Impact of RES modeling to the GeV global neutrino oscillation program (*i.e. NOvA* and DUNE)

NuSTEC – Pittsburgh 2019

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Chatty Cabby

Everything in Pittsburgh has French fries in it!

Da’ Pitts-burger is the greatest burger!

What is *NOvA* (currently running)

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

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

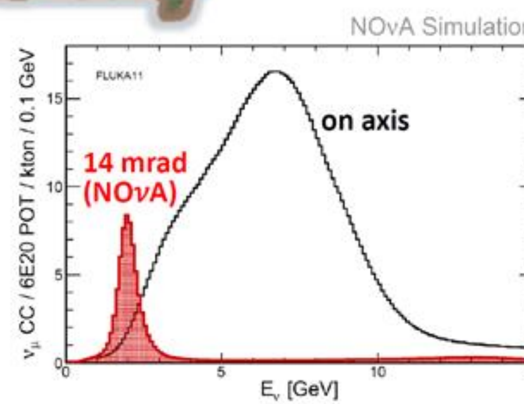
Two detector experiment

Near detector (Fermilab, IL)

Measure beam before oscillation

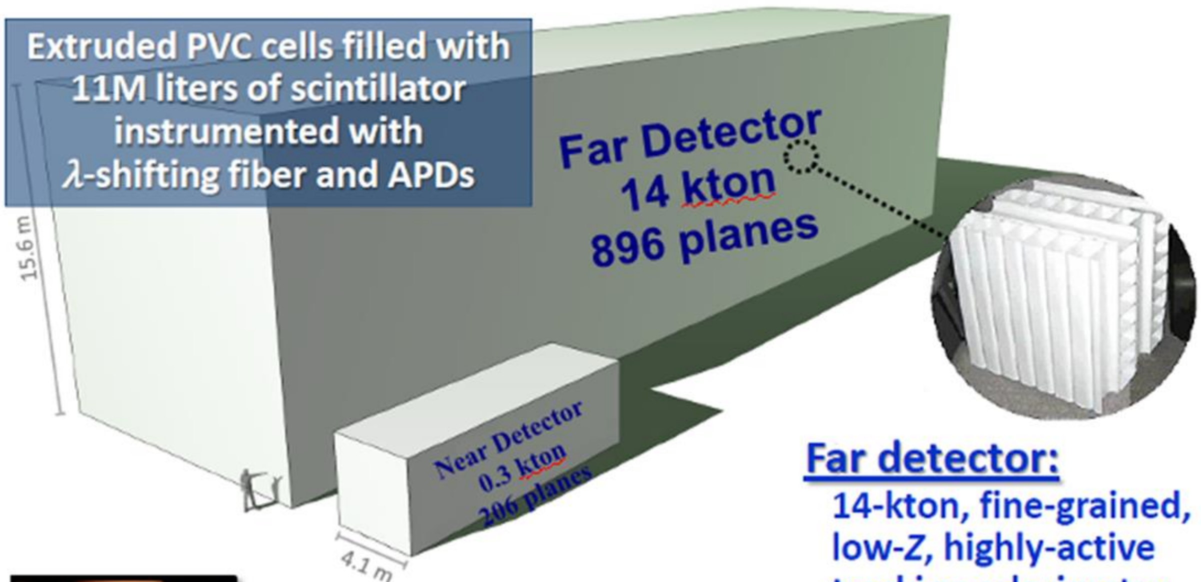
Far Detector (Ash River, MN)

Measure oscillated beam

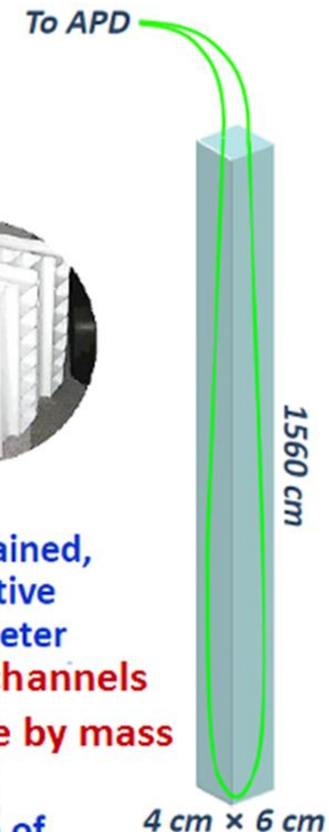


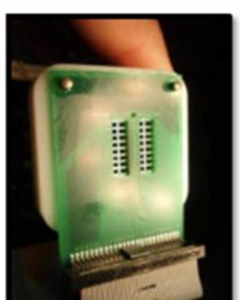
NOvA – Detector Experiment

Giant hydrocarbon nuclear target with 16% Cl



A NOvA cell





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

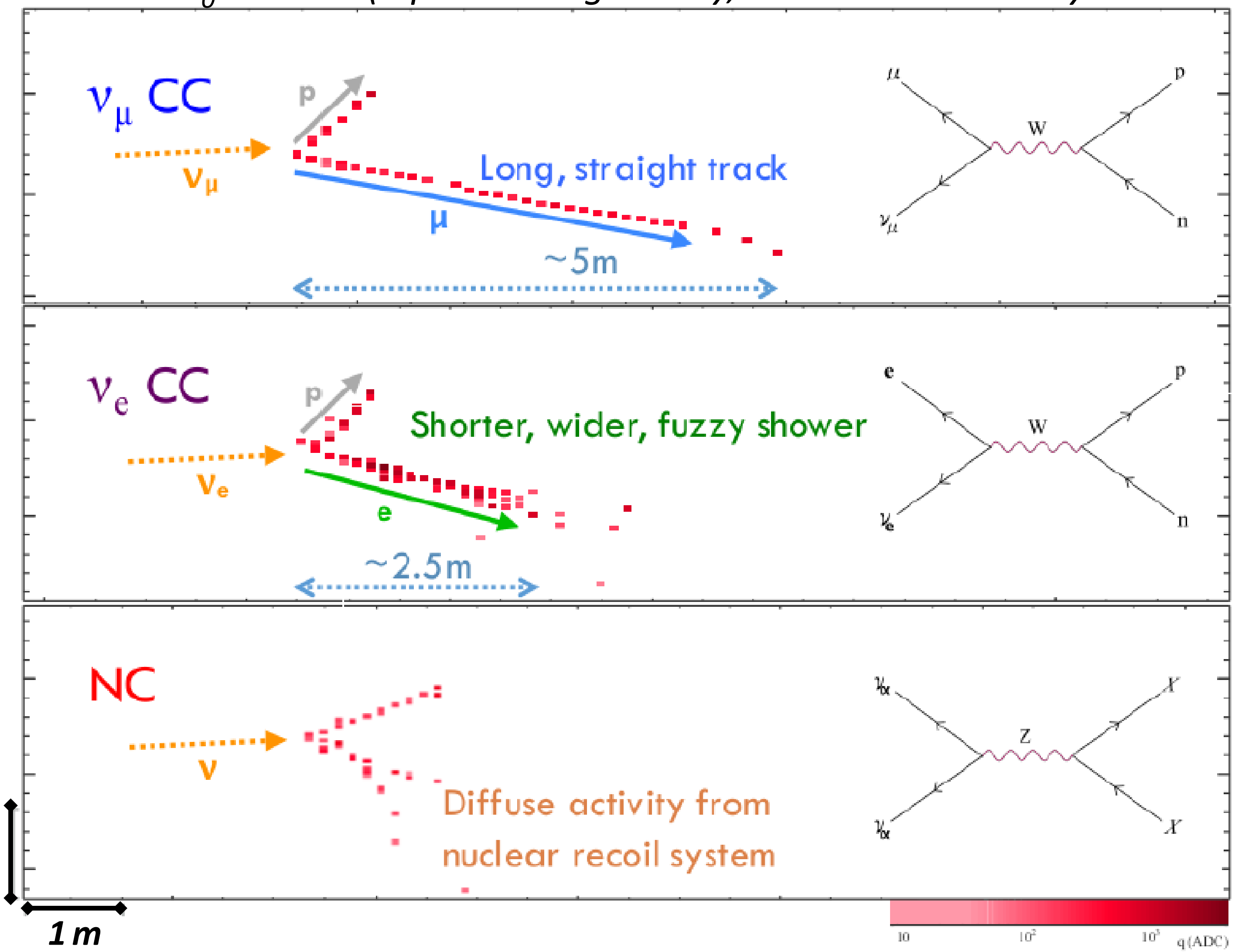
Near detector:

0.3-kton version of the same

18, 000 channels

NOvA – Event Topologies

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



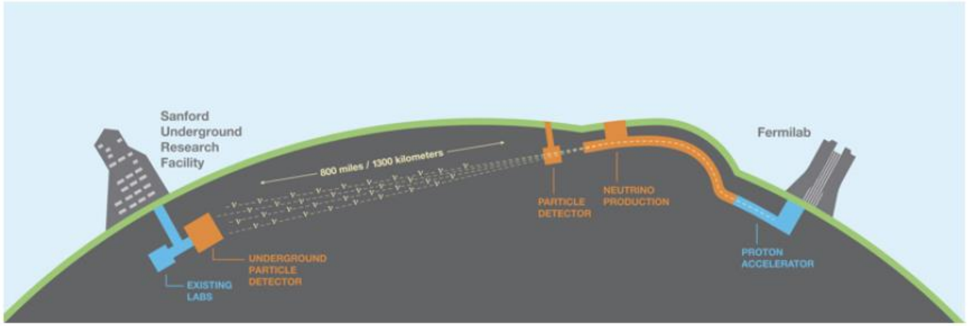
What is *DUNE* (in development)

Long baseline neutrino experiment

E ≈ sub-GeV to above 4 GeV
(on-axis wide band beam)

L = 1300 km

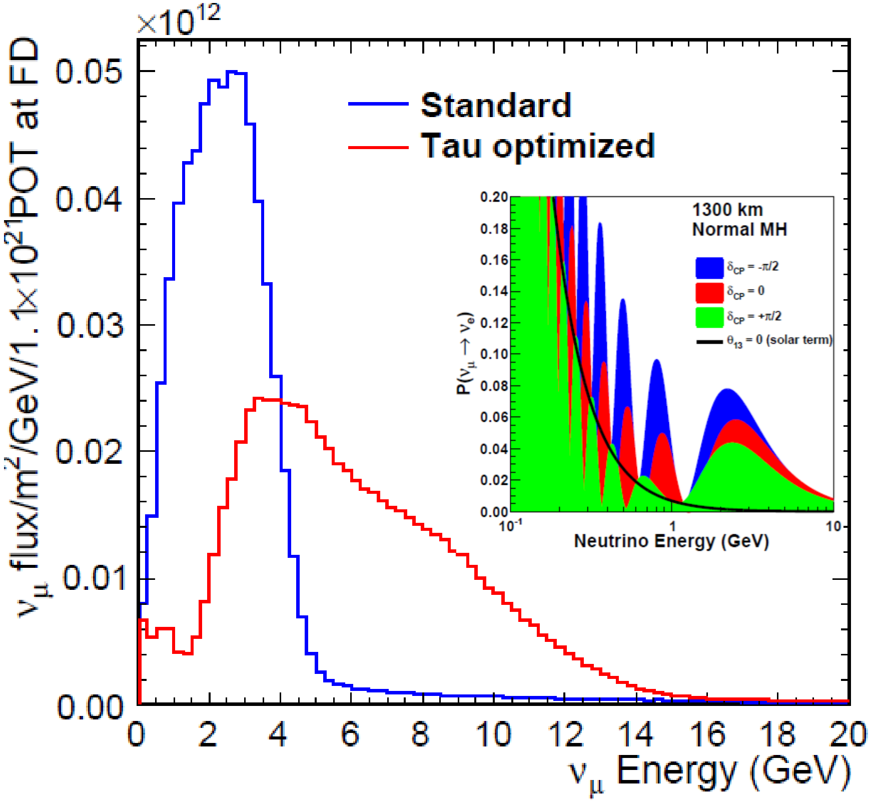
Oscillations governed by Δm^2_{32} (Δm^2_{31})



