Impact of cross-section modeling on the NOvA oscillation analyses

NuFact 2021 – Cagliari, Italy

Gregory Pawloski
University of Minnesota

Understanding how cross sections impact NOvA

What features of the neutrino interaction does the detector measure?

What models do we use to estimate those features?

How sensitive is the 3-flavor oscillation analyses to those features?

What is NOvA

Long-baseline neutrino experiment

E ≈ 2 GeV (off-axis narrow band beam)

L = 810 km

Oscillations governed by Δm^2_{32} (Δm^2_{31})

NuMI beam produced at Fermilab

ν_μ and $\bar{\nu}_\mu$ beam modes

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ oscillations

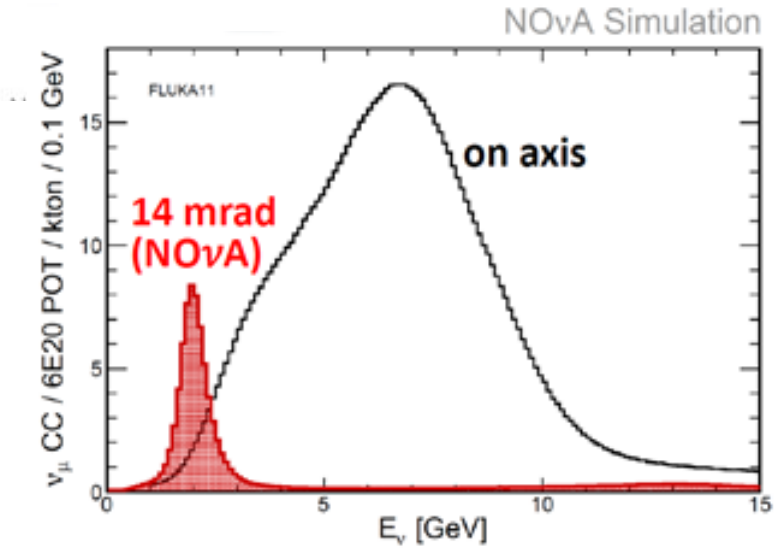
Two detector experiment

Near detector (Fermilab, IL)

Measure beam before oscillation

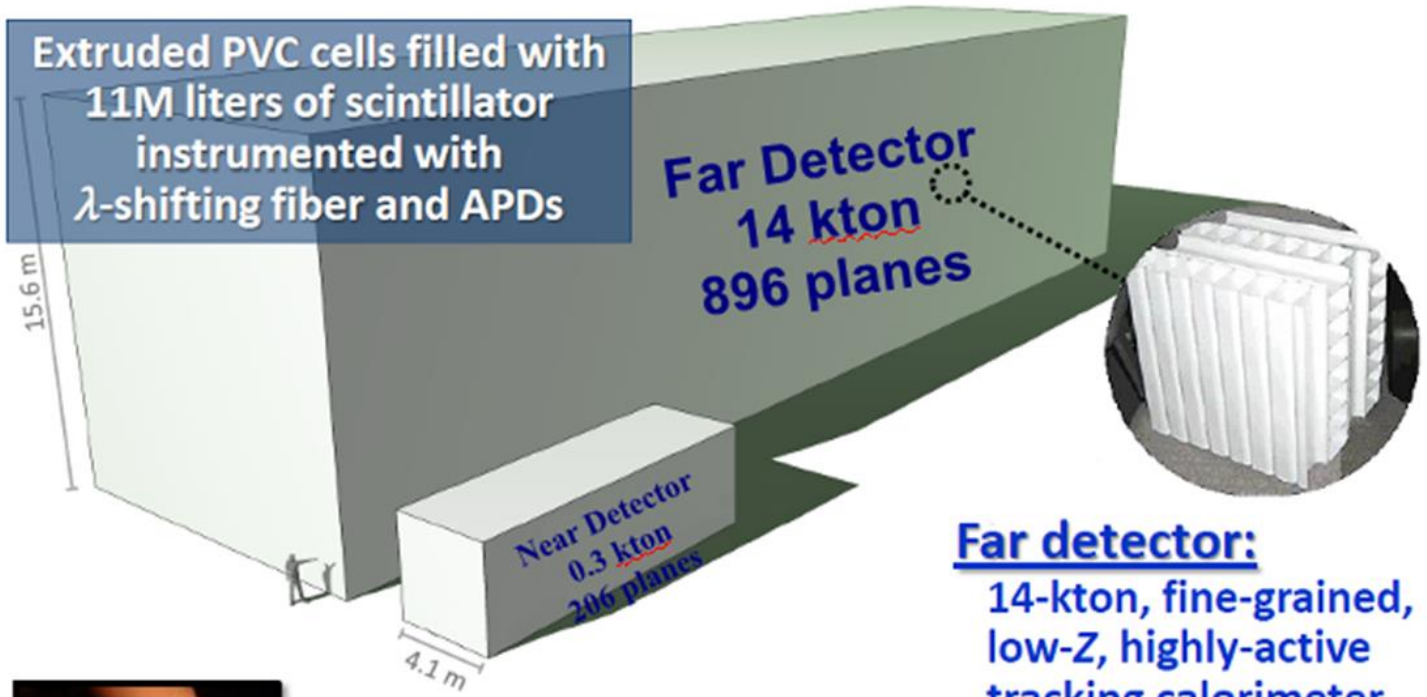
Far Detector (Ash River, MN)

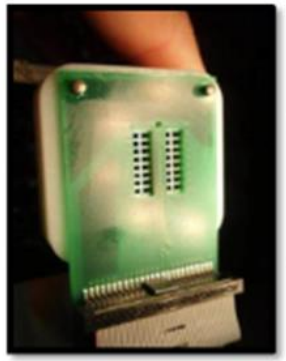
Measure oscillated beam



The NOvA Detectors

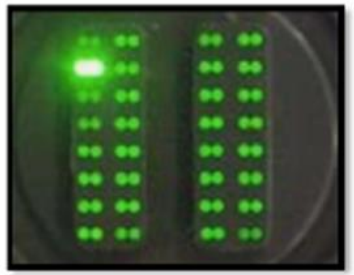
Giant hydrocarbon nuclear targets with 16% Cl





32-pixel APD

Fiber pairs
from 32 cells



Far detector:

14-kton, fine-grained, low-Z, highly-active tracking calorimeter

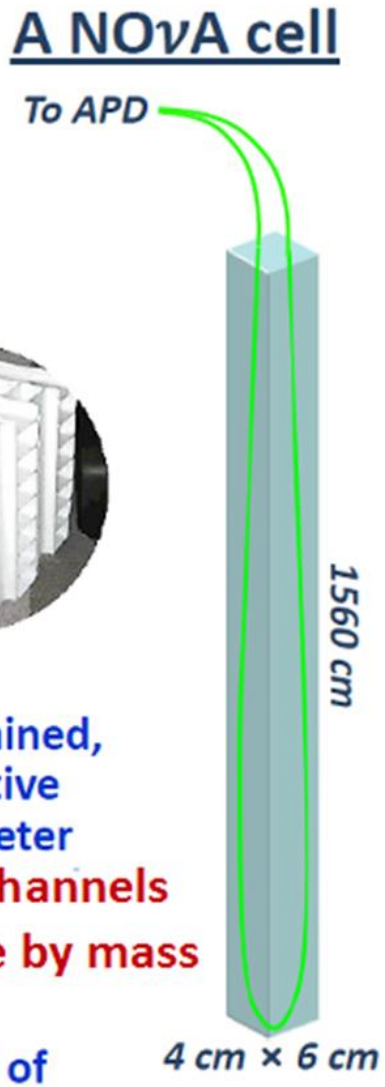
340, 000 channels

77% active by mass

Near detector:

