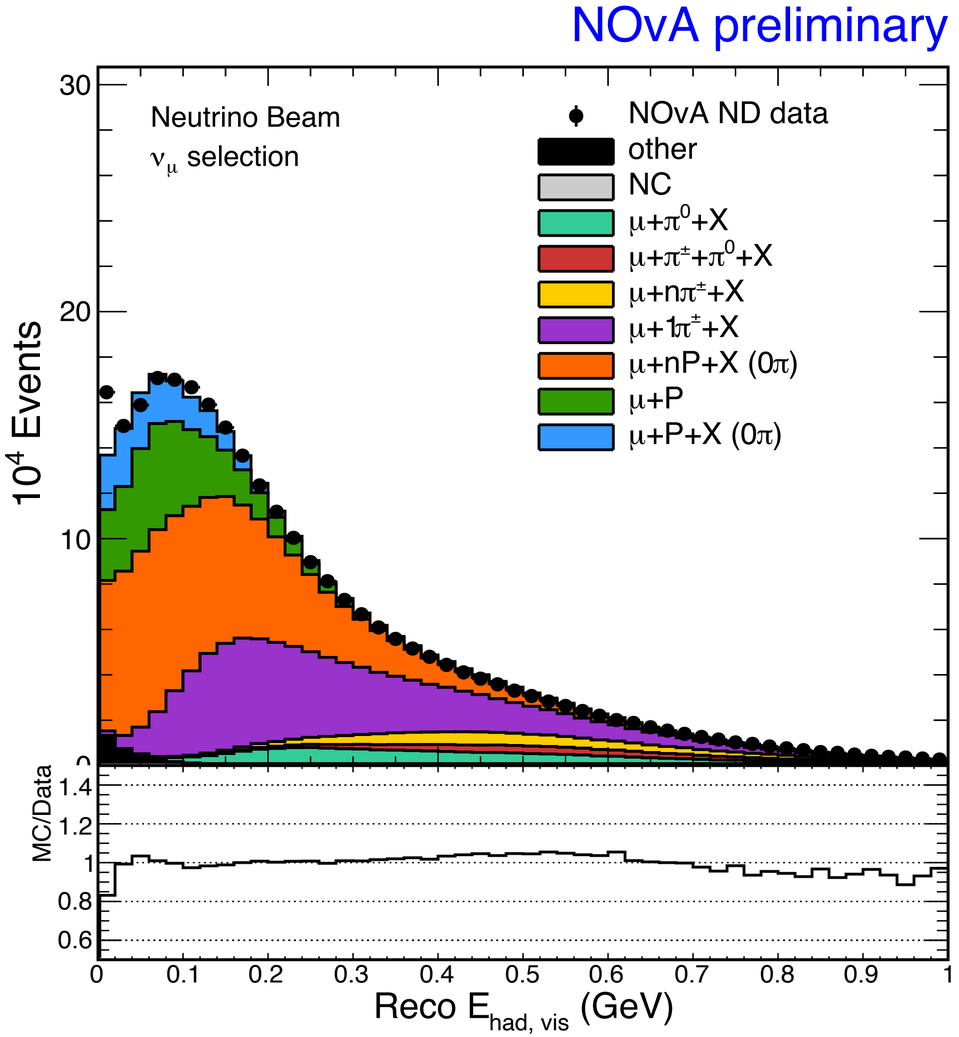
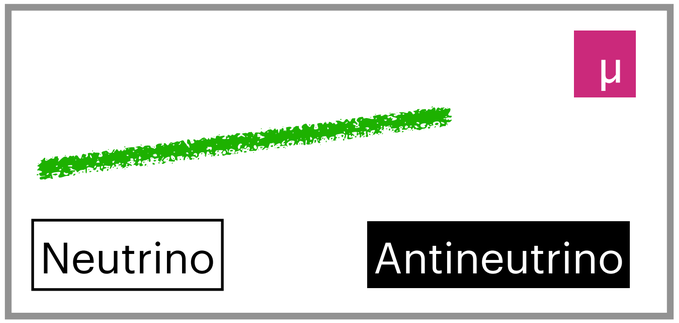
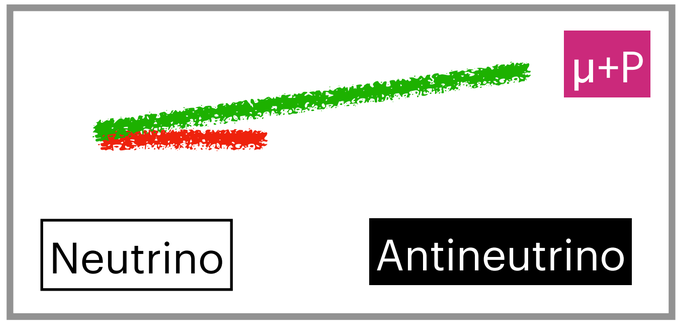
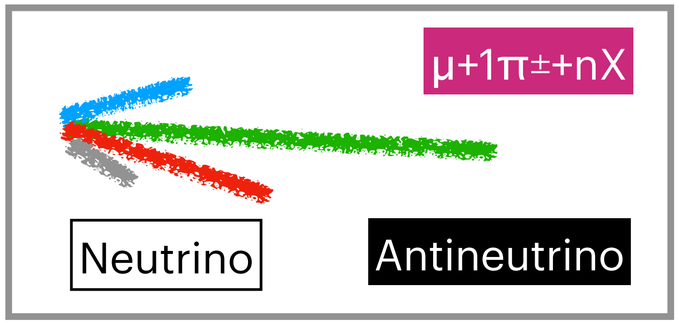


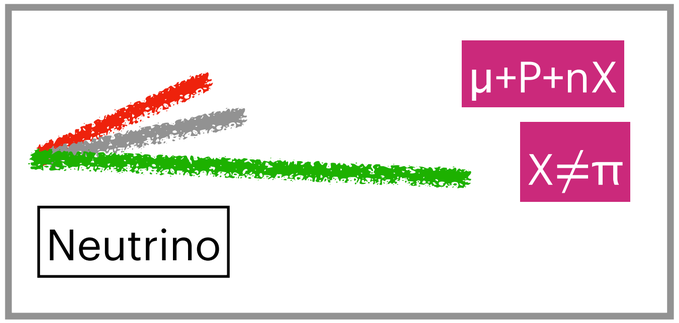
Subdividing the ND dataset

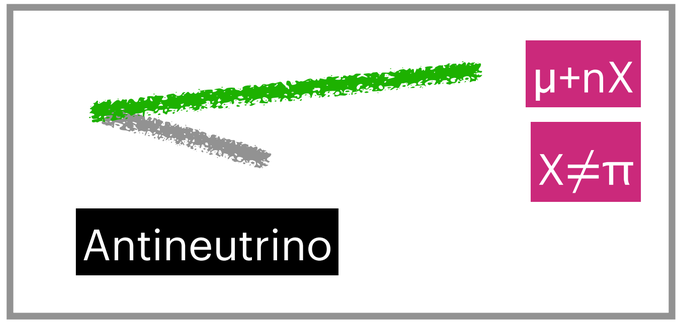
- We have developed 10 non-overlapping samples (5 for neutrino and 5 for antineutrino), defined by the number and type of prongs visible in the detector.
- The prongs are classified according to a convolutional neutral network as **muons**, **protons**, **charged pions** or **other.**