LBNF beam to be produced at Fermilab

ν_μ and $\bar{\nu}_\mu$ beam modes

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



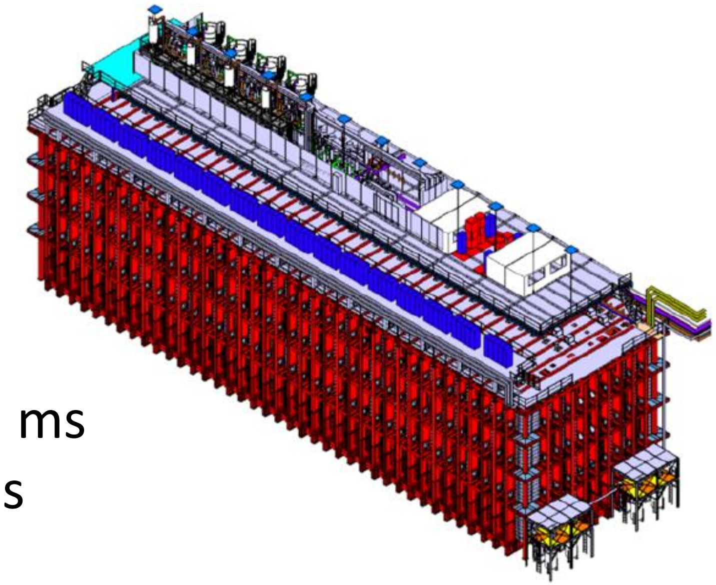
Two detector experiment

Near detectors (Fermilab, IL)
Measure beam before oscillation

Far Detectors (SURF, SD)
Measure oscillated beam

DUNE – Far Detectors

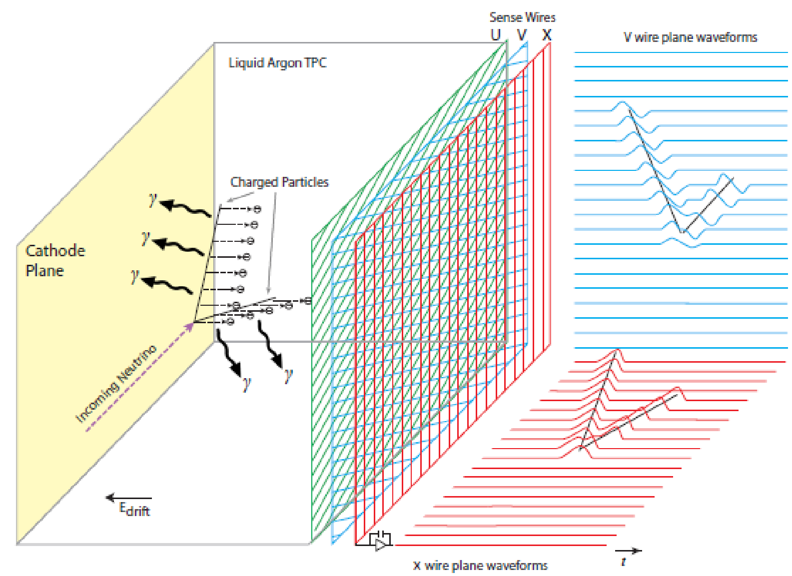
Giant argon nuclear target



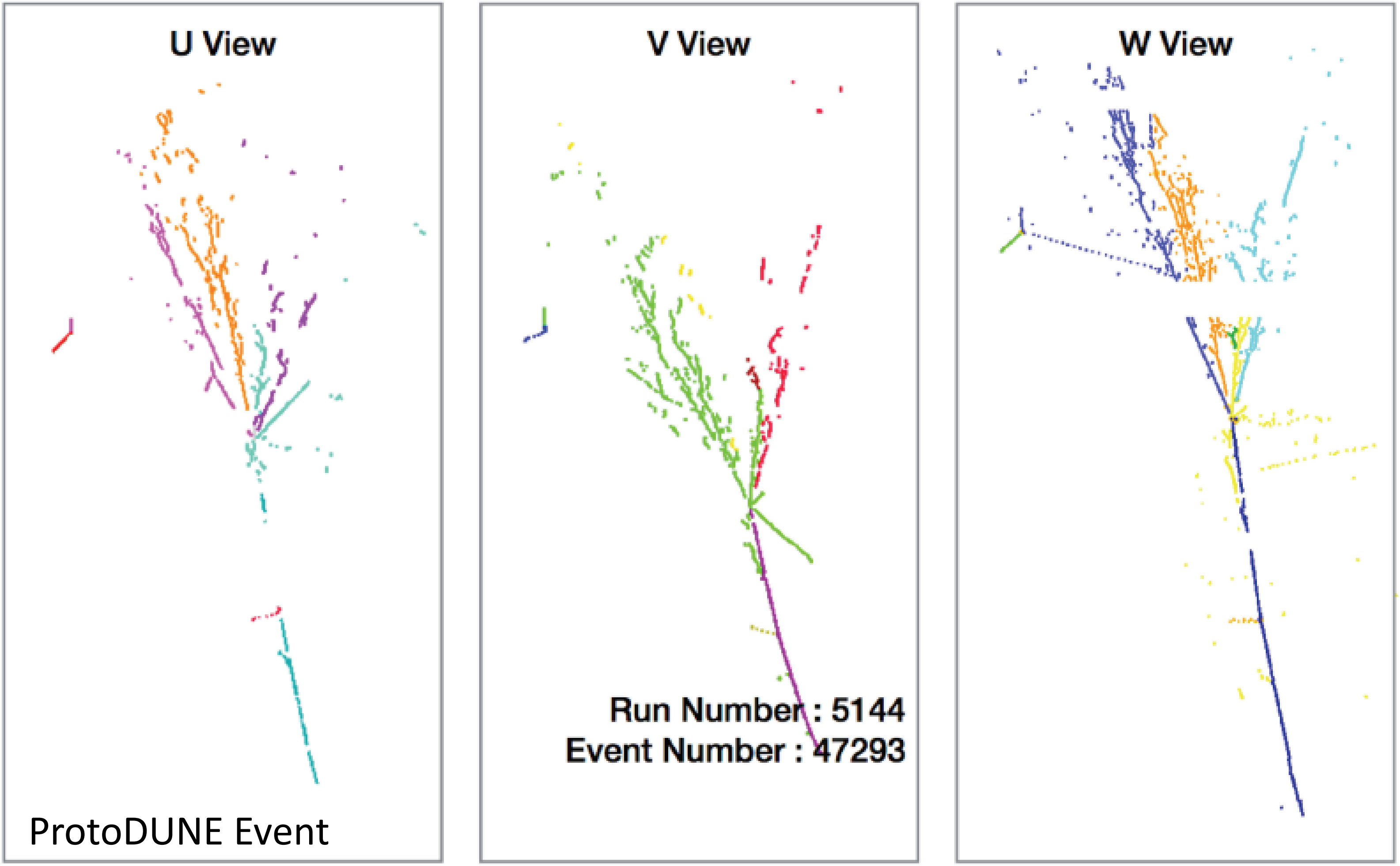
Four LArTPC detectors

- Cryostats: 14 m x 14 m x 62 m, each
- Fiducial mass: 10 kton, each
  - Single Phase: 3.5m drift length over 2.2 ms
  - Dual Phase: 12m drift length over 7.5ms

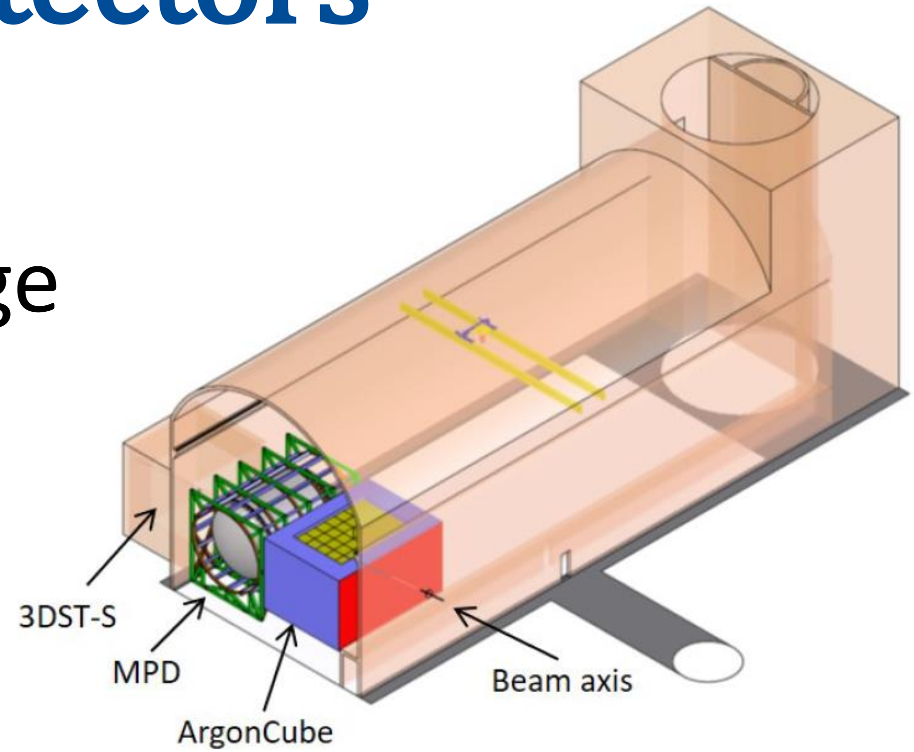
Single Phase



DUNE – Event Topologies



DUNE – Near Detectors



Conceptual Design Stage

Three detectors:

ArgonCube: LArTPC

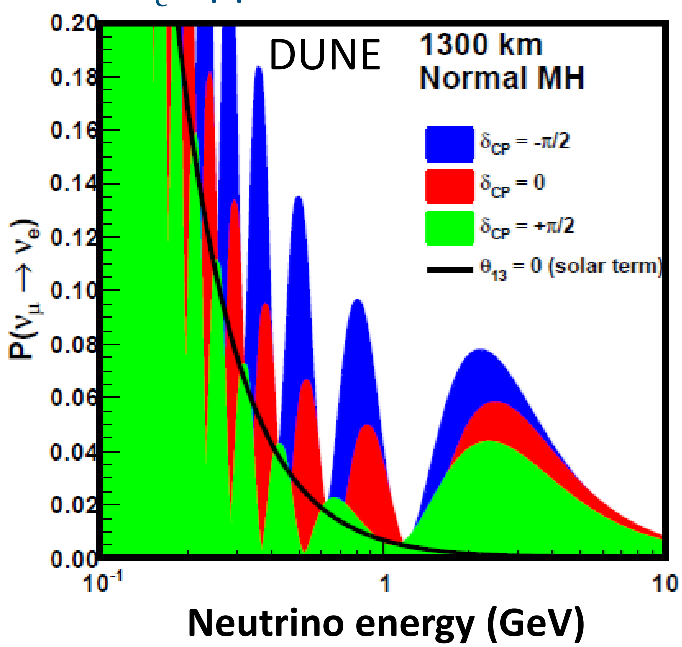
MPD: Magnetized HPgTPC
surrounded by EM calorimeter

3DST-S: Magnetized 3D scintillator tracker
surrounded by TPC and EM calorimeter

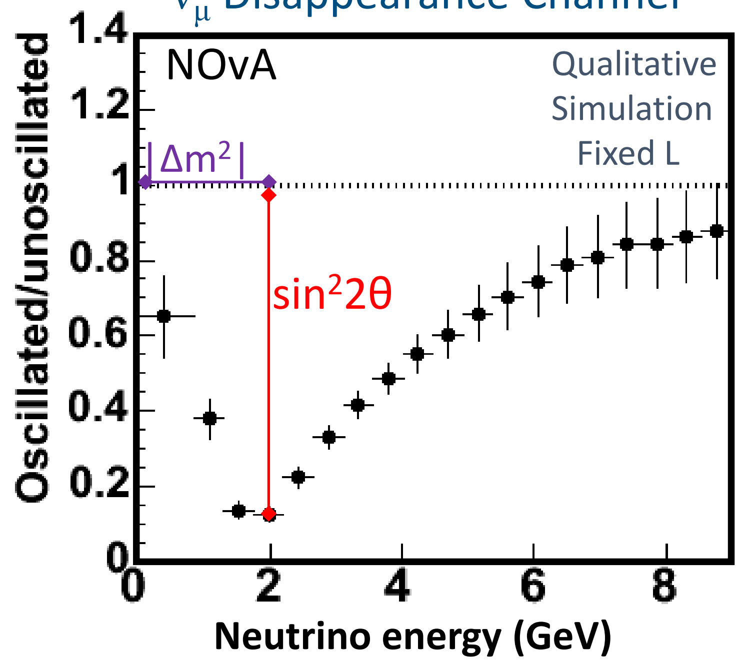
Oscillation Measurements

Both experiments measure δ_{CP}, θ_{23}, mass splitting (hierarchy /ordering)

ν_e Appearance Channel



ν_μ Disappearance Channel



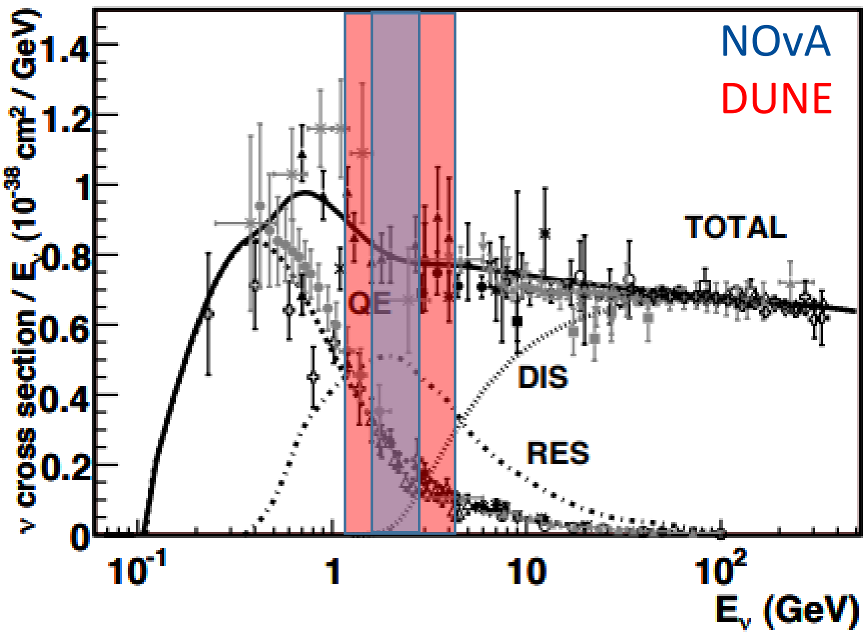
The key measurements for oscillation results

– Neutrino energy

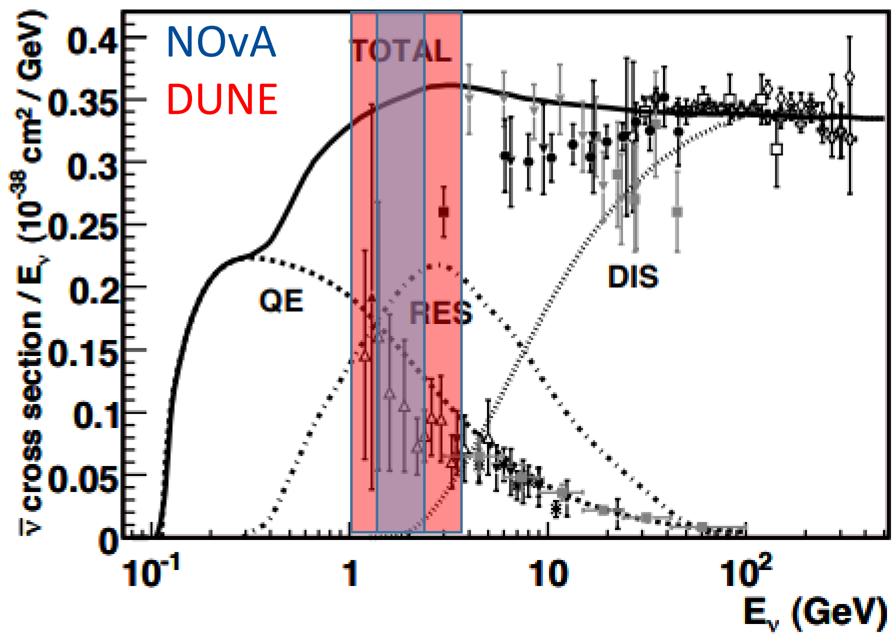
– Event yields

What processes are relevant

Neutrinos



Antineutrinos



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

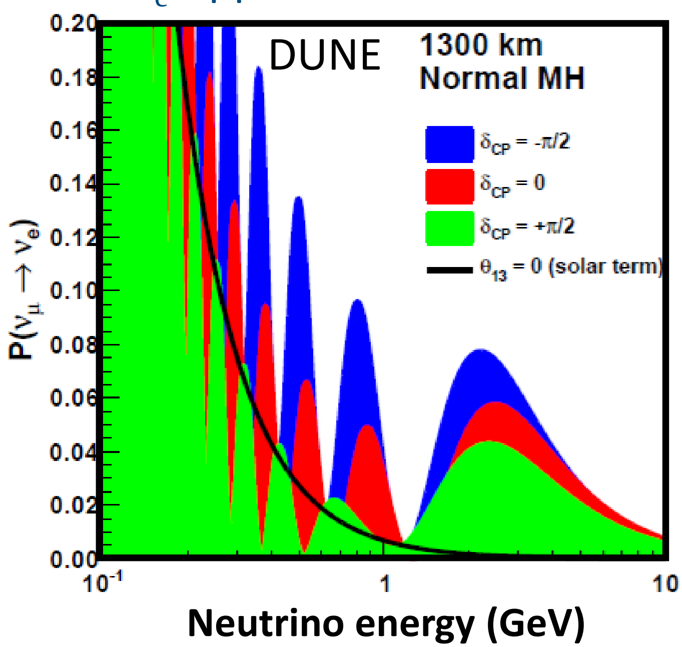
Both experiments are at an energy where resonant production is dominant

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

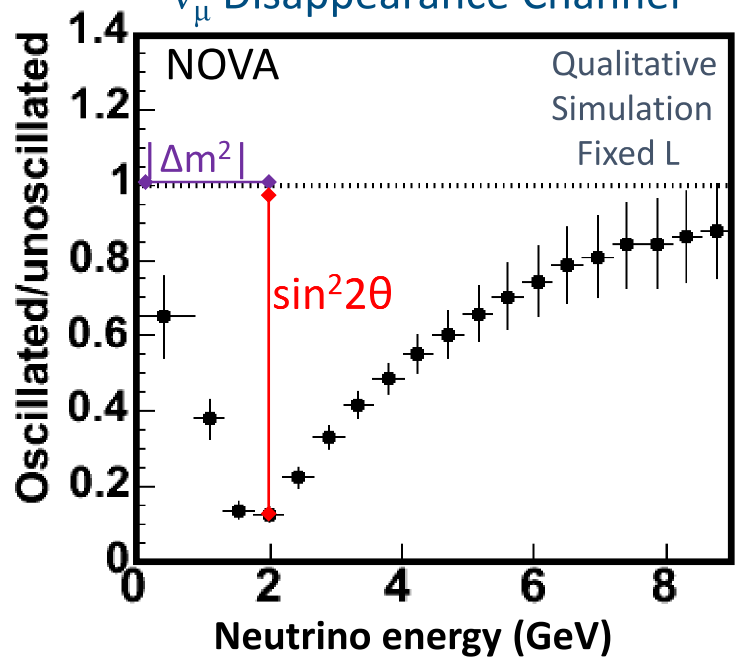
Oscillation Measurements

Both experiments measure δ_{CP}, θ_{23}, mass splitting (hierarchy /ordering)