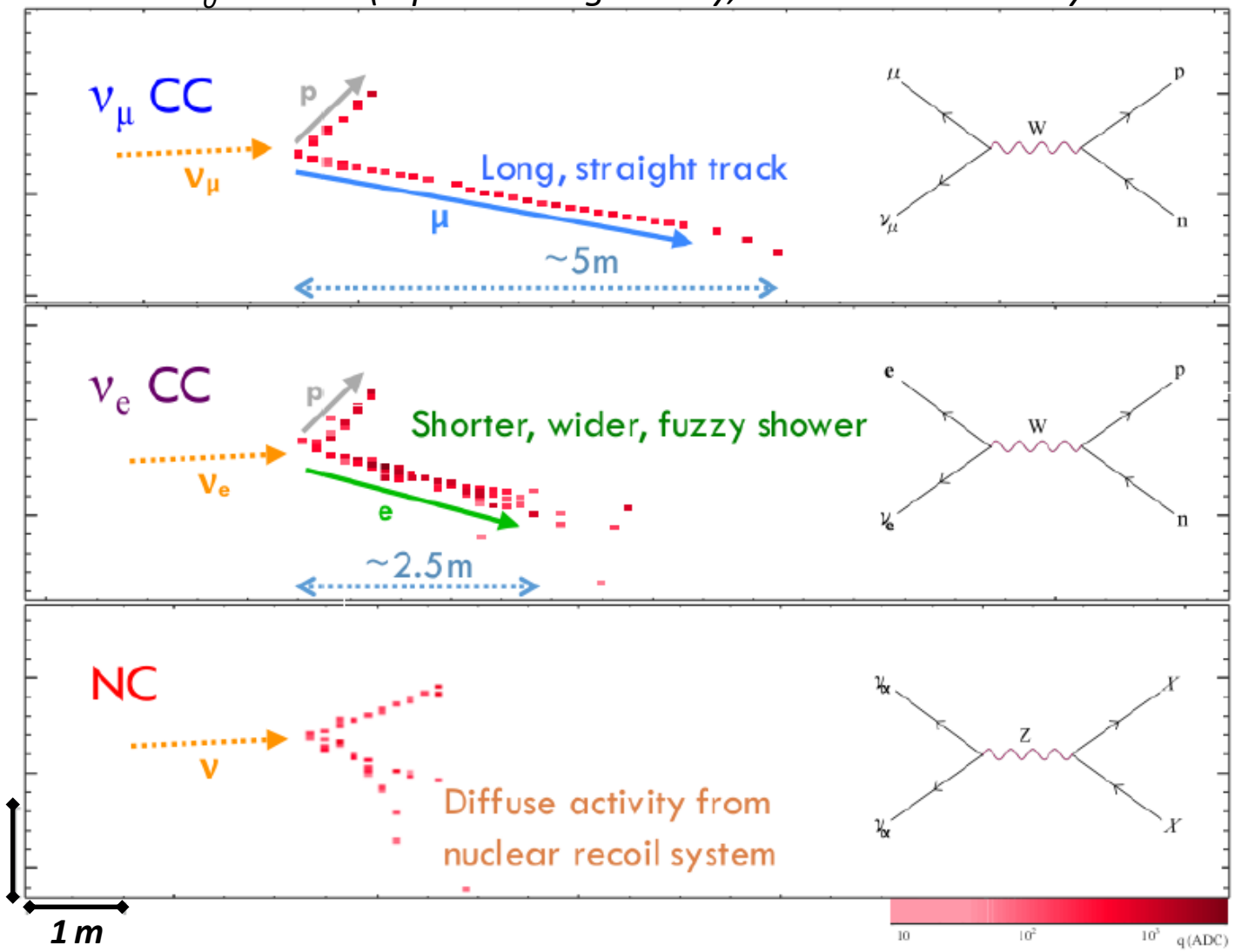
0.3-kton version of the same

18, 000 channels



NOvA Event Topologies

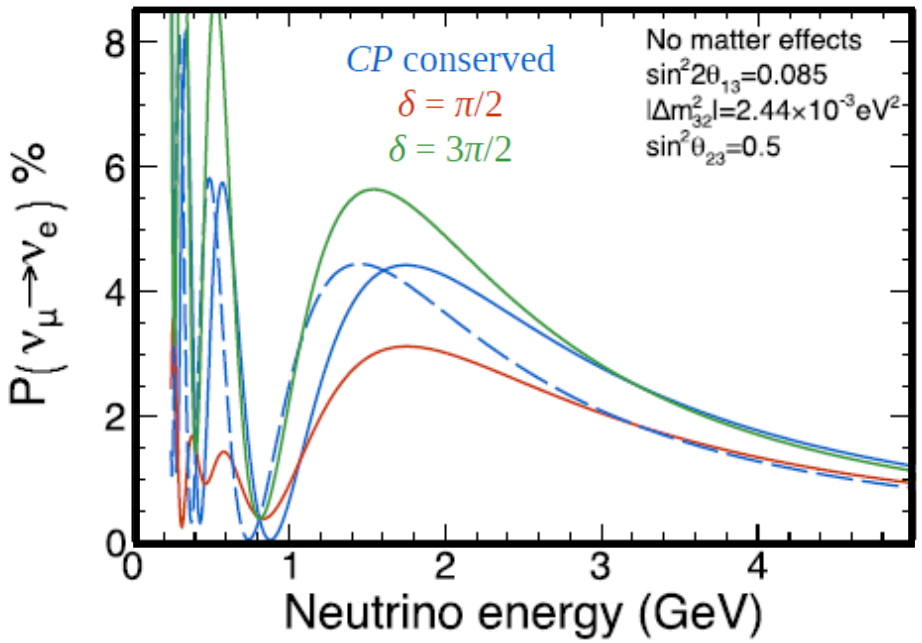
X_0 = 38 cm (6 planes longitudally, 10 cells transversely



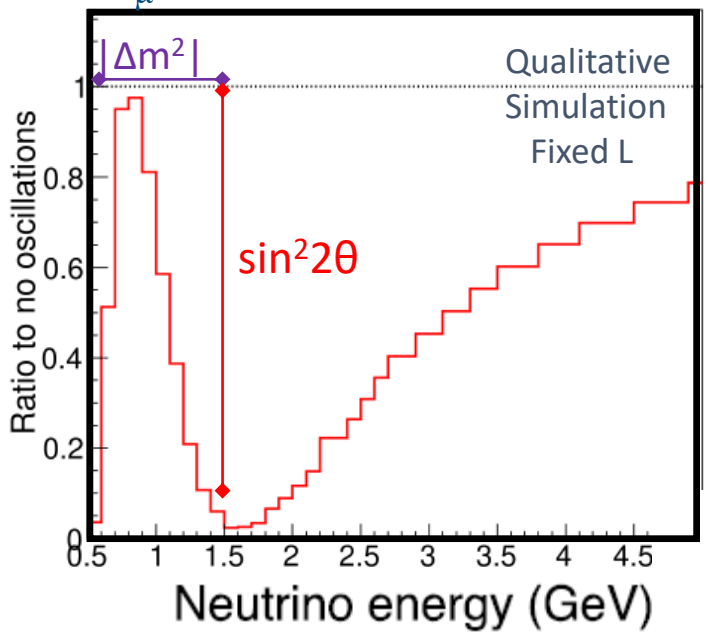
NOvA Oscillation Measurements

Sensitive to: δ_{CP}, θ_{23}, mass splitting (hierarchy /ordering)