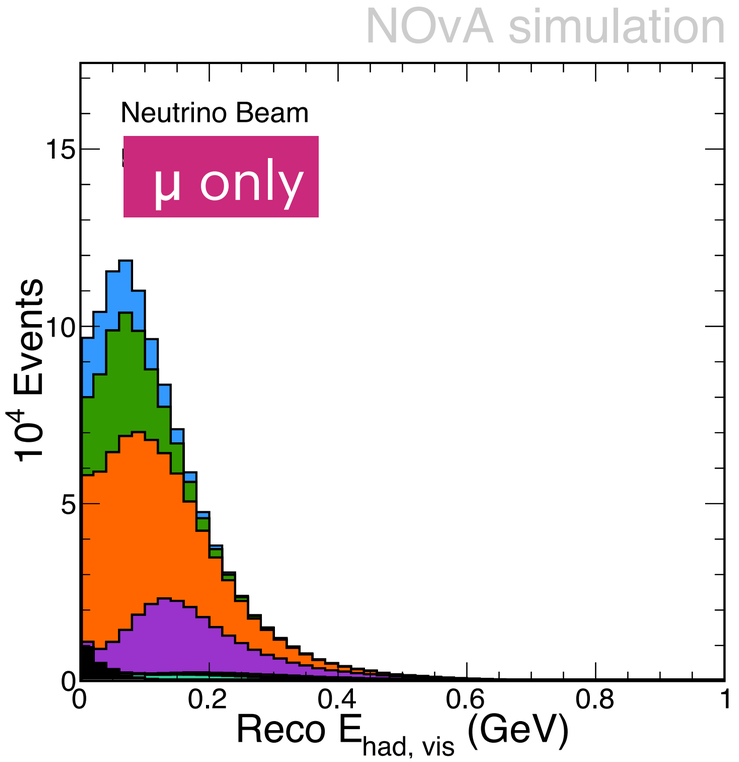


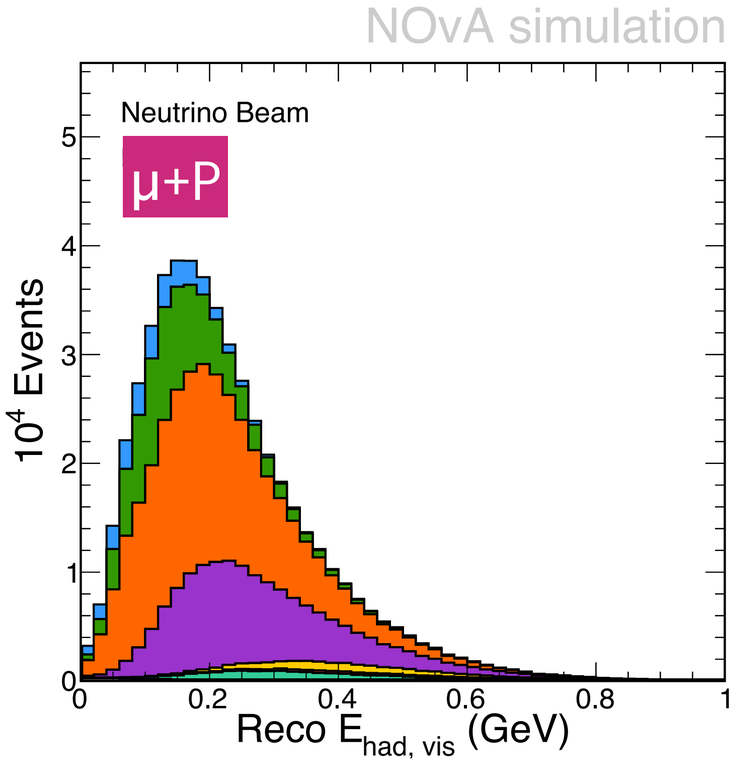


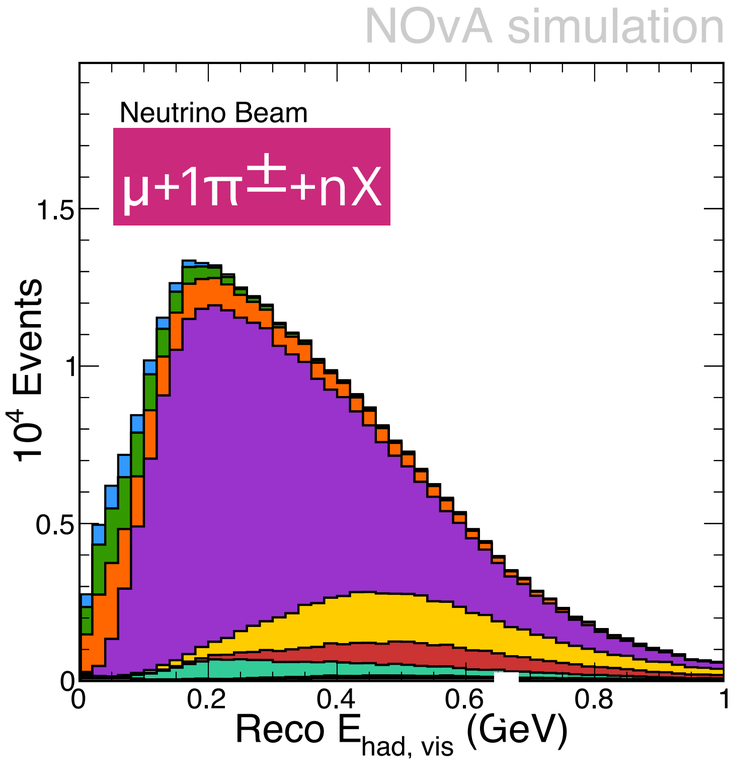




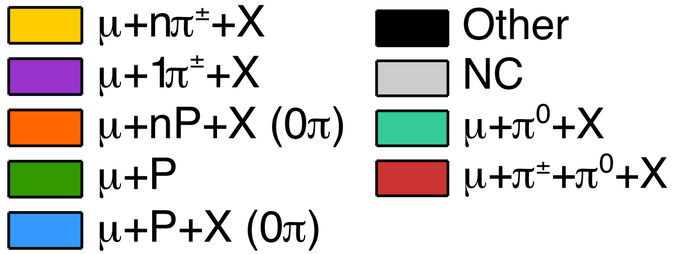
True final states in ND data







- The samples are effective at separating different amounts of final states.
- **μ** and **μ+P** samples contain mostly interactions without pions.
  - Also dominated by Quasi-Elastic and Meson Exchange Current interactions.
- **μ+π+X** sample has a high purity of interactions with one charged pion.



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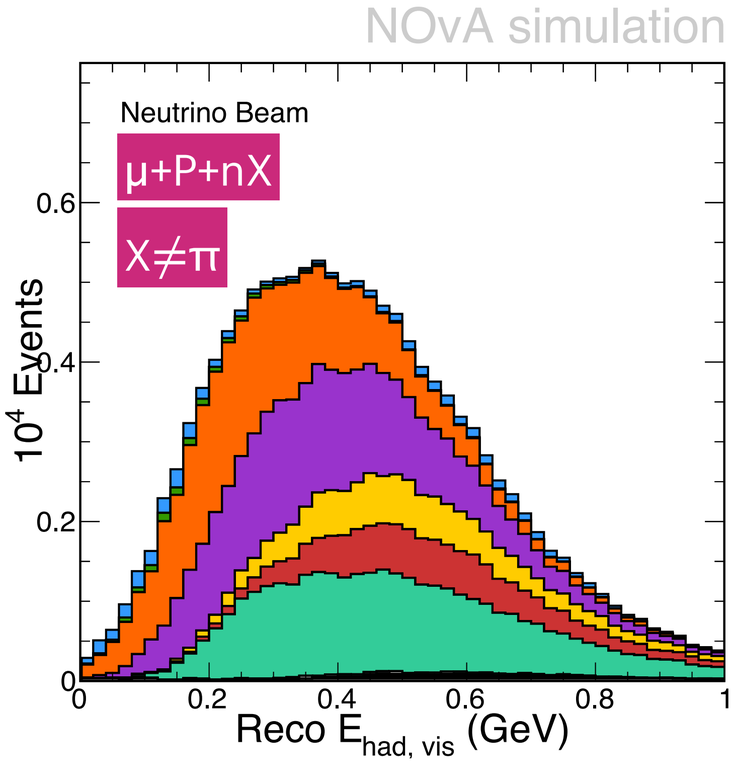
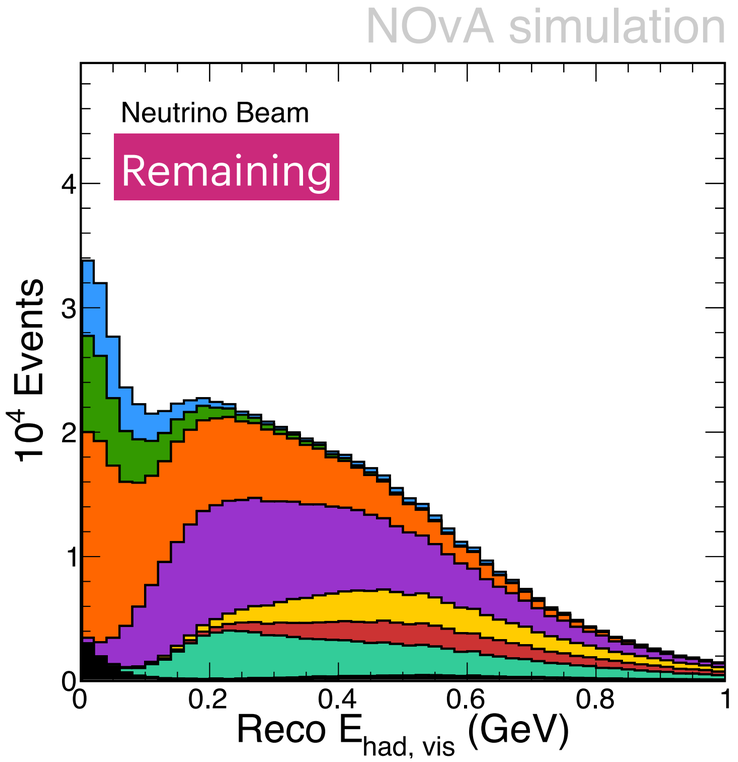
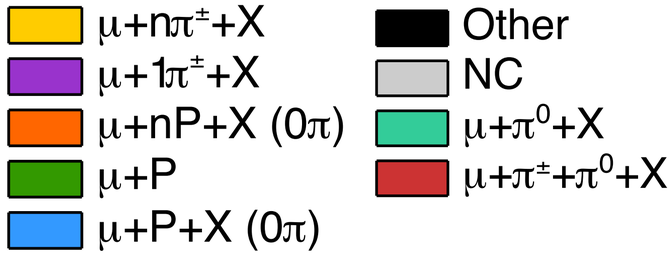