ν_e Appearance Channel



ν_μ Disappearance Channel

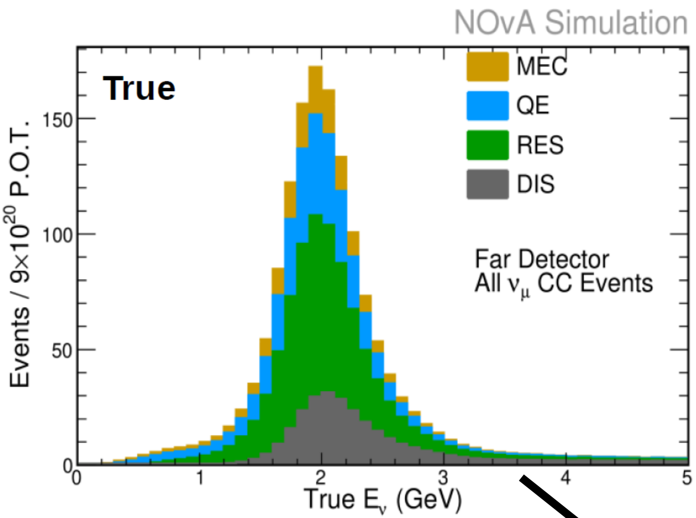


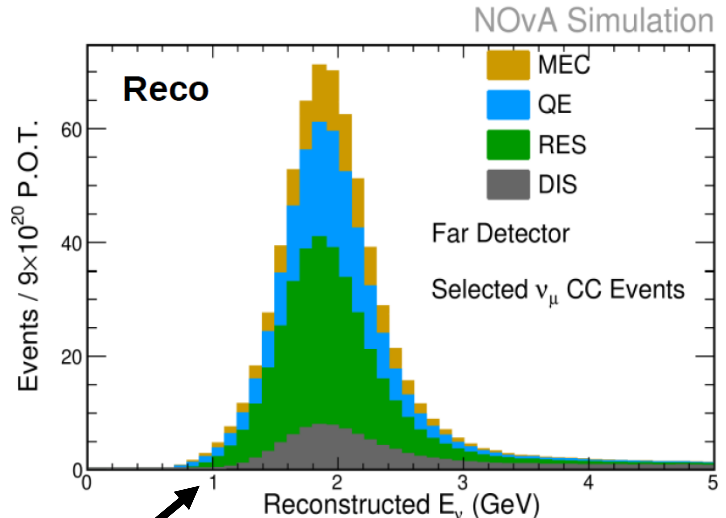
The key measurements for oscillation results

– Neutrino energy

– Event yields

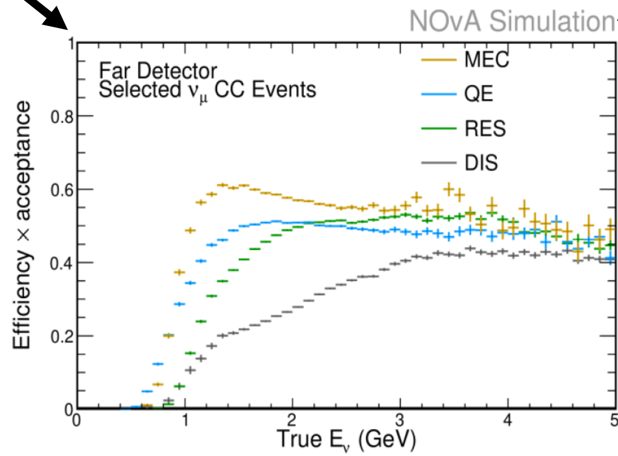
Events Yields





Different processes have different selection efficiencies

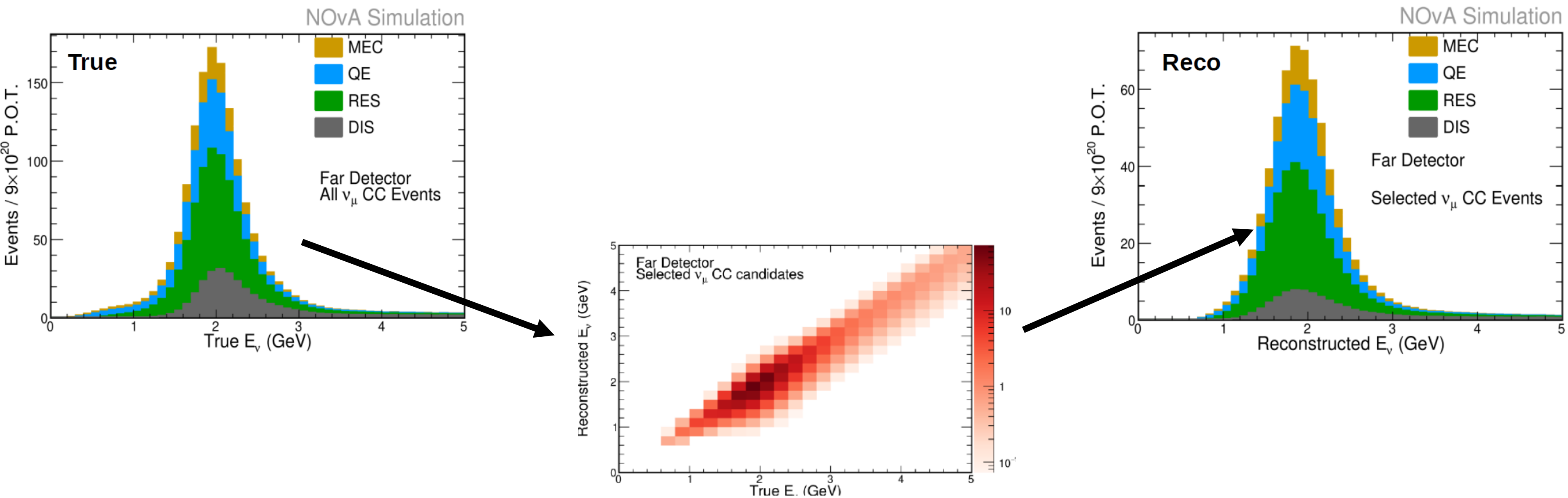
How much 4-momentum goes to the lepton, how much goes to the hadronic system



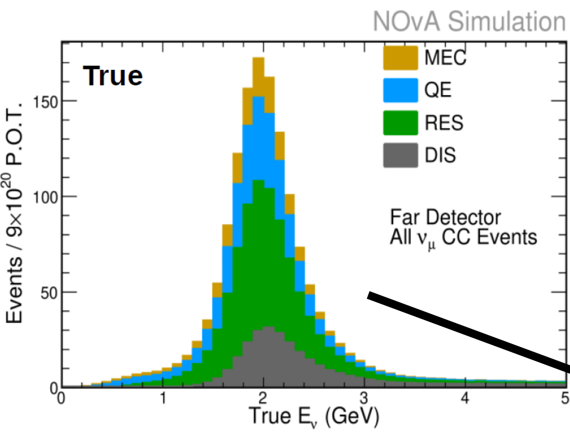
Ideally apply same selection in ND and FD, so they have same efficiencies, but the mix of processes are not exactly identical in both detectors

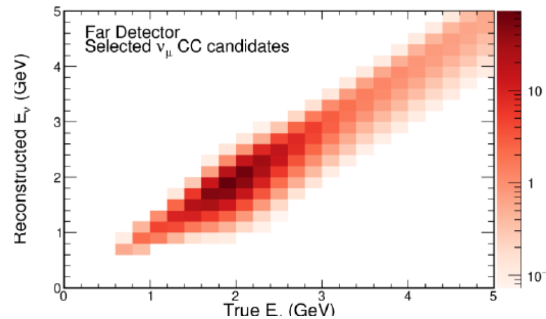
Flux is different (eg oscillation)

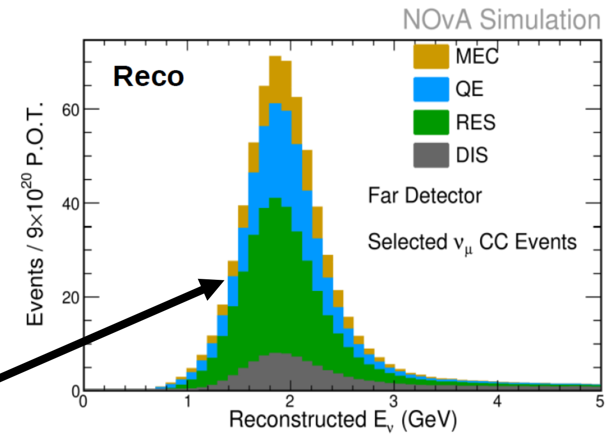
Neutrino Energy



Neutrino Energy



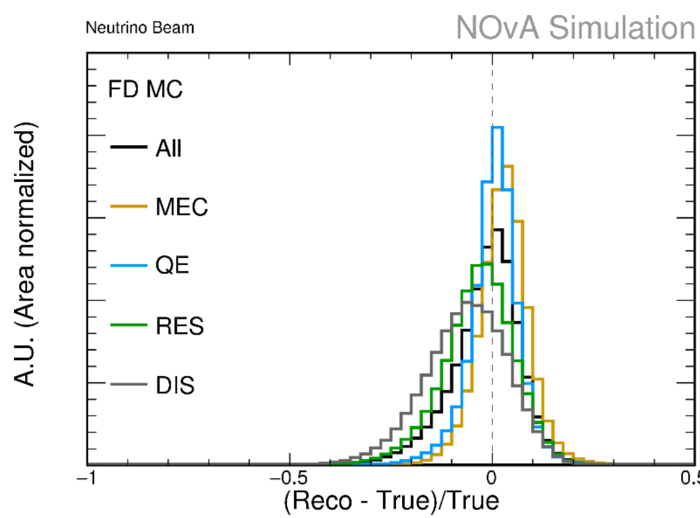


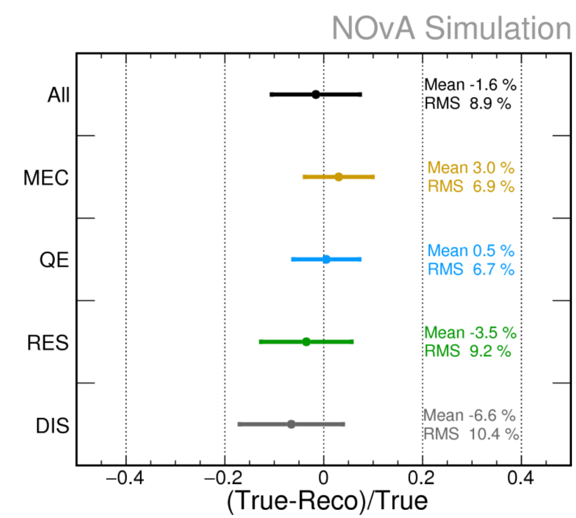


Different processes have different energy resolutions and energy scales

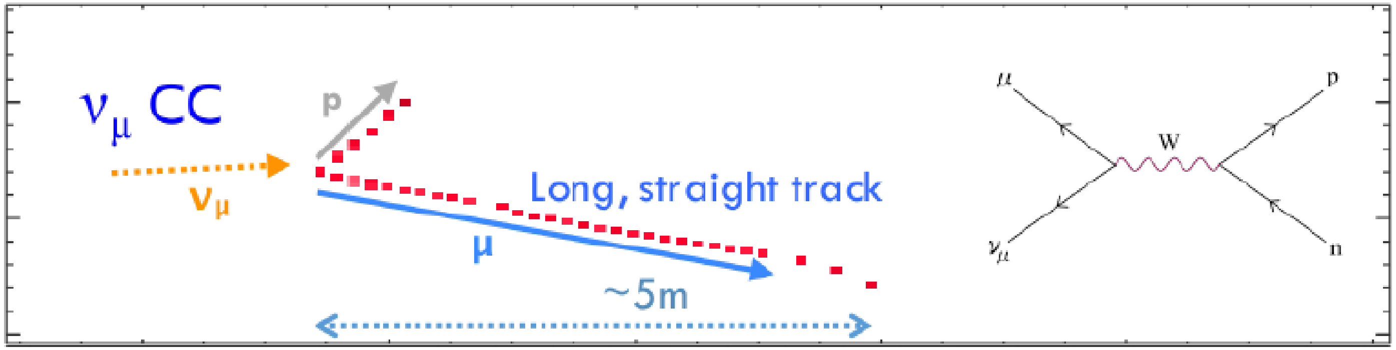
How much 4-momentum goes to the lepton, how much goes to the hadronic system