ν_e Appearance Channel

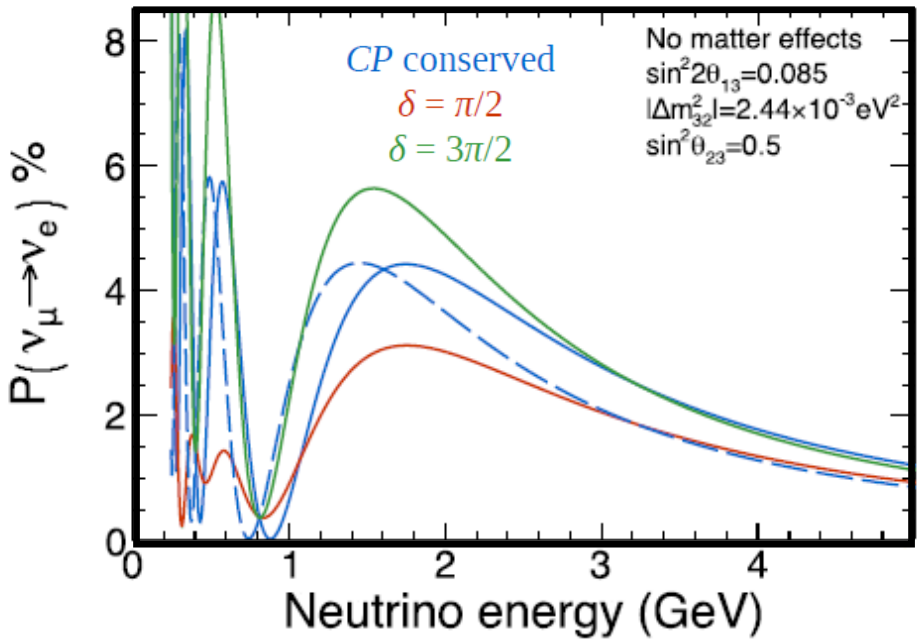


ν_μ Disappearance Channel

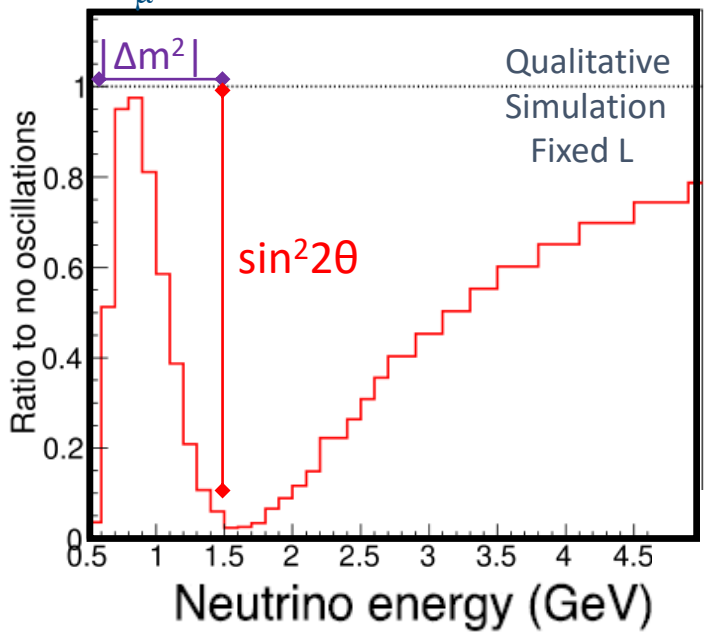


NOvA Oscillation Measurements

ν_e Appearance Channel



ν_μ Disappearance Channel

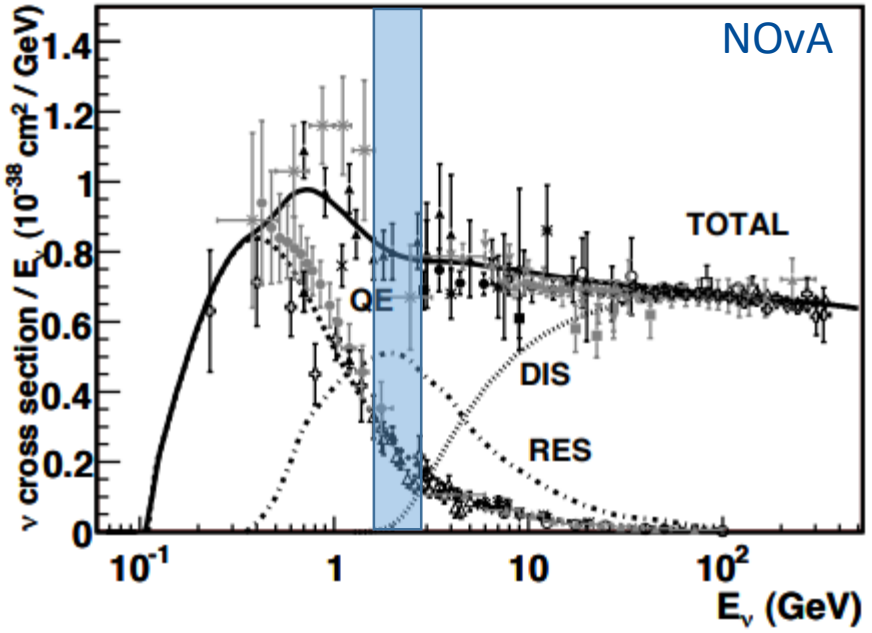


The key measurements for oscillation results

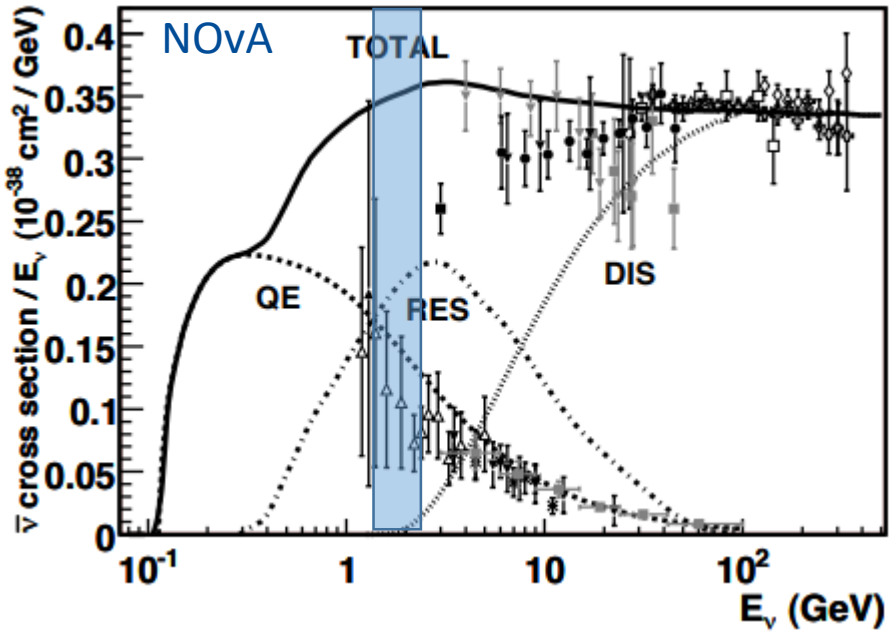
- Neutrino energy
- Event yields

What processes are relevant

Neutrinos



Antineutrinos

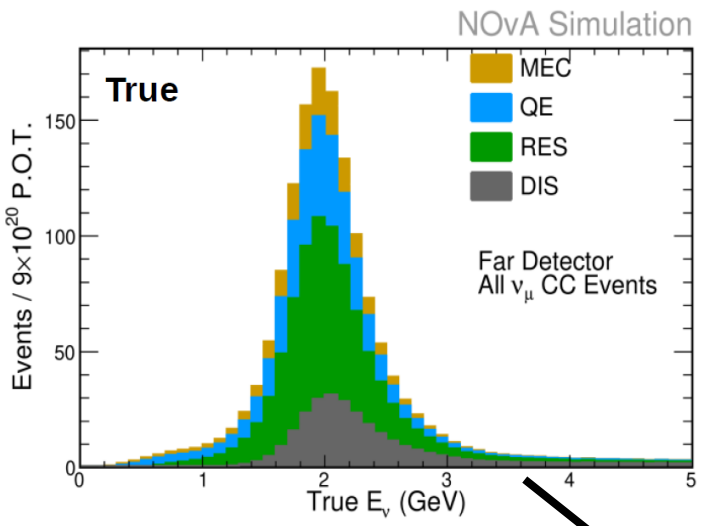


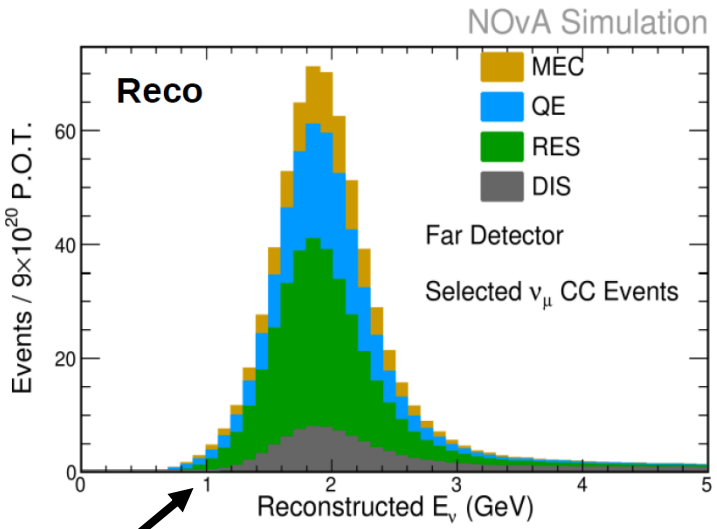
Rev. Mod. Phys. 84, 1307 (2012)