- **μ+P+X** contains a large fraction of interactions with multiple pions.
- The remaining sample contains a mixture of all the categories.
- These are also dominated by Resonance and Deep-Inelastic Scattering interactions.

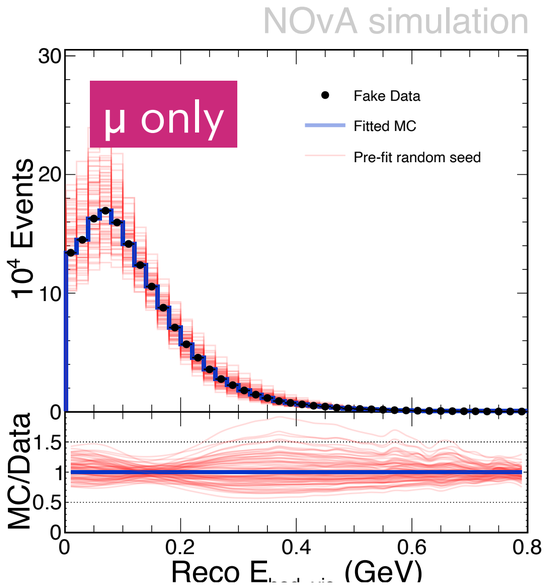


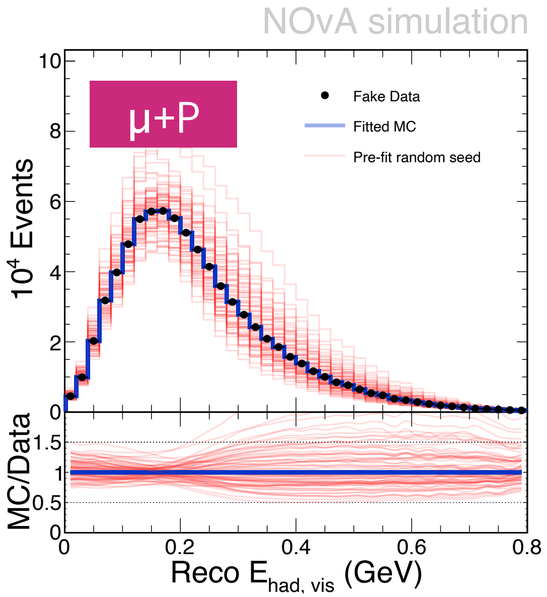
Using the samples to constrain uncertainties

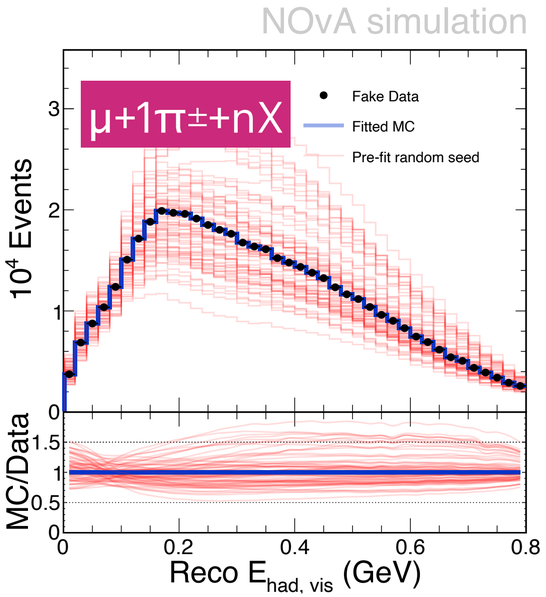
- The first step towards using this samples to constrain uncertainties is to prototype a fit using fake data.
  - The fit minimizes the χ^2 between the fake data and the simulation in the space of reconstructed three-momentum transfer and visible hadronic energy ($|q|$,E_{had}) for the 10 samples simultaneously.
  - The fake data is generated from the simulation applying with random shift values to each systematic uncertainty.
  - The fit presented here uses systematic uncertainties related to Resonance, Quasi-elastic and Final State Interactions.