How much 4-momentum is invisible





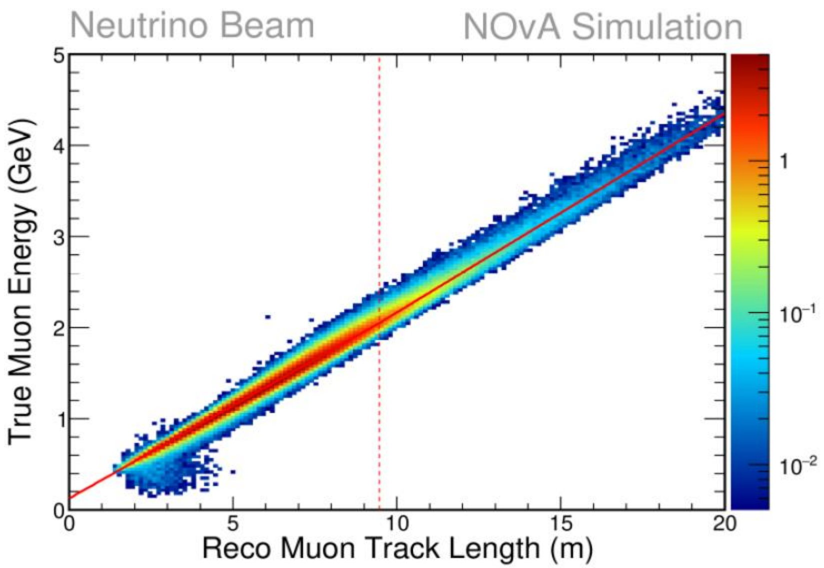
NOvA – Event Topologies



NOvA – Energy measurement

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

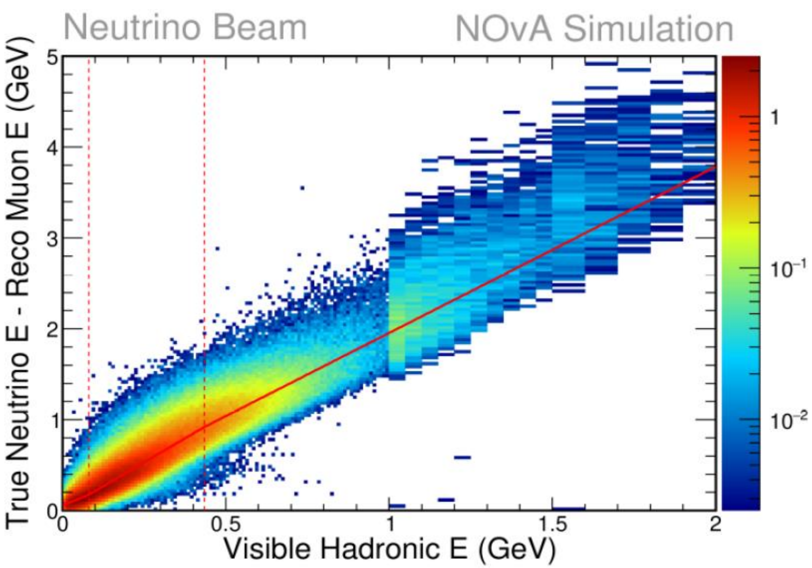
E_μ



Muon energy by range

ν cross-section independent

$E_{Everything\ Else}$



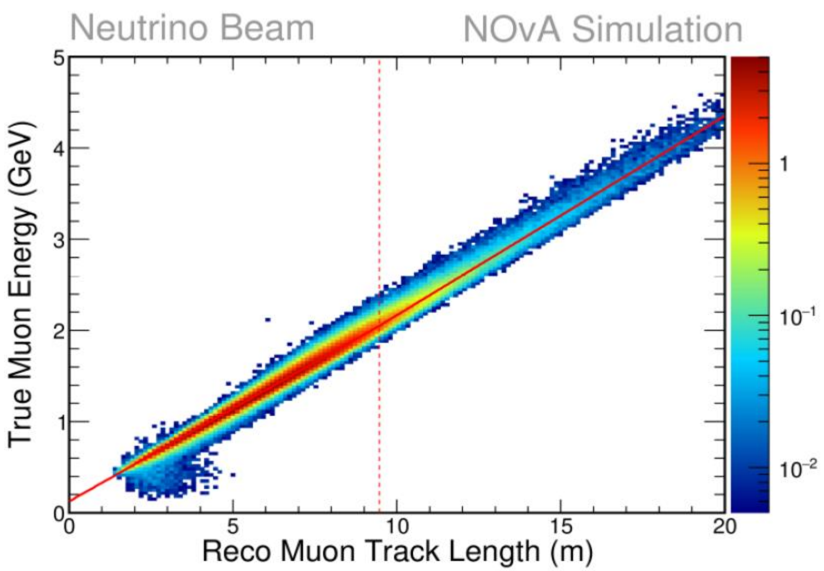
Calorimetric sum of non-muon hits

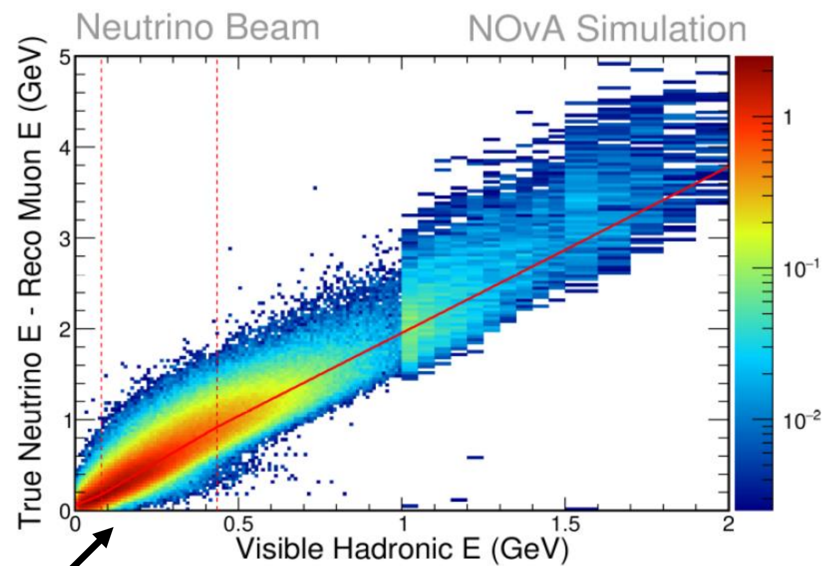
Modelling dependent

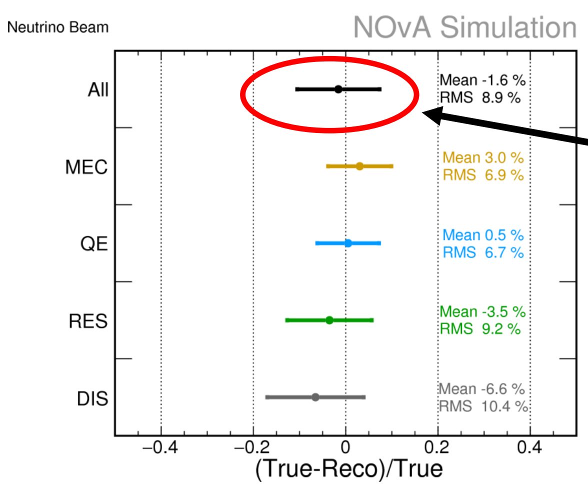
DUNE has similar approach for TDR analysis

NOvA – Energy measurement

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

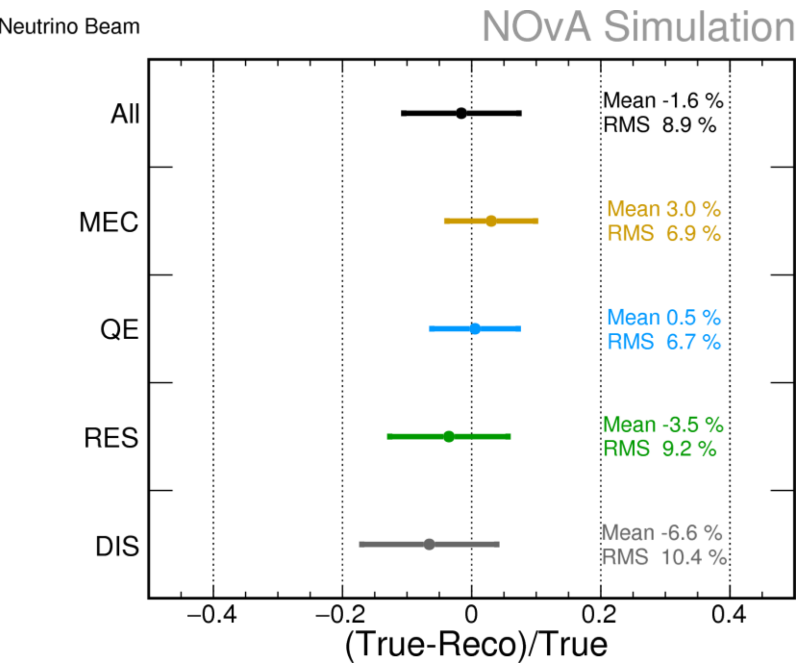


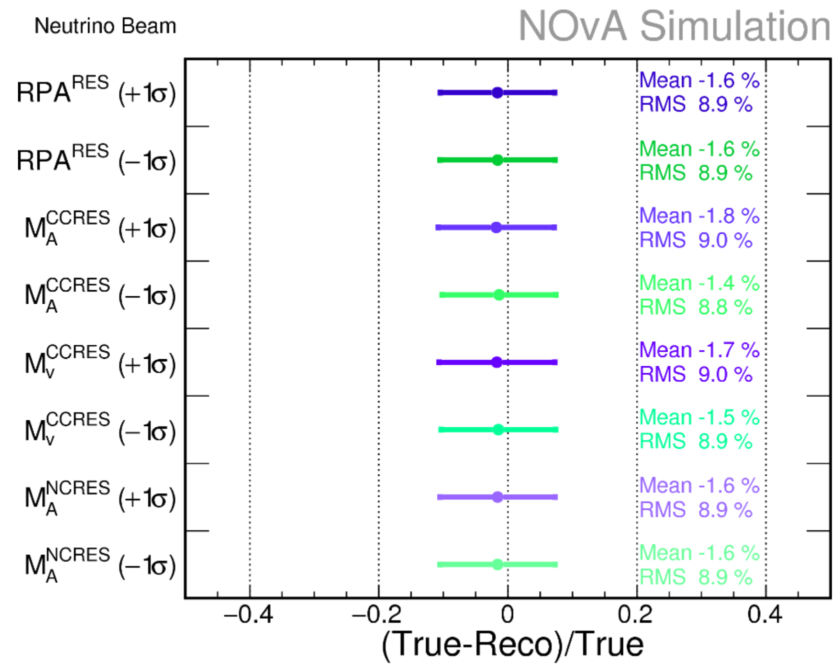




With this method, the average value depends on the relative mix of the processes and how much energy goes to the lepton