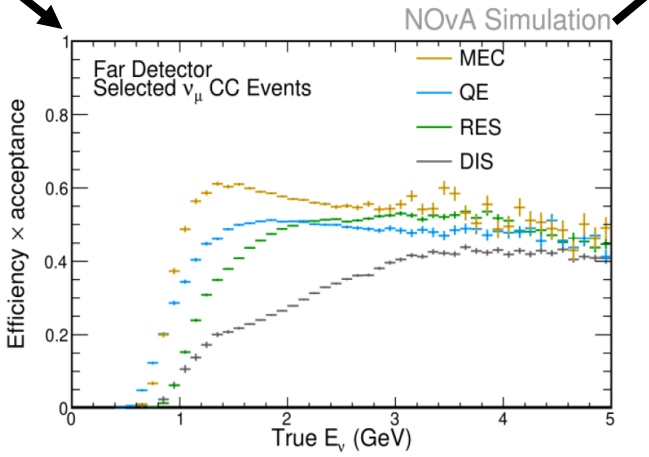
NOvA at an energy where resonant production is dominant

However the mix of QE, 2p2h, RES, and DIS is important and muddles things

Event Yields







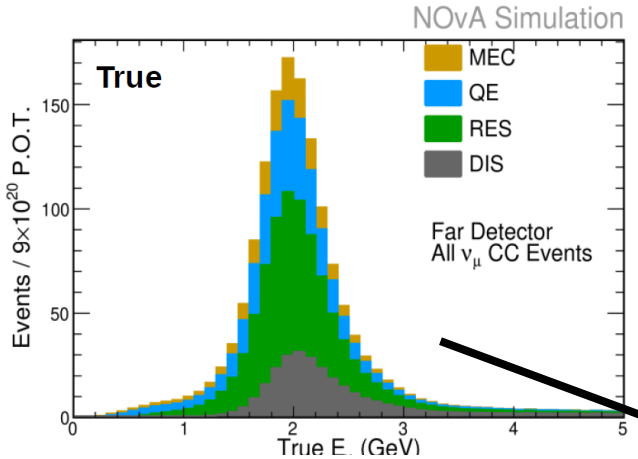
Different processes have different selection efficiencies

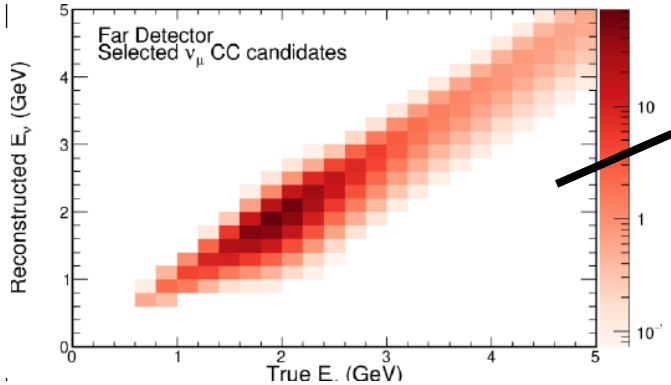
How much 4-momentum goes to the lepton, how much goes to the hadronic system

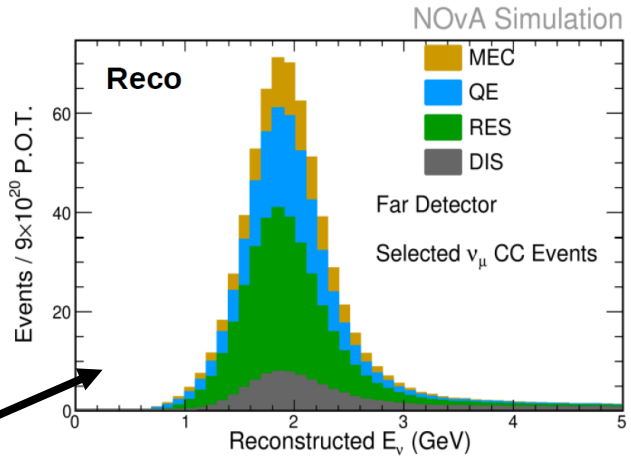
Ideally apply same selection in ND and FD, so they have same efficiencies, but the mix of processes is not exactly identical in both detectors