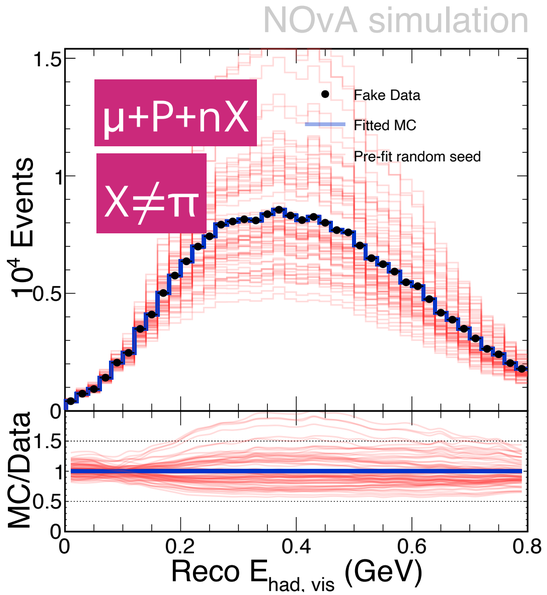
Fake data fit result

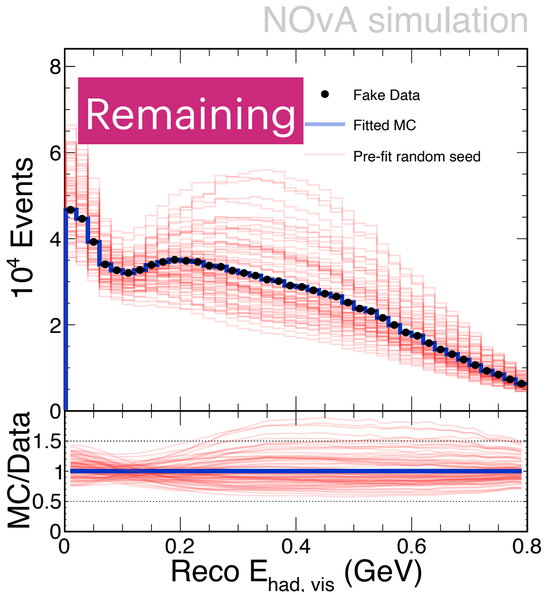
Neutrino







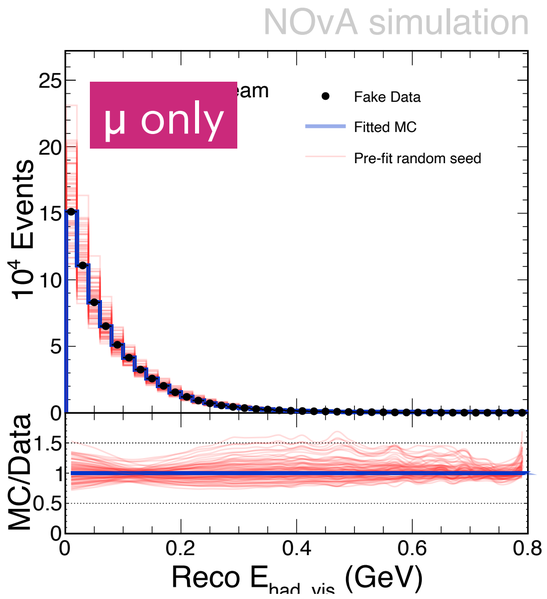


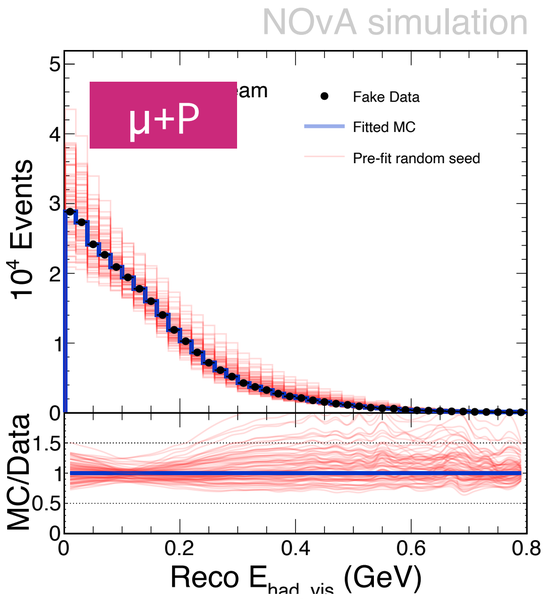


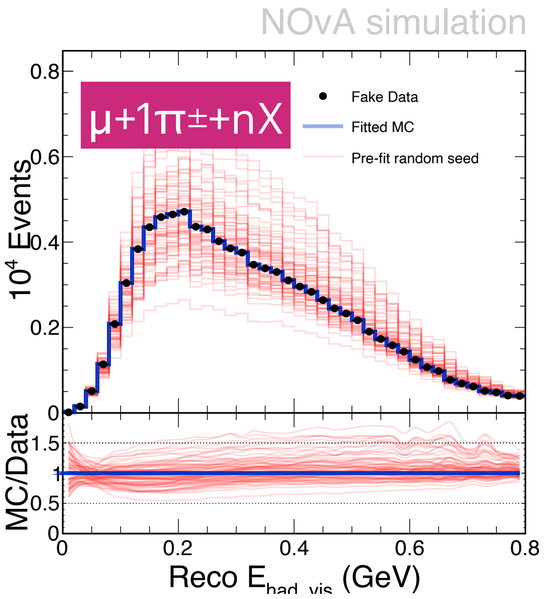
- The fit is performed multiple (150) times with a different seed.
- Each fit result agrees with the fake data across all the samples.

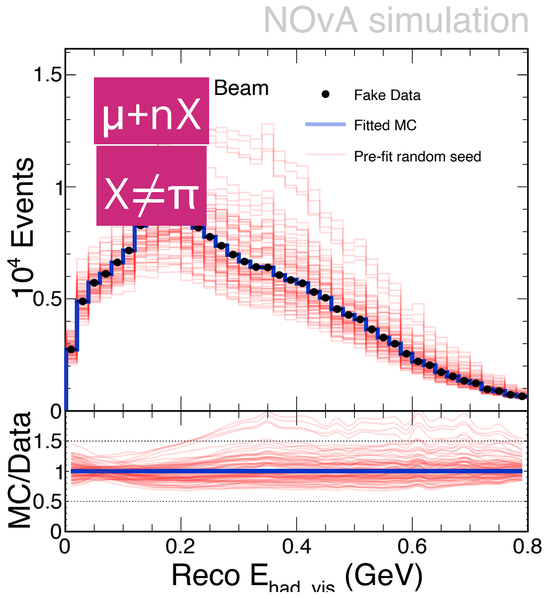
Fake data fit result

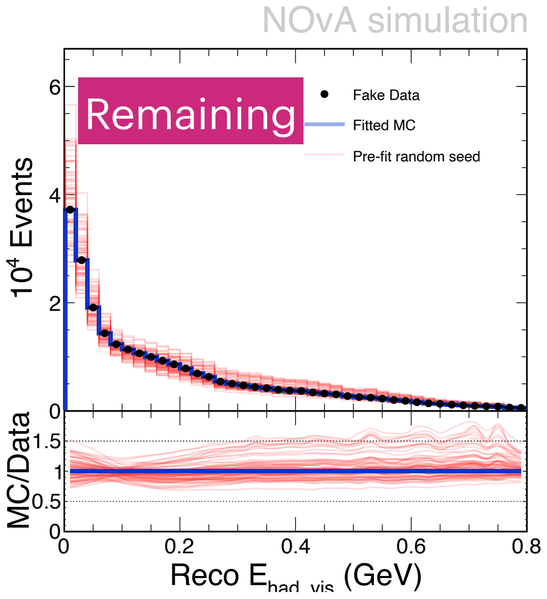
Antineutrino











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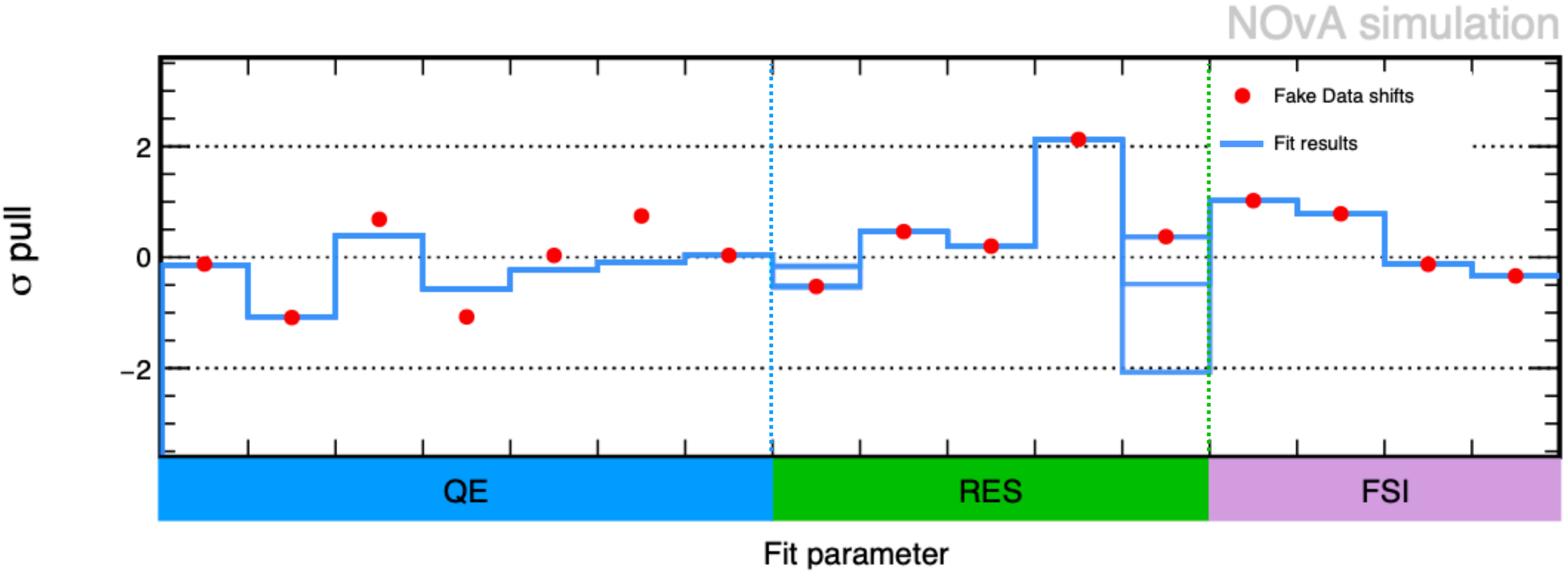
- Each fit result agrees with the fake data across all the samples.