NOvA – Energy measurement





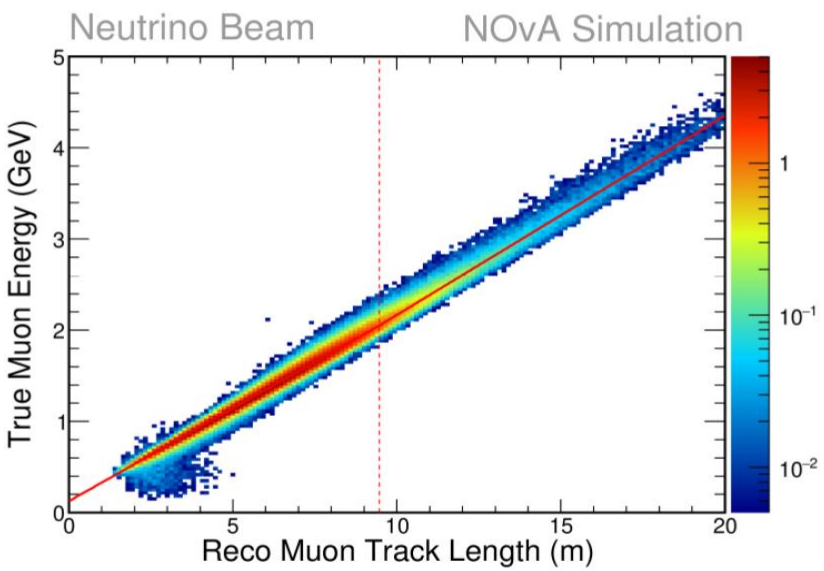
These differences in energy scale & resolution would represent our uncertainty if we had complete uncertainty on the relative contribution from each process

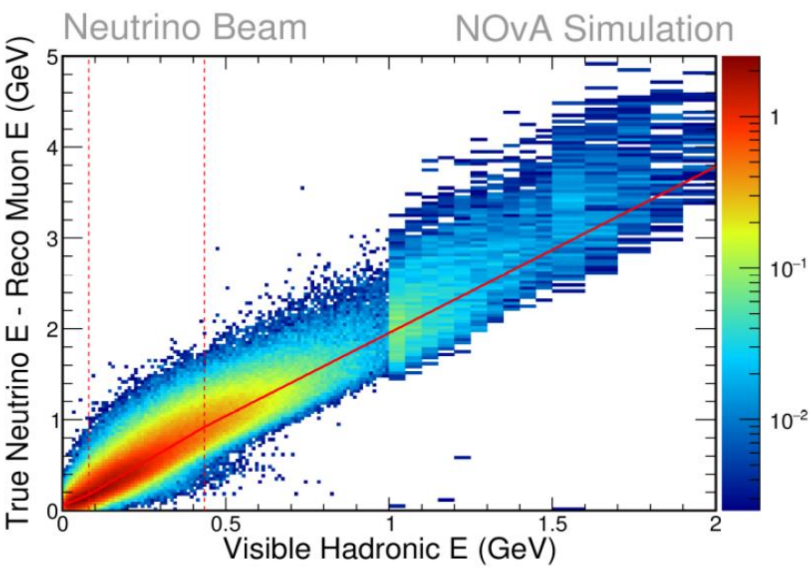
Fortunately, we know the relative contribution from each process fairly well

As determined by our model uncertainties

NOvA – Energy measurement

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

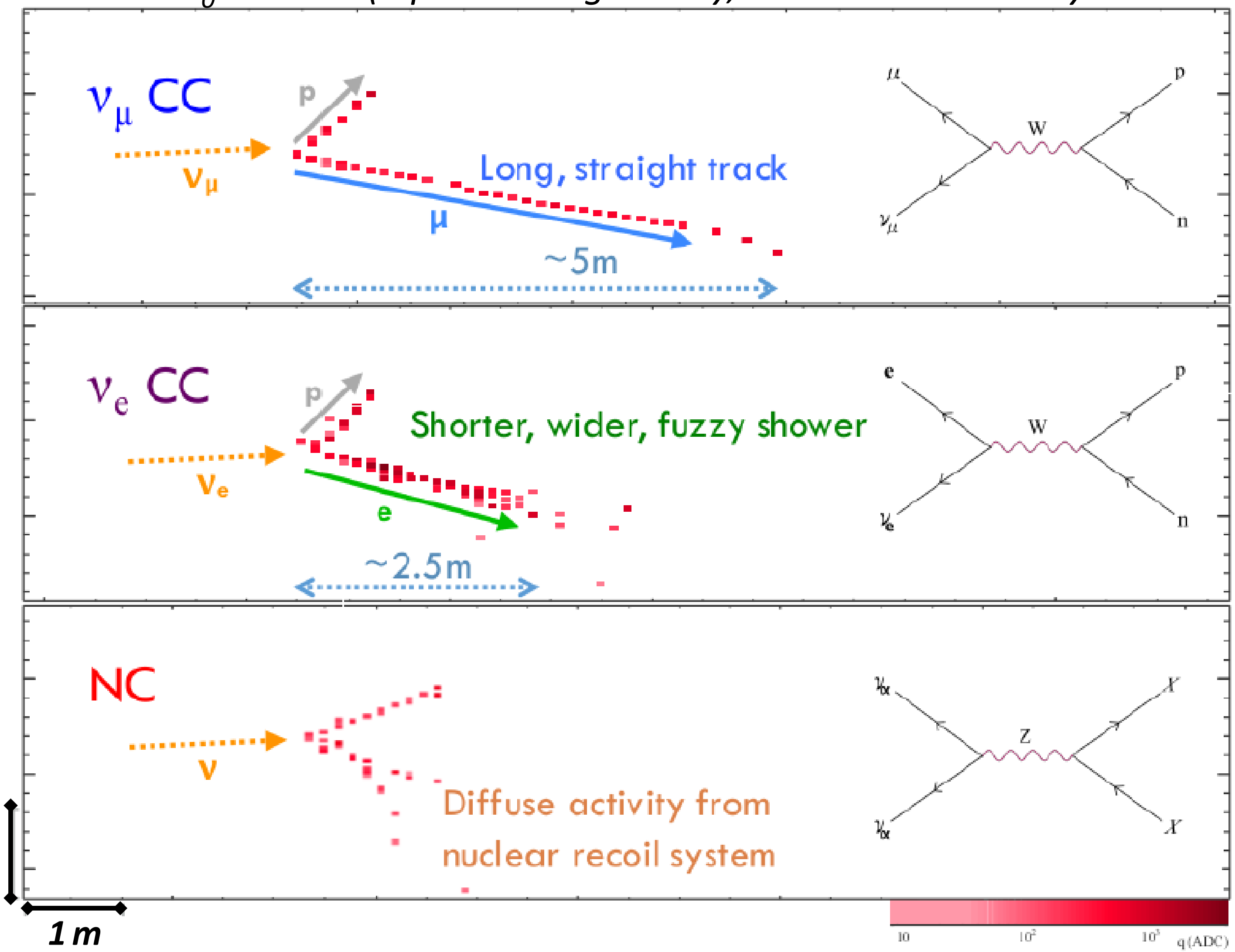




Note that you can reduce model dependence by using more information
i.e. Measure individual particles in the hadronic activity
(muddled by FSI and neutrons)

NOvA – Event Topologies

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



DUNE – Event Topologies

ProtoDUNE Event

ND energy resolutions

$$E'_{rec} = E_{rec} \times (p_0 + p_1\sqrt{E_{rec}} + \frac{p_2}{\sqrt{E_{rec}}})$$

Particle	p_0	p_1	p_2
all (except muons)	2%	1%	2%
μ (range)	2%	2%	2%
μ (curvature)	1%	1%	1%
p, $\pi^\pm$	5%	5%	5%
e, γ, π^0	2.5%	2.5%	2.5%
n	20%	30%	30%