Flux is different (eg oscillation)
Containment is different

Neutrino Energy



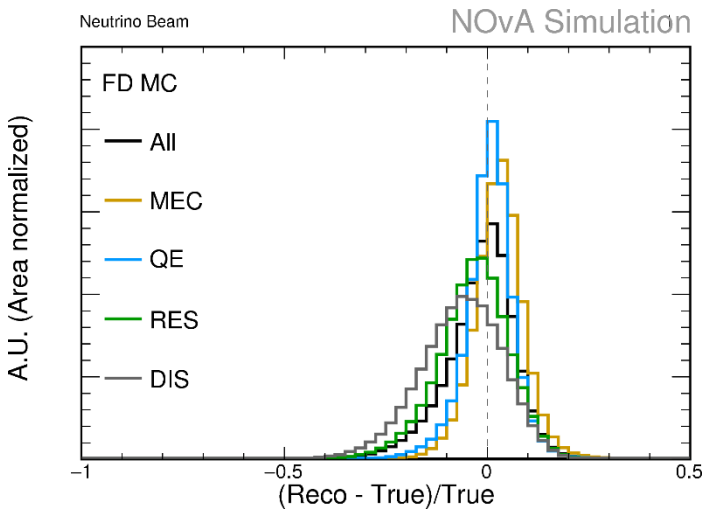


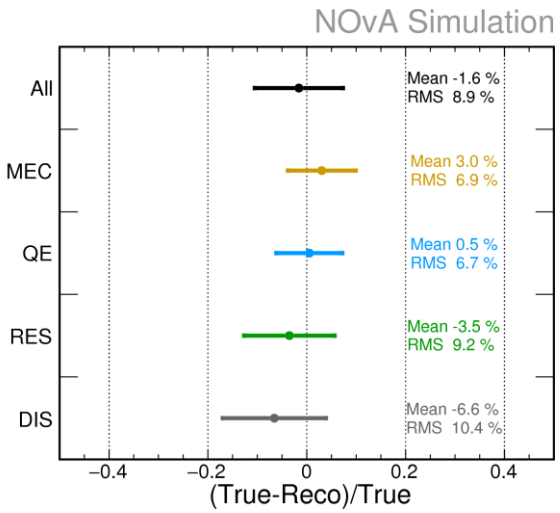


Different processes have different energy resolutions and energy scales

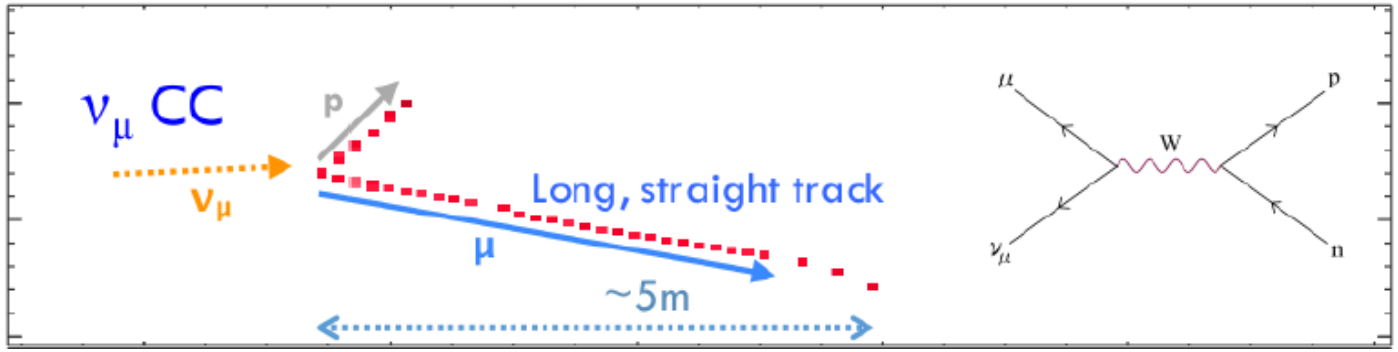
How much 4-momentum goes to the lepton, how much goes to the hadronic system