ND fake data fit result



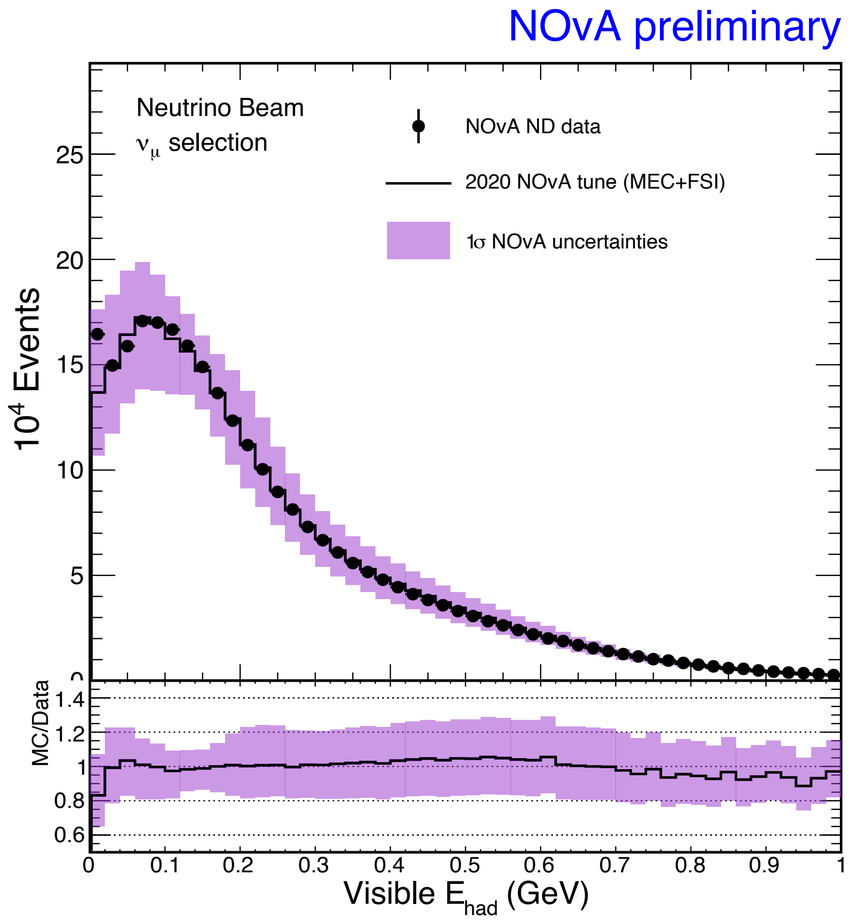
- A set of the parameters are well constrained.
- The fitted samples agree with the fake data even with a subset of the fit parameters not matching the exact shift value in the fake data.
- This results allows us to understand that the samples are sensitive to some of the interaction model parameters.
- We are working toward developing additional samples or kinematic space to better constrain some of these parameters.

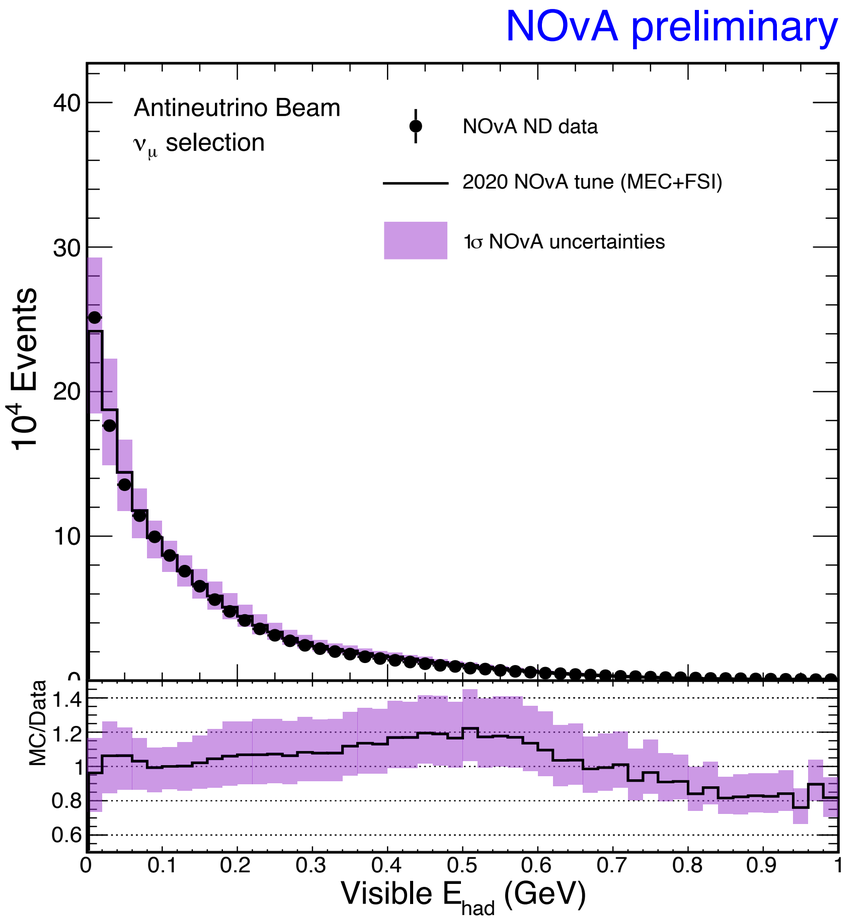
Summary

- The neutrino/antineutrino selection in the NOvA ND can be subdivided into samples of different topology that contain different characteristics.
- These have been useful to prototype a near detector fit capable of constraining a subset of the neutrino interaction model uncertainties.
- Additional systematic uncertainties for the samples are in progress.
- This work could be used in the oscillation analysis.

Backup

ND muon neutrino/antineutrino selection

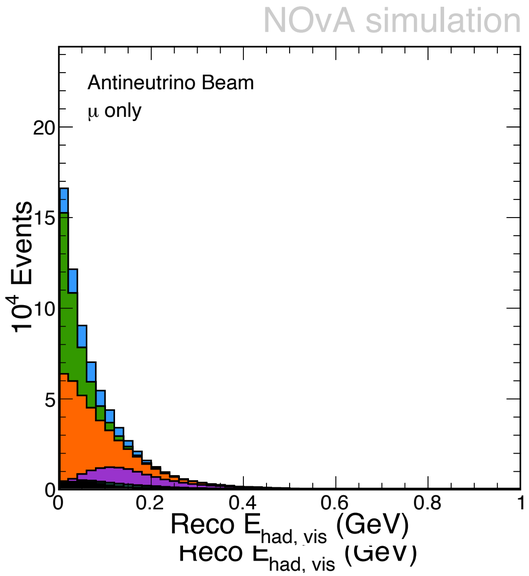


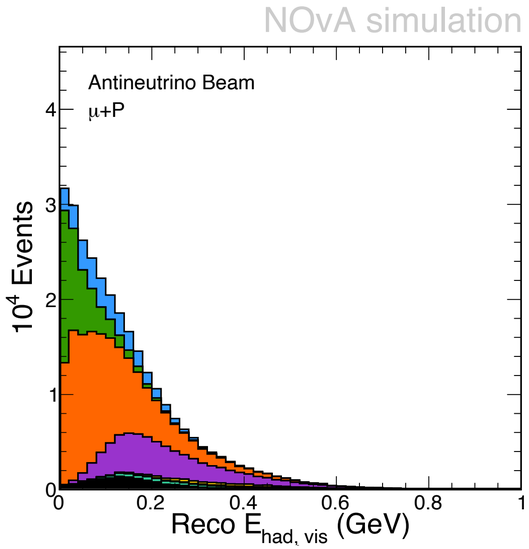


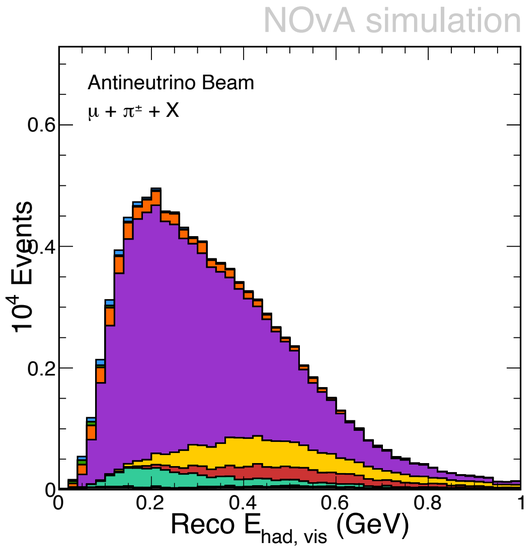
- The current oscillation analysis uses a set of uncertainties that account for the overall differences in the Near Detector charged muon neutrino/antineutrino datasets.