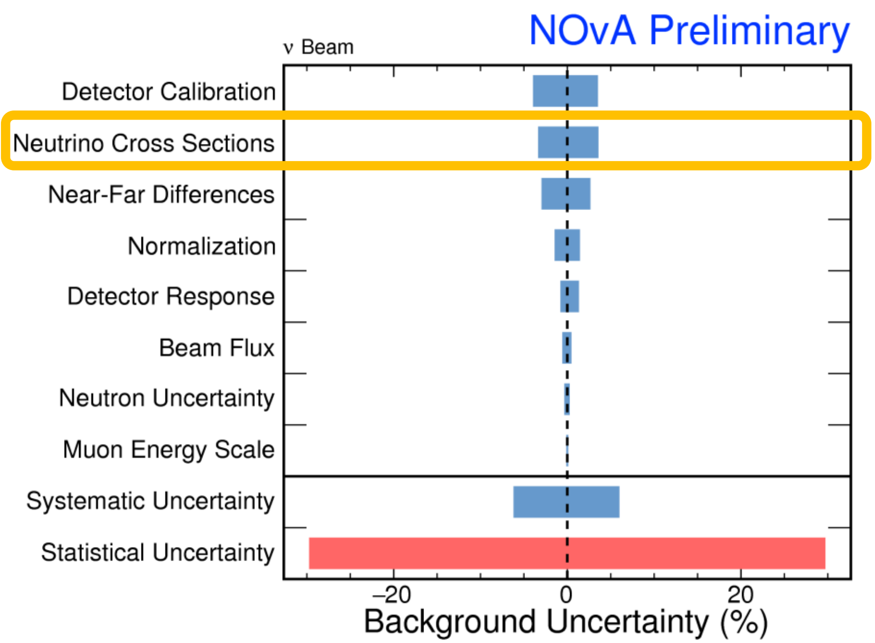
Some fries inside…

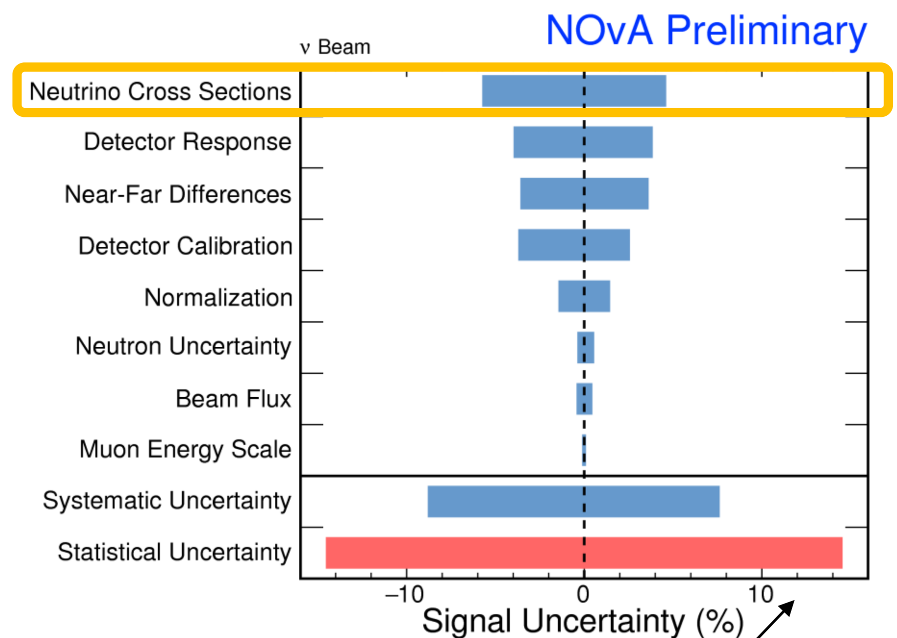
Impact of systematics

NOvA and DUNE both use GENIE as the default MC generator

Current public studies based on v2.12

NOvA Systematics – ν_e Apperance





Stats approaching systematics for signal

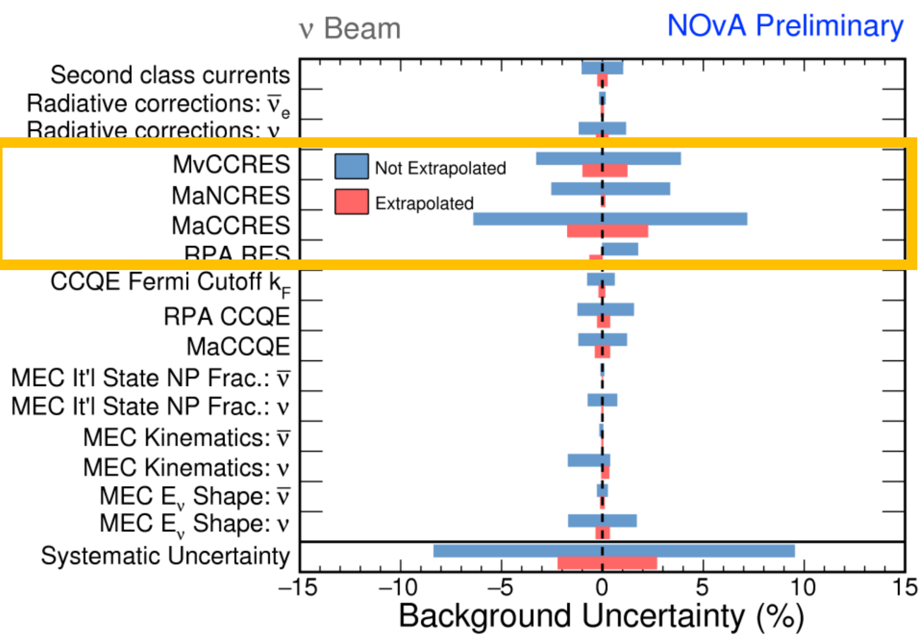
NOvA currently statistics limited

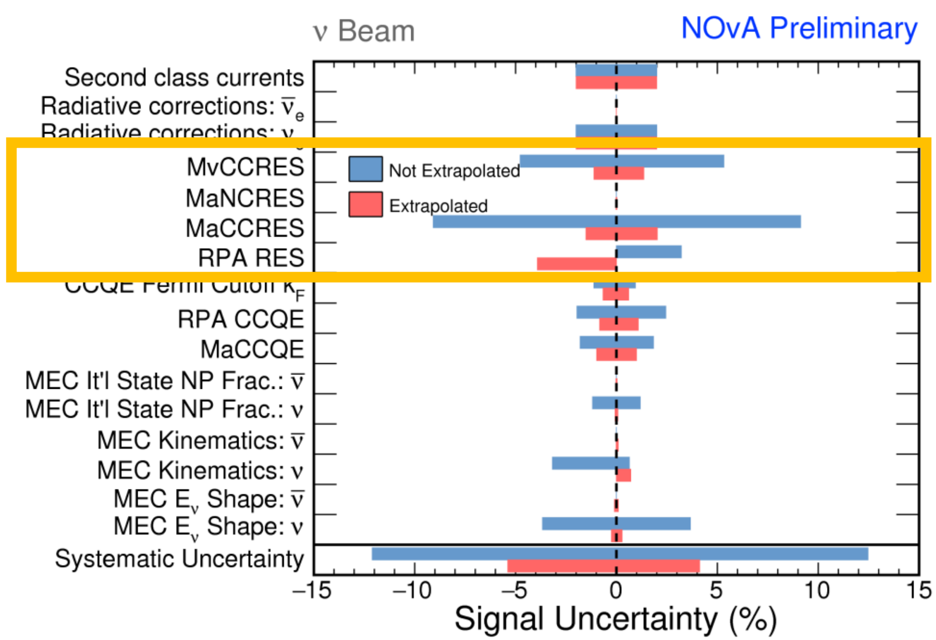
DUNE will have more stats!

Dominant systematics related to cross sections and calorimetric response

NOvA Systematics – ν_e Apperance

Breakdown of cross-section systematics



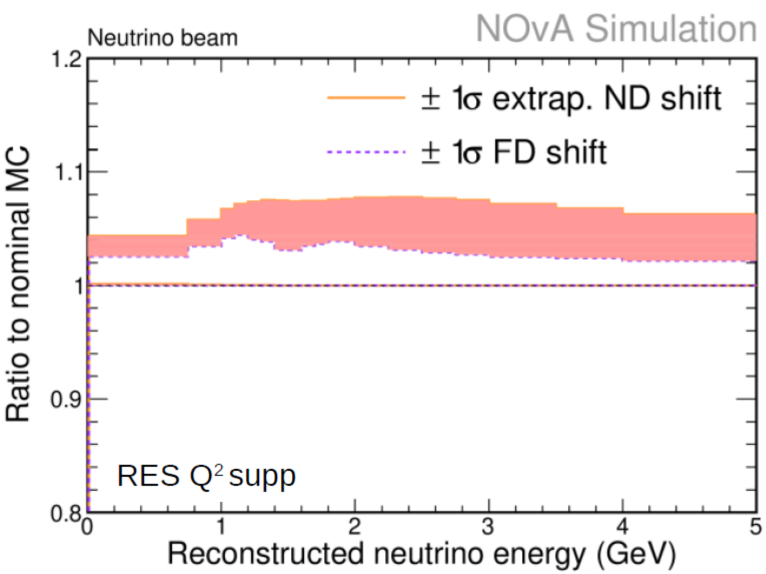


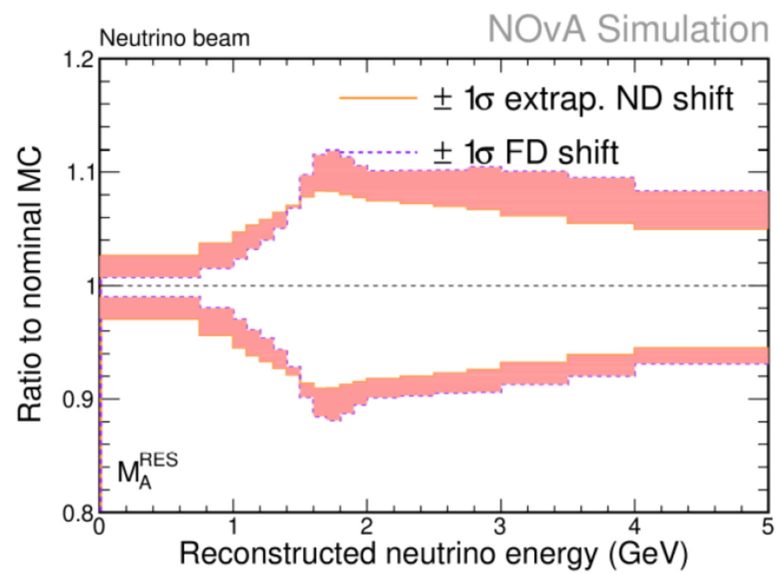
Dominant cross-section systematic from RES uncertainties (GENIE knobs + low Q^2 suppression)
Even bigger than 2p2h uncertainties