How much 4-momentum is invisible





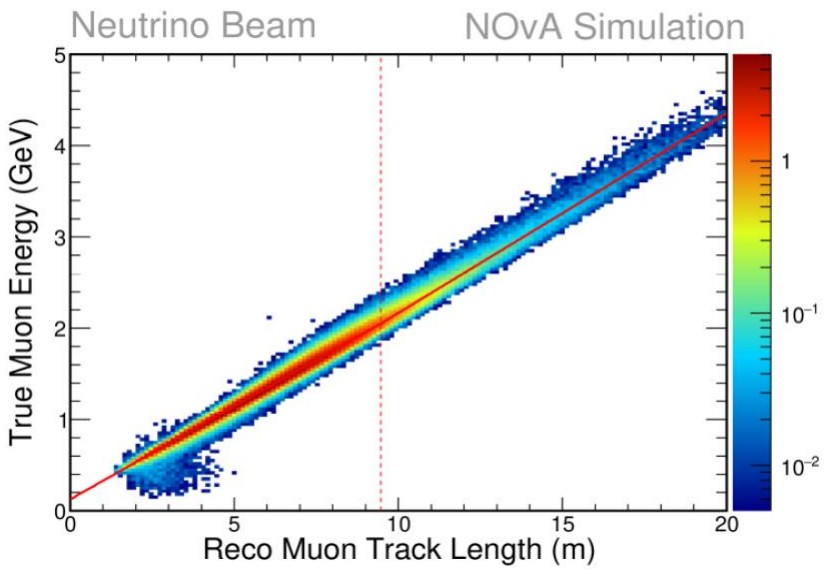
Event Topology



Energy Measurement

$$E_\nu = E_\mu + E_{Everything\ Else}$$

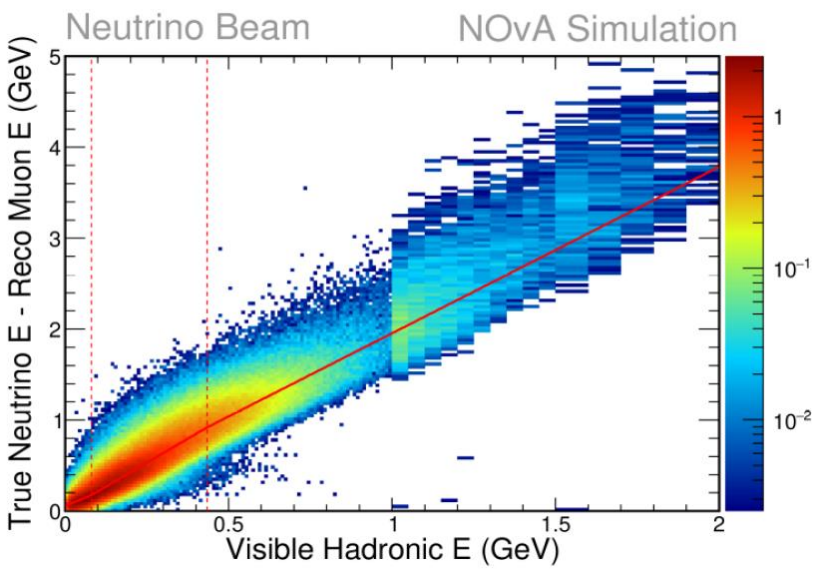
E_μ



Muon energy by range

ν cross-section independent

$E_{Everything\ Else}$

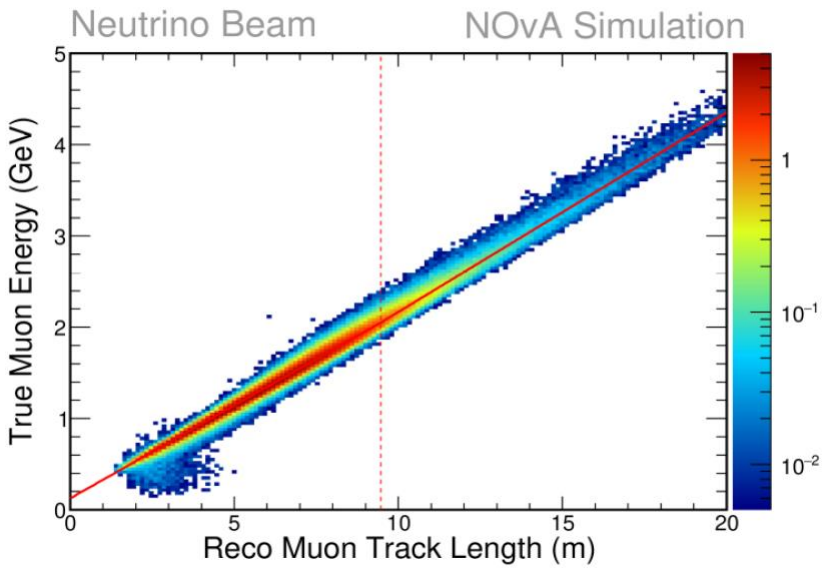


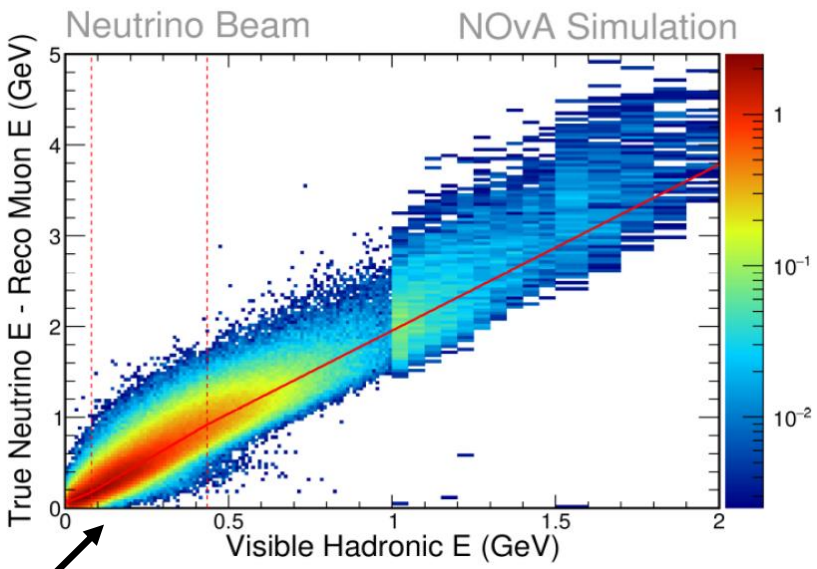
Calorimetric sum of non-muon hits

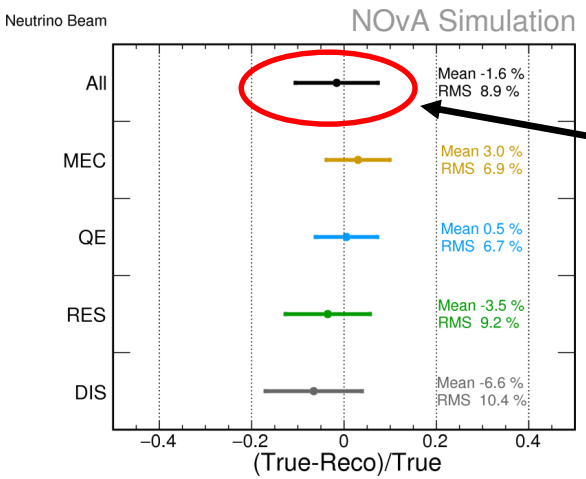
Modelling dependent

Energy Measurement

$$E_\nu = E_\mu + E_{Everything\ Else}$$

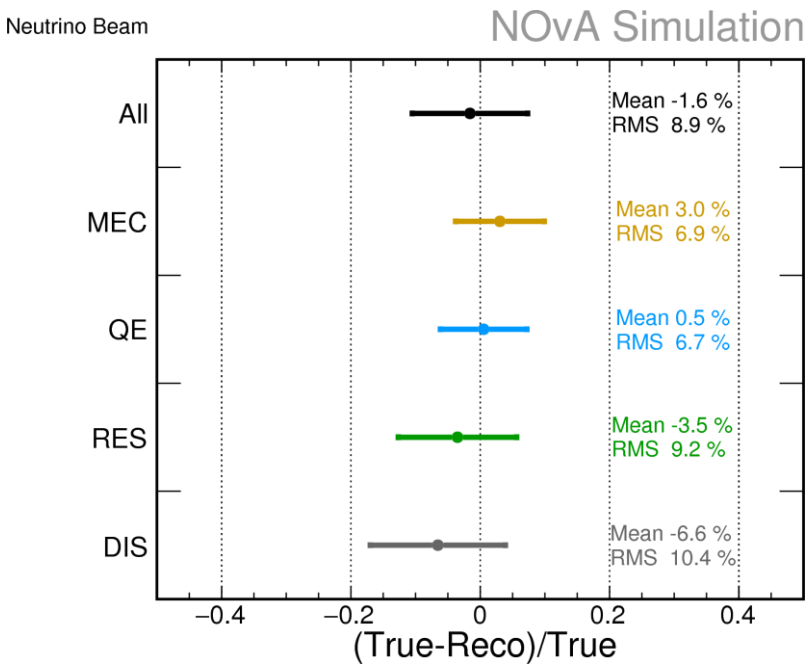


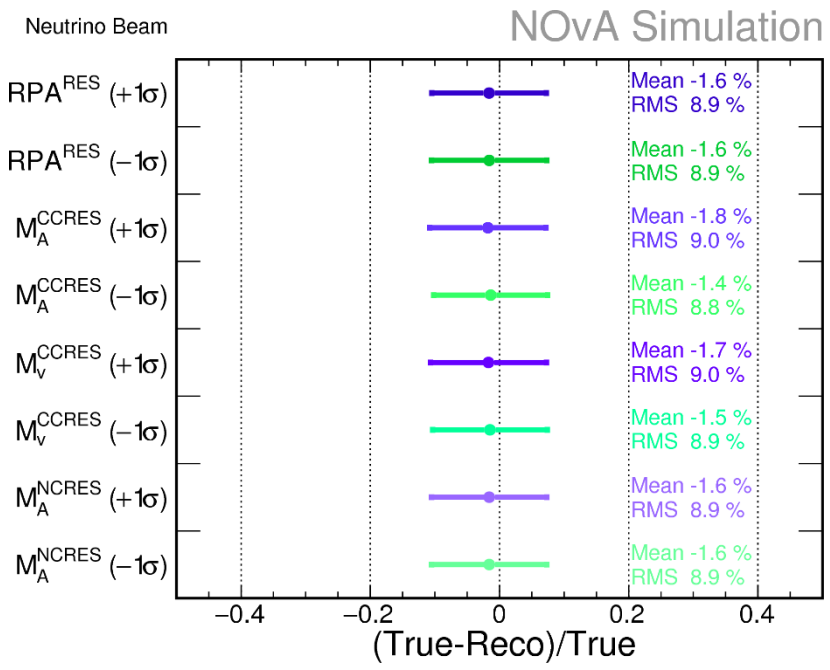




With this method, the average value depends on the relative mix of the processes and how much energy goes to the lepton

Energy Measurement





These differences in energy scale & resolution would represent our uncertainty if we had complete uncertainty on the relative contribution from each process

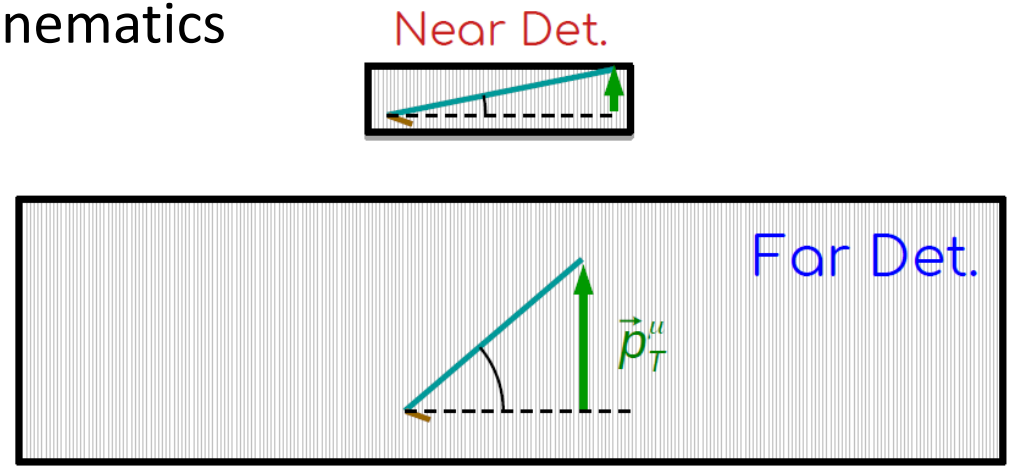
Fortunately, we know the relative contribution from each process fairly well