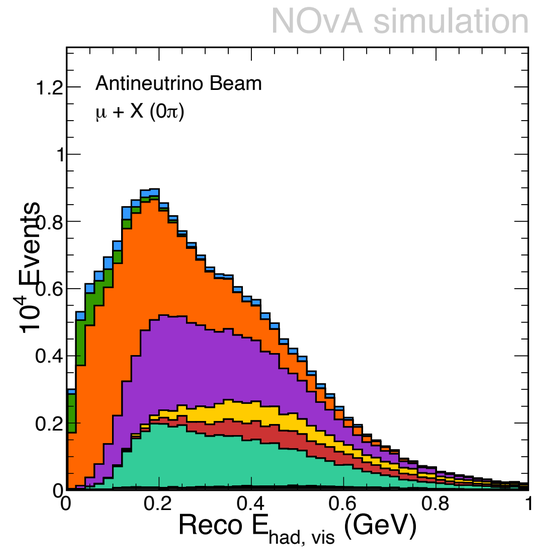
True final states in ND data - antineutrinos

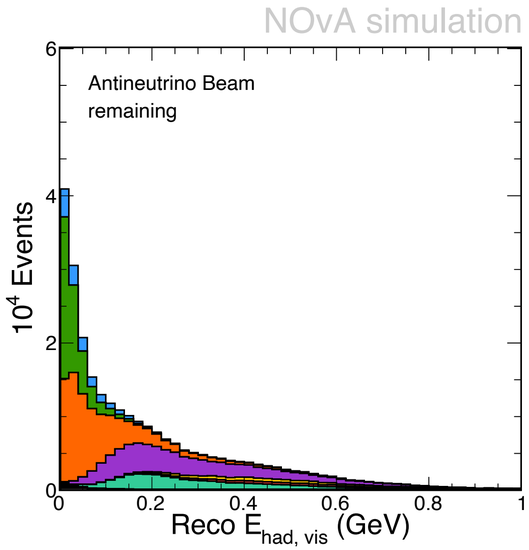
- The samples are effective at separating different amounts of final states.
- **μ+π+X** sample has a high purity of interactions with one charged pion.
- **μ+P+X** contains a large fraction of interactions with multiple pions.
- The rest of the samples contain a mixture of all the categories.

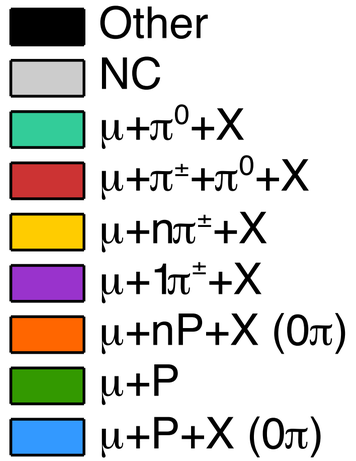






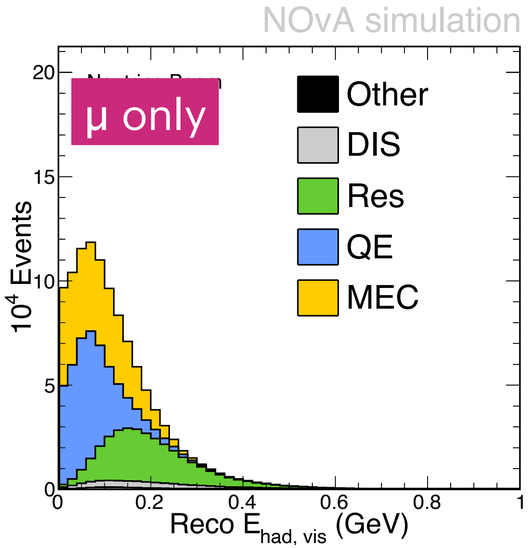


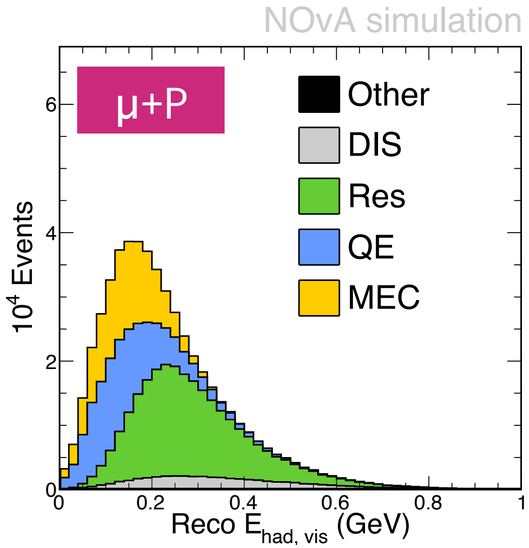


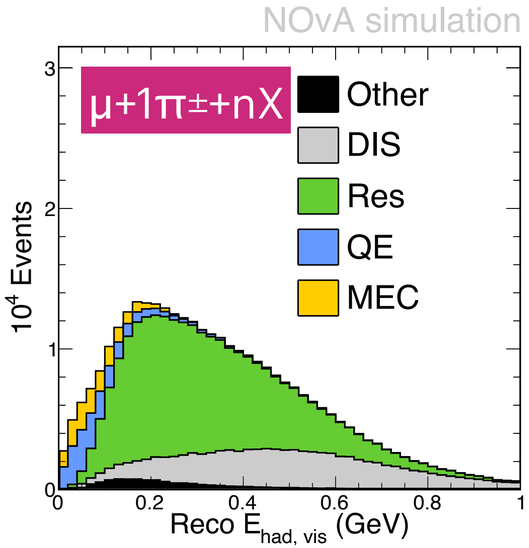


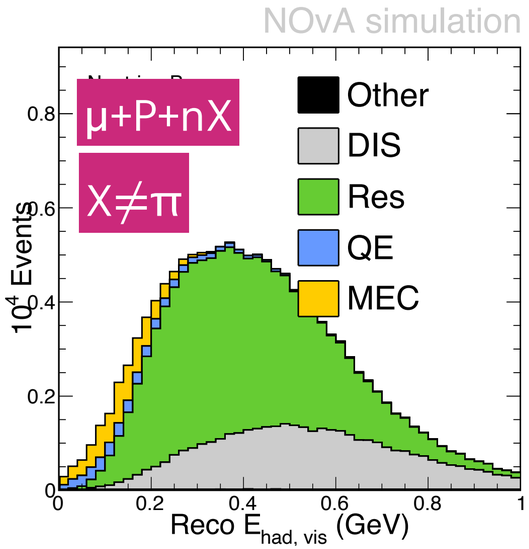
Interaction type in ND data

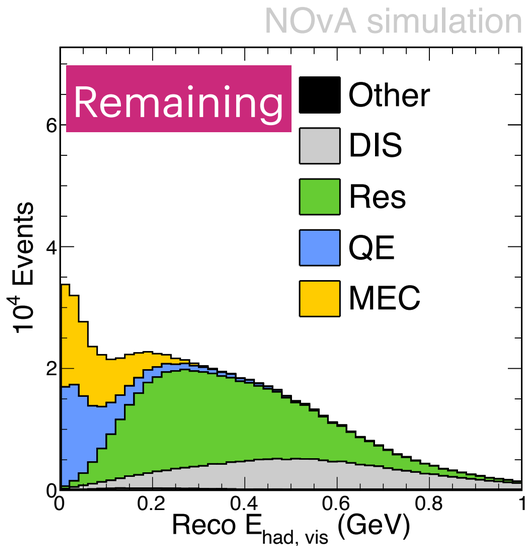
- **μ** and **μ+P** sample contain most of the QE/MEC interactions.
  μ+π+X and **μ+P+X** are dominated by resonance and deep inelastic scattering.