As determined by our model uncertainties

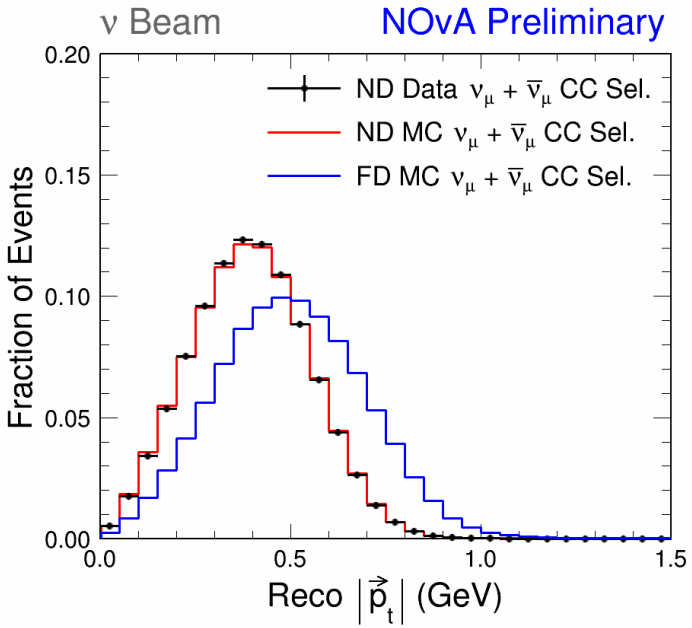
The primary impact of cross-section modelling on analyses is through event yields not energy reconstruction!

Mitigating Acceptance Uncertainties

Acceptance of smaller ND events depends on event kinematics

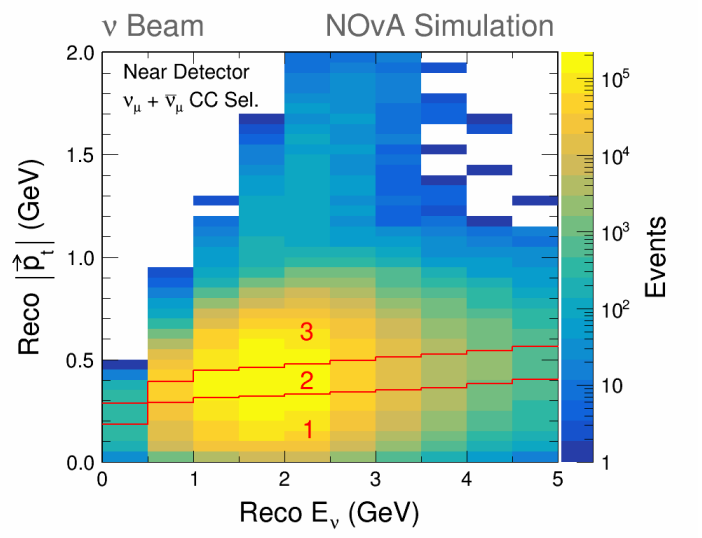


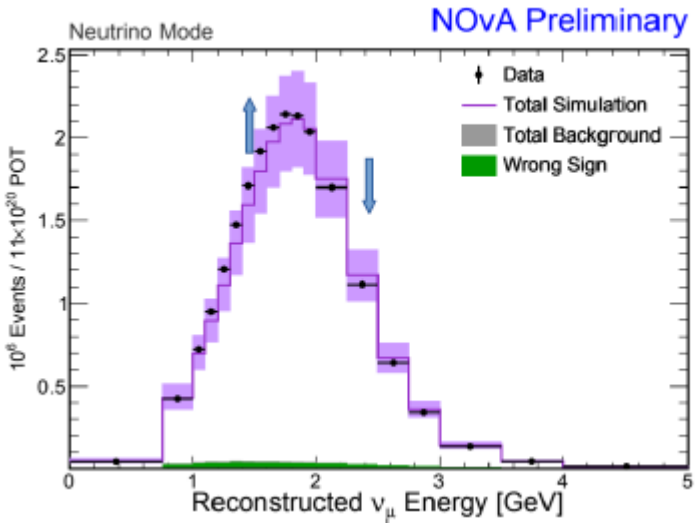
Acceptance correlated with lepton p_T



Mitigating Acceptance Uncertainties

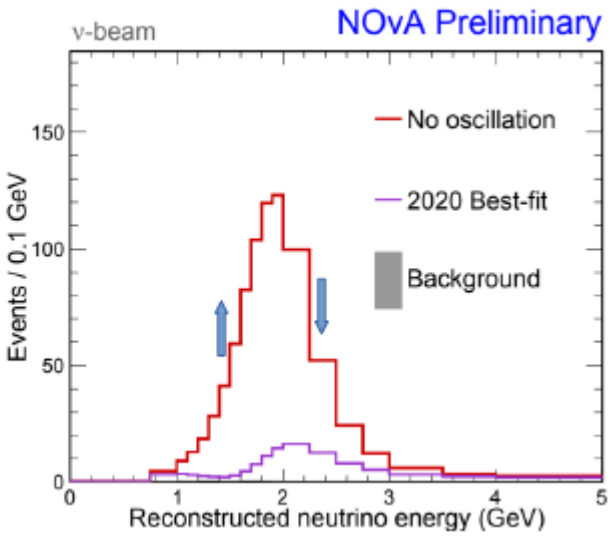
Subdivide samples by lepton p_T and extrapolate ND to FD





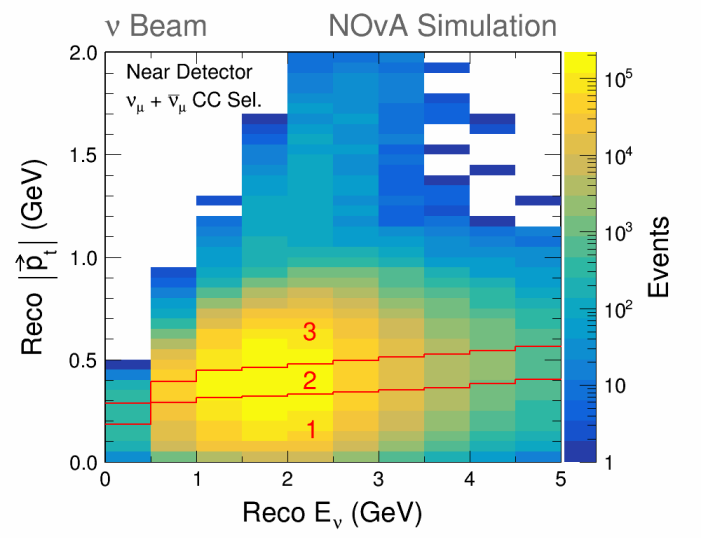
"Extrapolation"