Interaction type in ND data - antineutrino

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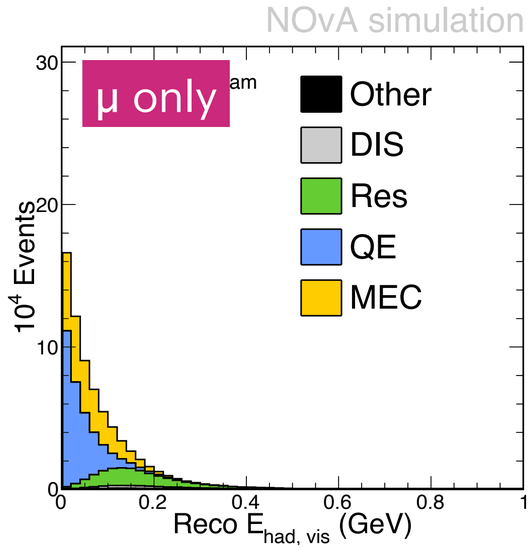
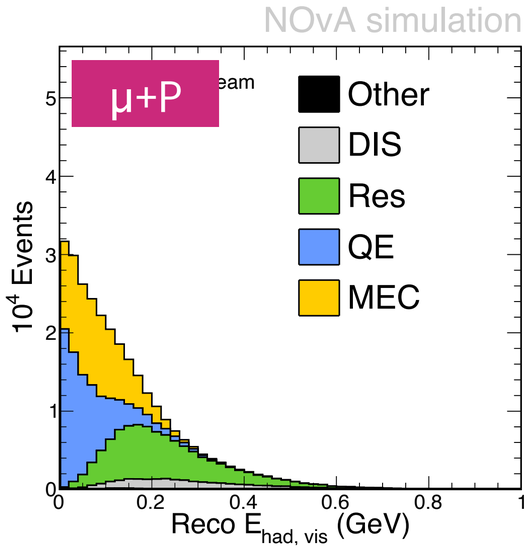
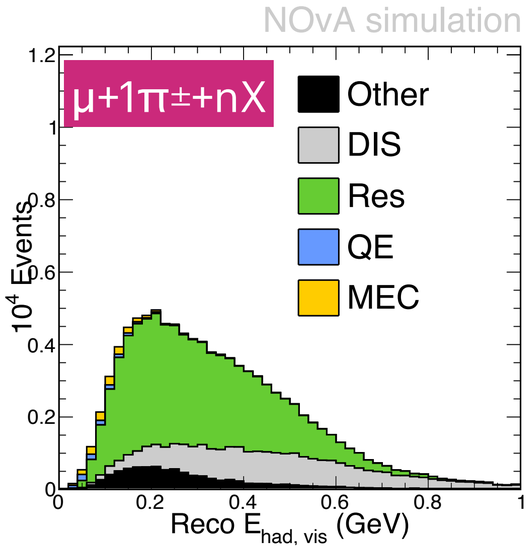
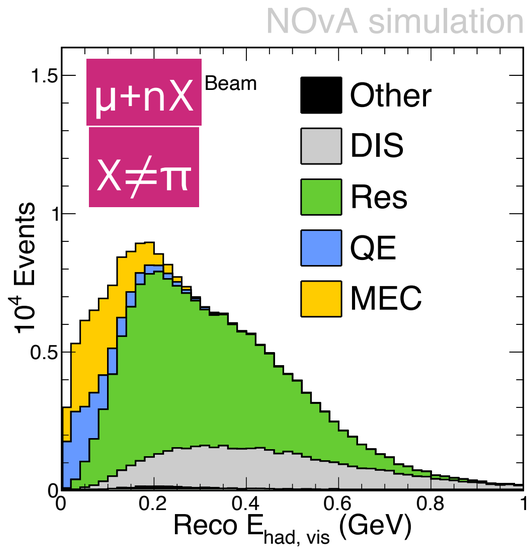
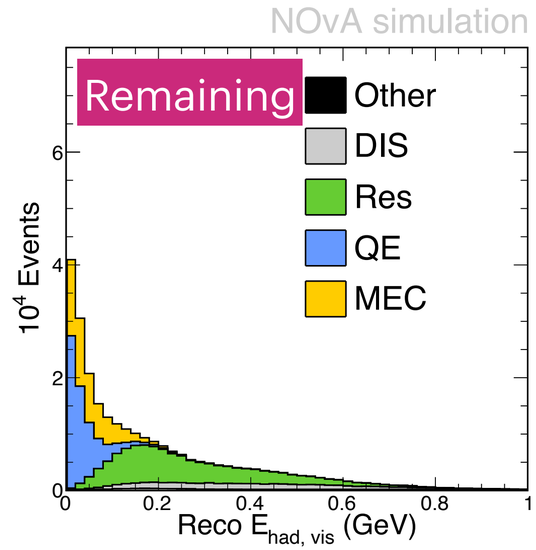