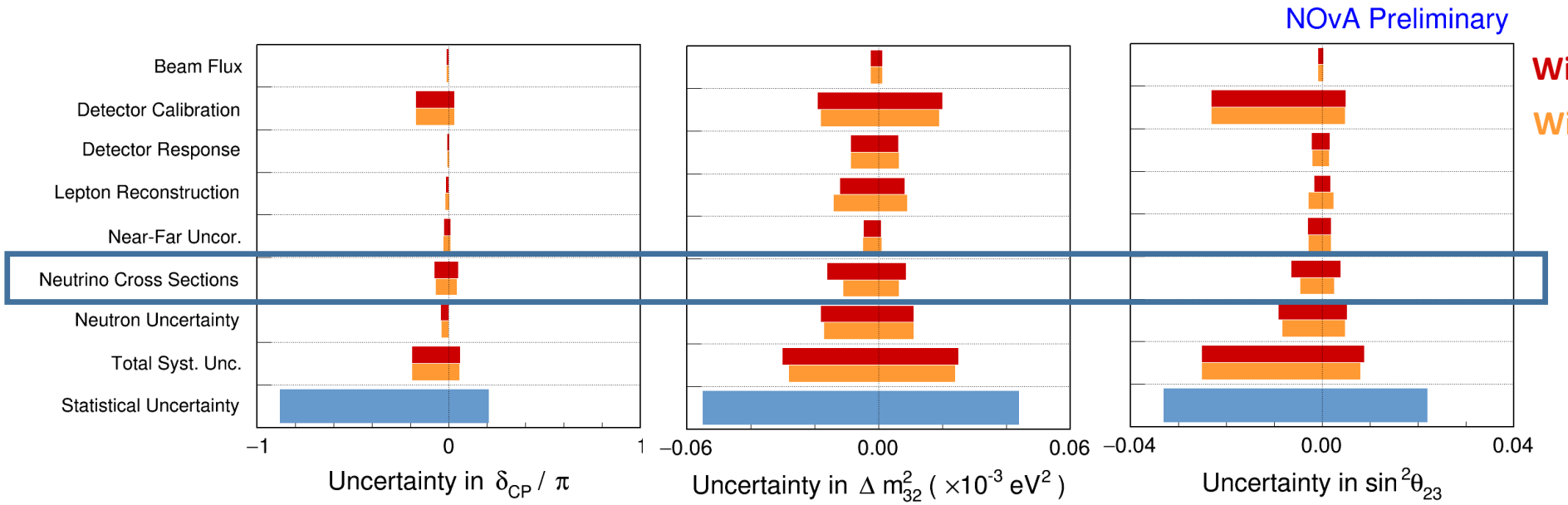
(account for beam divergence, detector size difference, etc. w/ MC)



Mitigating Acceptance Uncertainties

Subdivide samples by lepton p_T and extrapolate ND to FD





Without p_T extrap.

With p_T extrap.

Up to 30% reduction to impact of cross-section uncertainties on analyses

Stats Limited

Cross sections not dominant systematic

Cross-section model

Genie 3.0.6

QE: Valencia 1p1h with Z-expansion axial form factor

MEC: Valencia reweighted to ND data

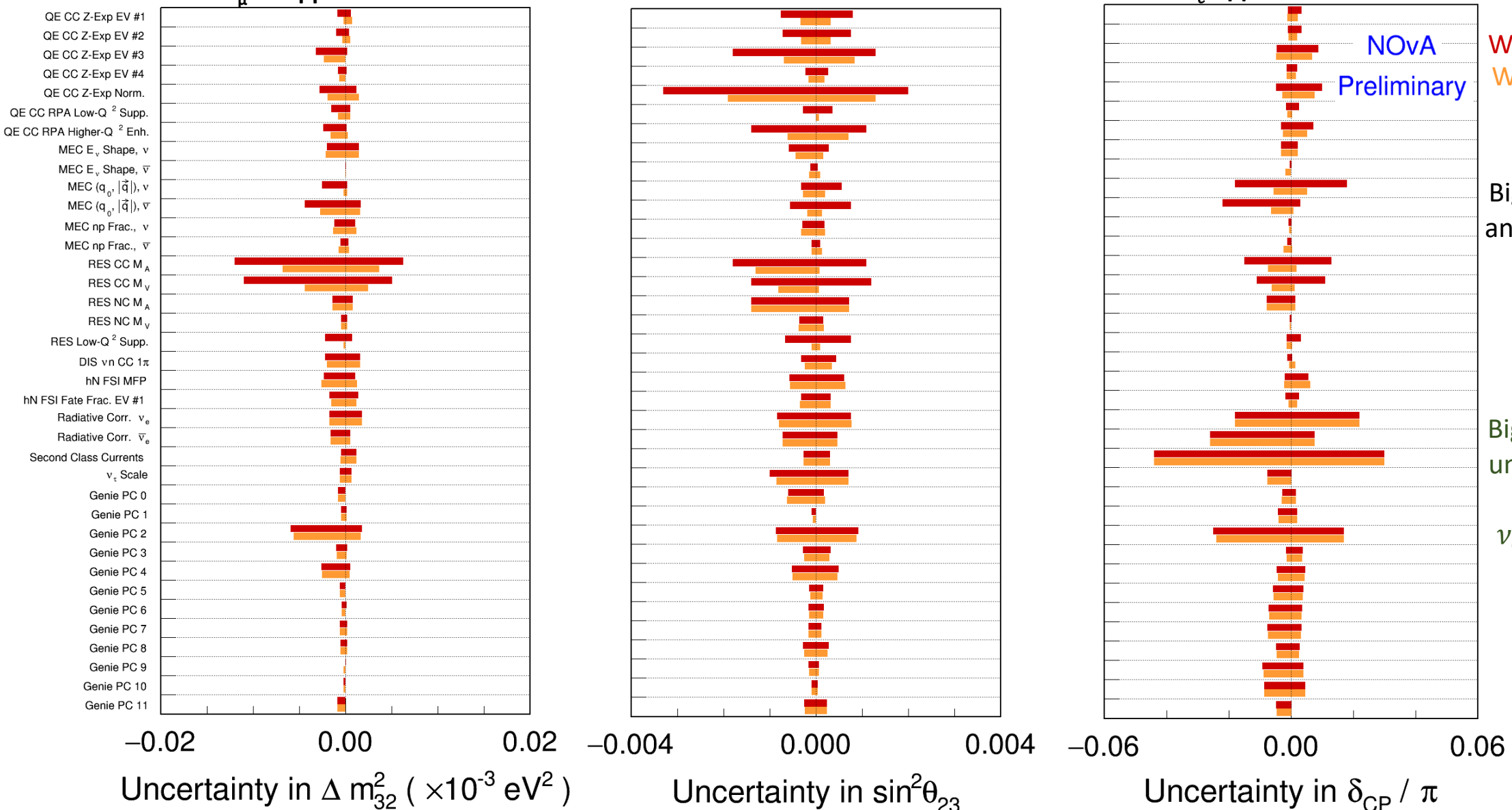
RES: Berger-Sehgal

DIS: Bodek-Yang

FSI: hN (semi-classical cascade) reweighted to pion scattering data

Impact Cross-sections – Joint $\nu_\mu + \nu_e$ Analysis

Constraint mainly from ν_μ Disappearance → **Constraint mainly from ν_e Appearance**



Without p_T extrap.
With p_T extrap.

Biggest cross-section analysis uncertainties affect relative normalization of QE and RES

Biggest cross-section uncertainties for δ_{CP} related to $\nu_e - \nu_\mu$ differences

Summary

Cross-section uncertainties impact NOvA oscillation analyses through

- 1 - Event Yields
  - Primary cross-section effect
- 2 - Energy Estimation
  - Less dominant effect, mitigated by:
    - Event energy primarily being leptonic
    - Calorimetric response to charged-particles

NOvA energies correspond to a mix of production modes

- Resonant production is leading cross-section uncertainty

ν_e appearance prediction depends on observed ν_μ events

- $\nu_e - \nu_\mu$ cross-section differences important

NOvA analyses are statistics limited and systematic uncertainties are dominated by calorimetric and neutron systematics (not cross sections)