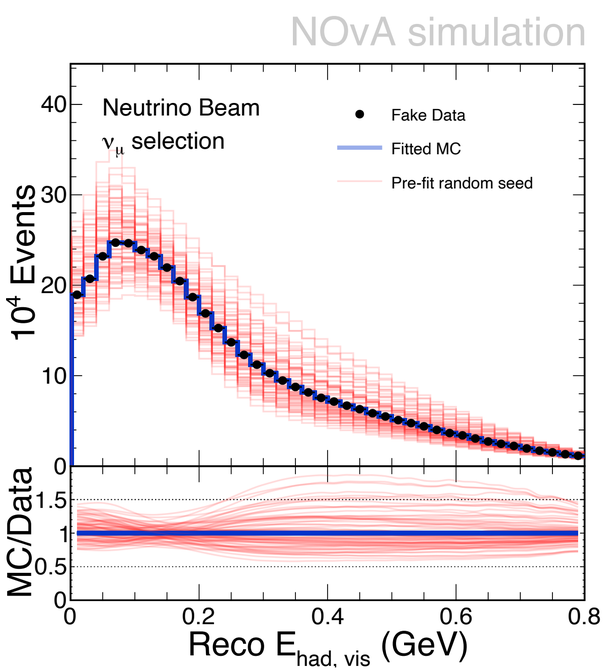


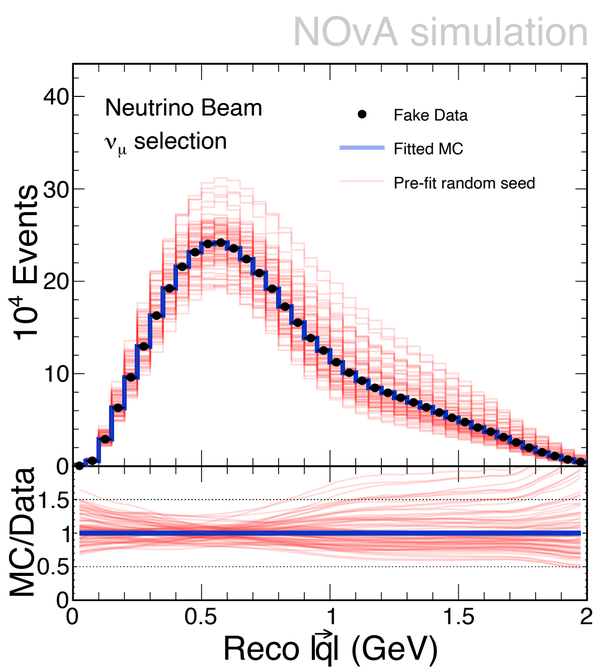




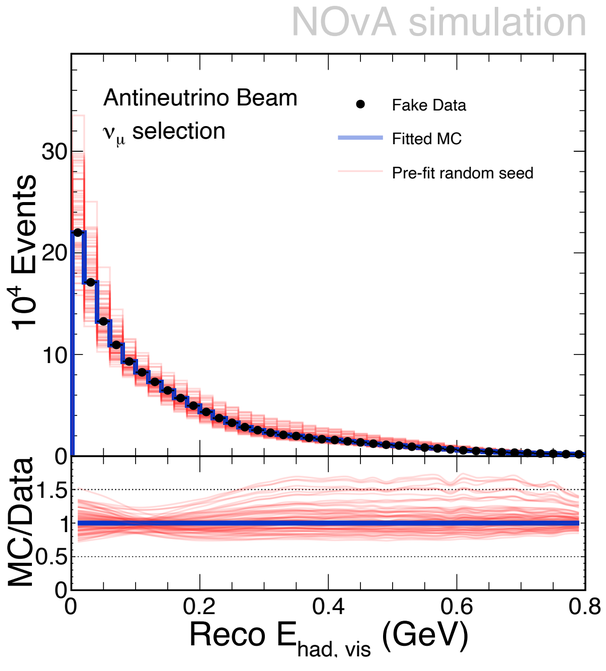


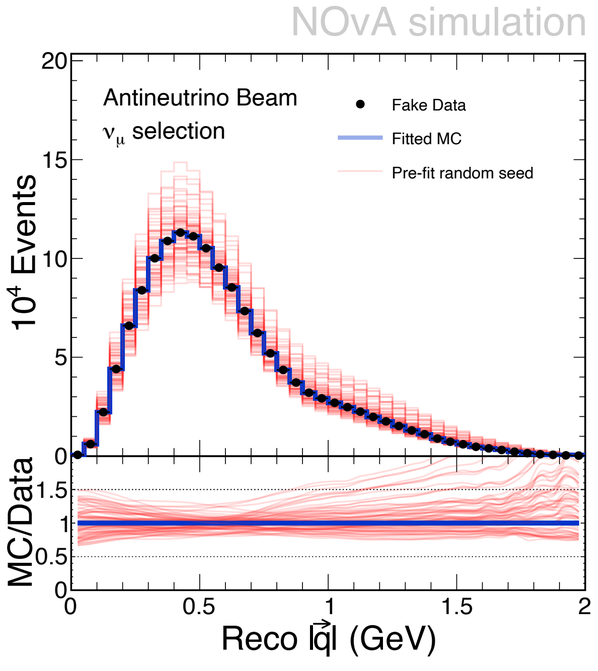
ND fake data fit result





Neutrinos





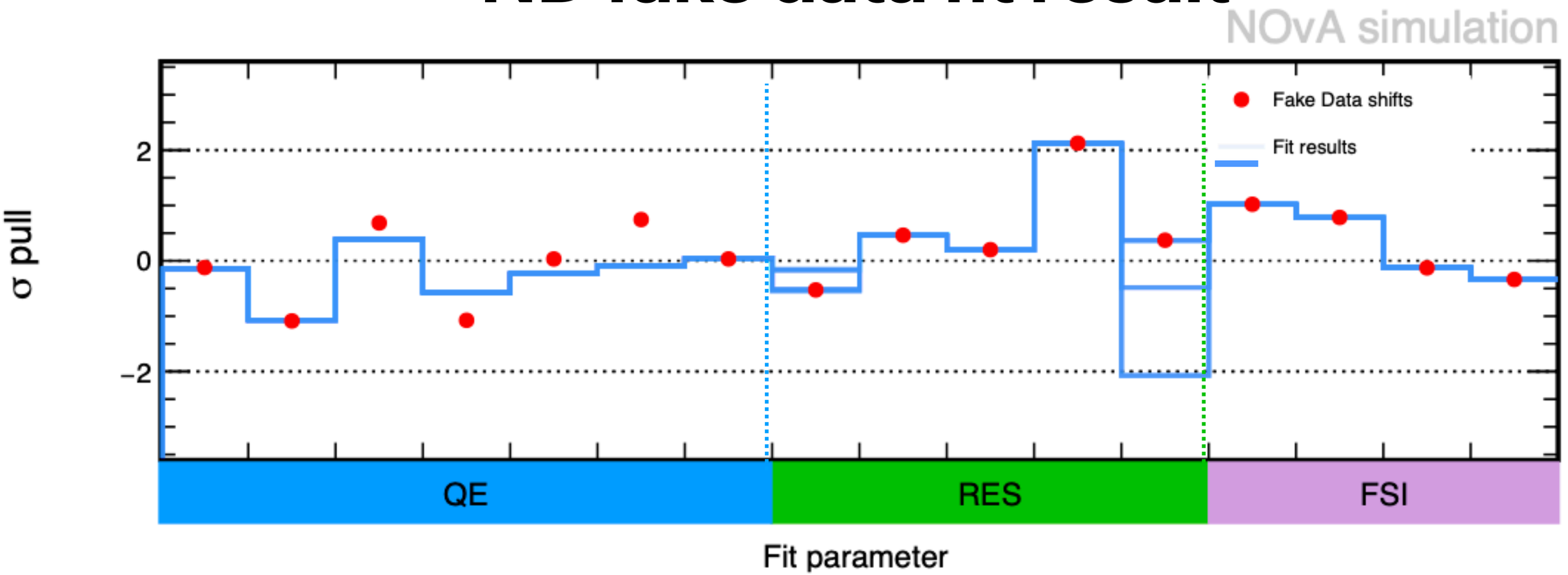
Antineutrino

- The fit is performed multiple (150) times with a different seed.
- Each fit result agrees with the fake data in the inclusive neutrino and antineutrino selections.

GENIE base model

- The current analysis uses GENIE 3, with the Comprehensive Model Configuration N1810j0211a:
  - Quasi-Elastic (QE) interactions are described by local Fermi Gas nuclear model and Z-expansion systematic uncertainties.
  - Berger-Sehgal Resonance Production (RES) model tuned to data.
  - Bodek-Yang Deep-Inelastic Scattering (DIS) model tuned to data.
  - Meson Exchange Currents (MEC) described by Valencia model for CC 2p2h and empirical MEC for neutral current (NC) interactions, with adjusted central value and custom systematic uncertainties.
  - Final State Interactions (FSI) described by the hN model with central value adjustments.

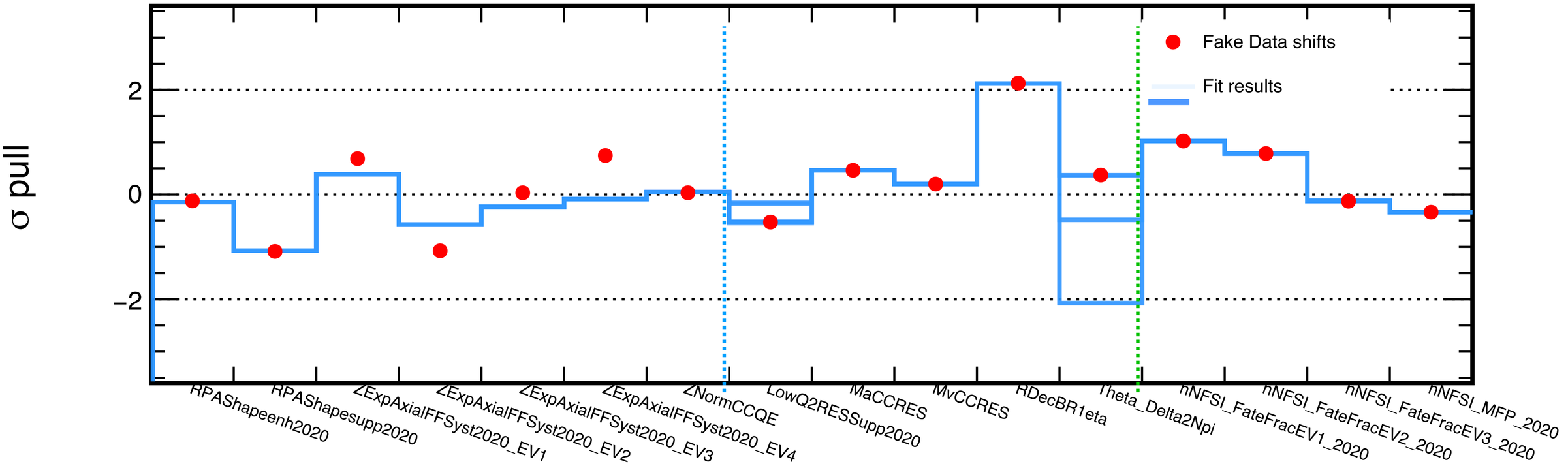
ND fake data fit result



QE	RES	FSI
RPA Shape Enhancement	Low Q^2 Suppression	Fate fractions 1,2,3
RPA Shape Suppression	Ma Resonance	Mean Free Path
Z Expansion 1-4 Eigen Values	Mv Resonance	
CCQE normalization	R Decay Br Eta	

ND fake data fit result

NOvA simulation



QE	RES	FSI
RPA Shape Enhancement	Low Q^2 Suppression	Fate fractions 1,2,3
RPA Shape Suppression	Ma Resonance	Mean Free Path
Z Expansion 1-4 Eigen Values	Mv Resonance	
CCQE normalization	R Decay Br Eta	