ND constraints (through extrapolation) reduce uncertainties

Low Q^2 suppression & MaCCRES uncertainties largest effect on signal

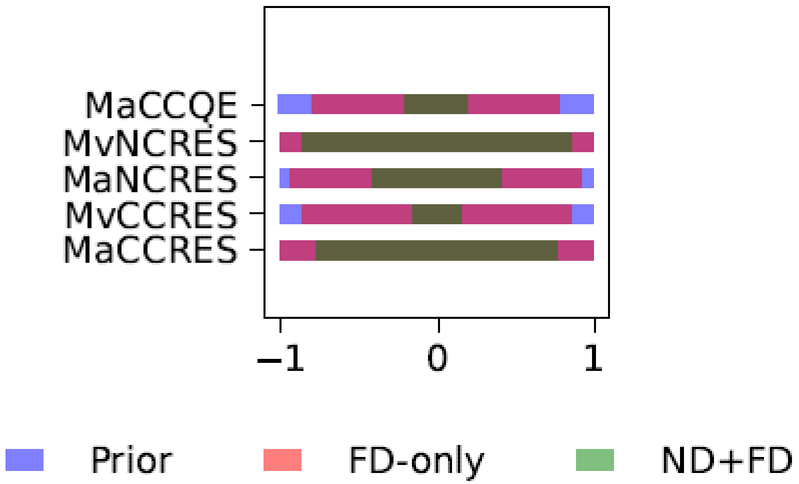
NOvA Systematics – ν_μ Spectrum

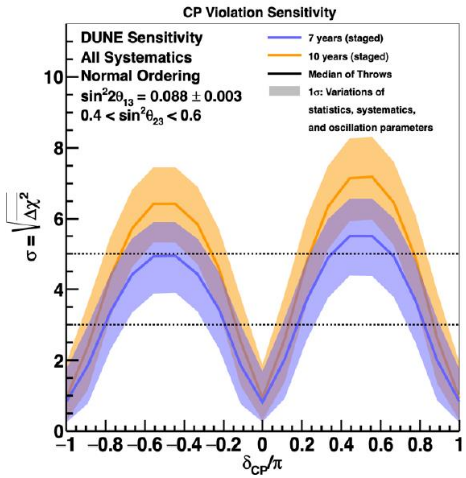


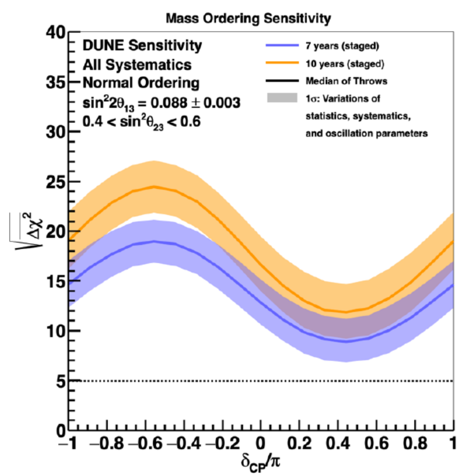


DUNE Systematics

TDR Analysis







MaCCRES uncertainties not constrained as much

Large source of cross-section uncertainty for NOvA

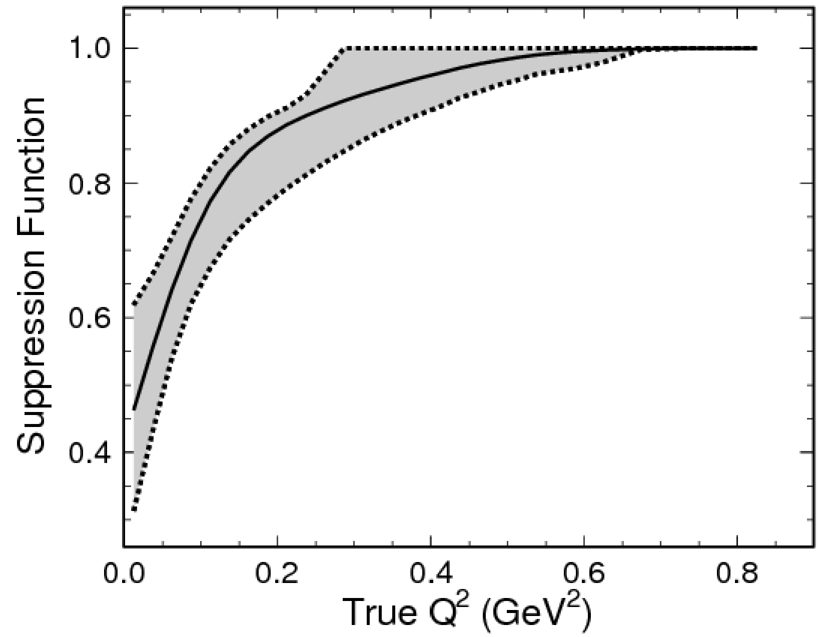
Analysis also includes uncertainties for:

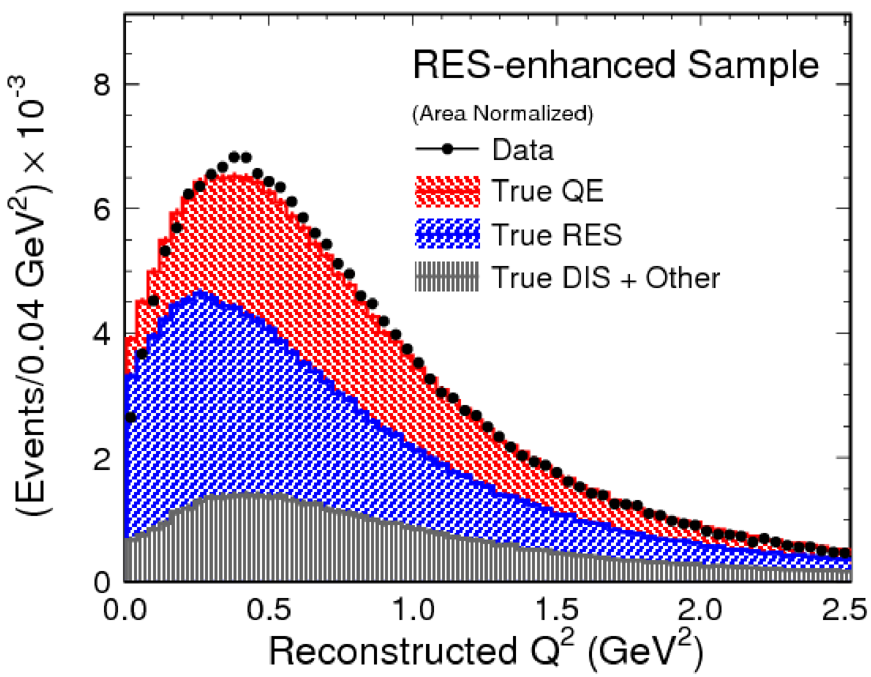
Low Q^2 suppression via Minerva data (arXiv:1903.01558)

Reweighing Rein-Sehgal for interference between RES and non-RES pion production, etc (Phys. Rev. D97 (2018) 013002)

Suppression of resonant events

The MINOS experiment previously measured less resonant events at lower Q^2 than predicted

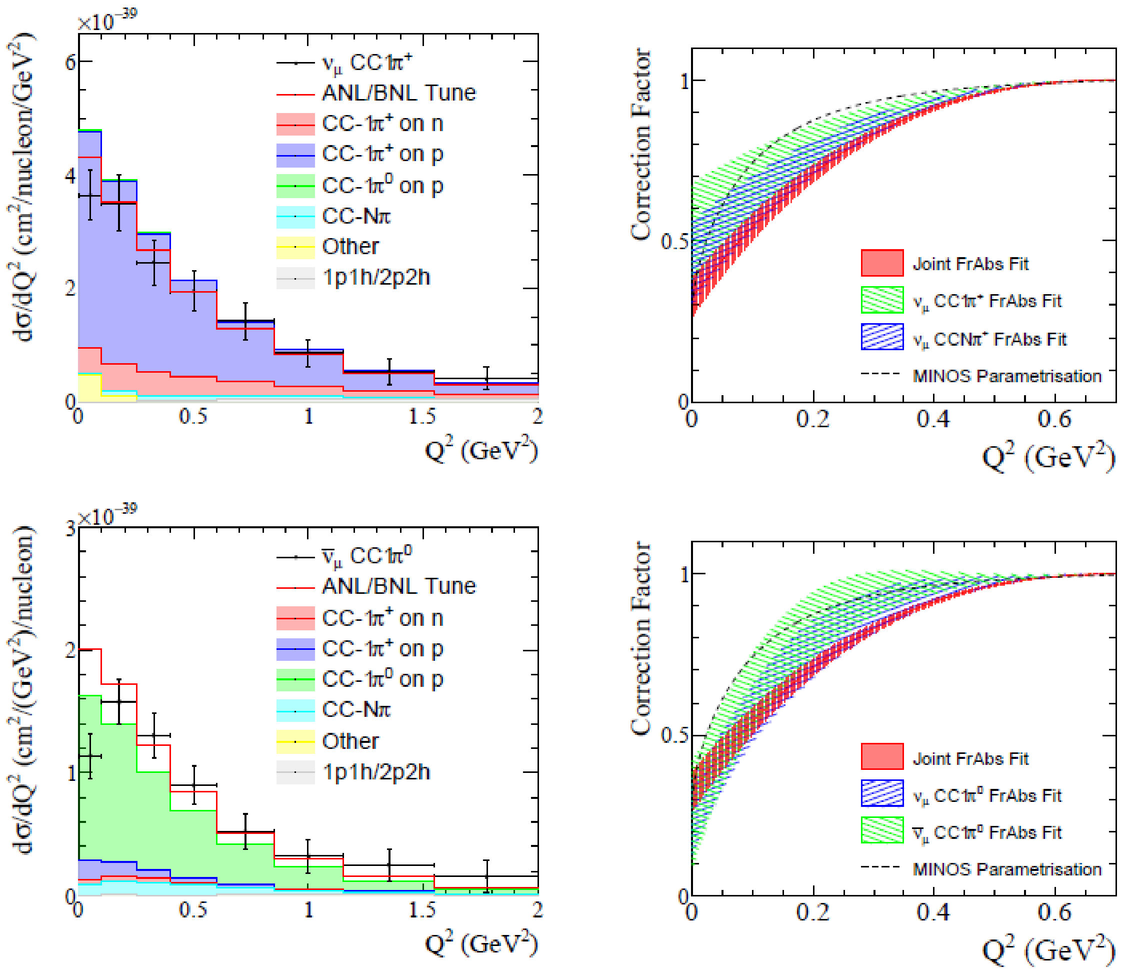




DOI:10.1103/PhysRevD.91.012005

Suppression of resonant events

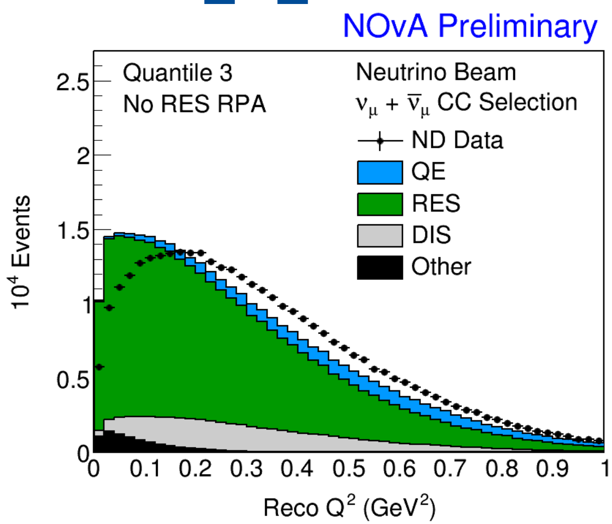
Minerva also measures less pion events at lower Q^2 than predicted

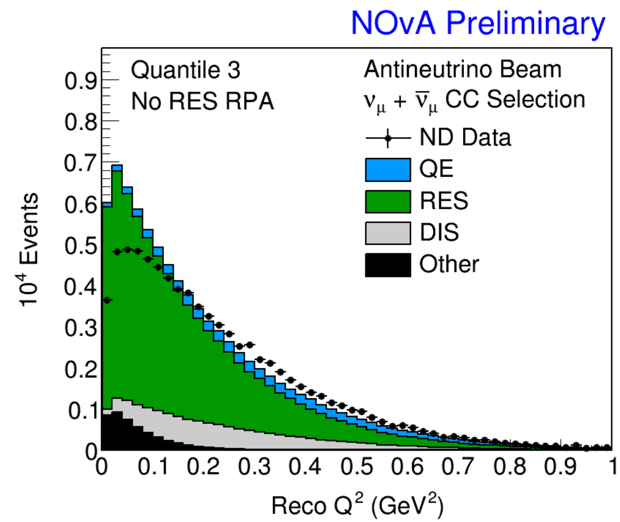


arXiv:1903.01558

NOvA – RES Suppression

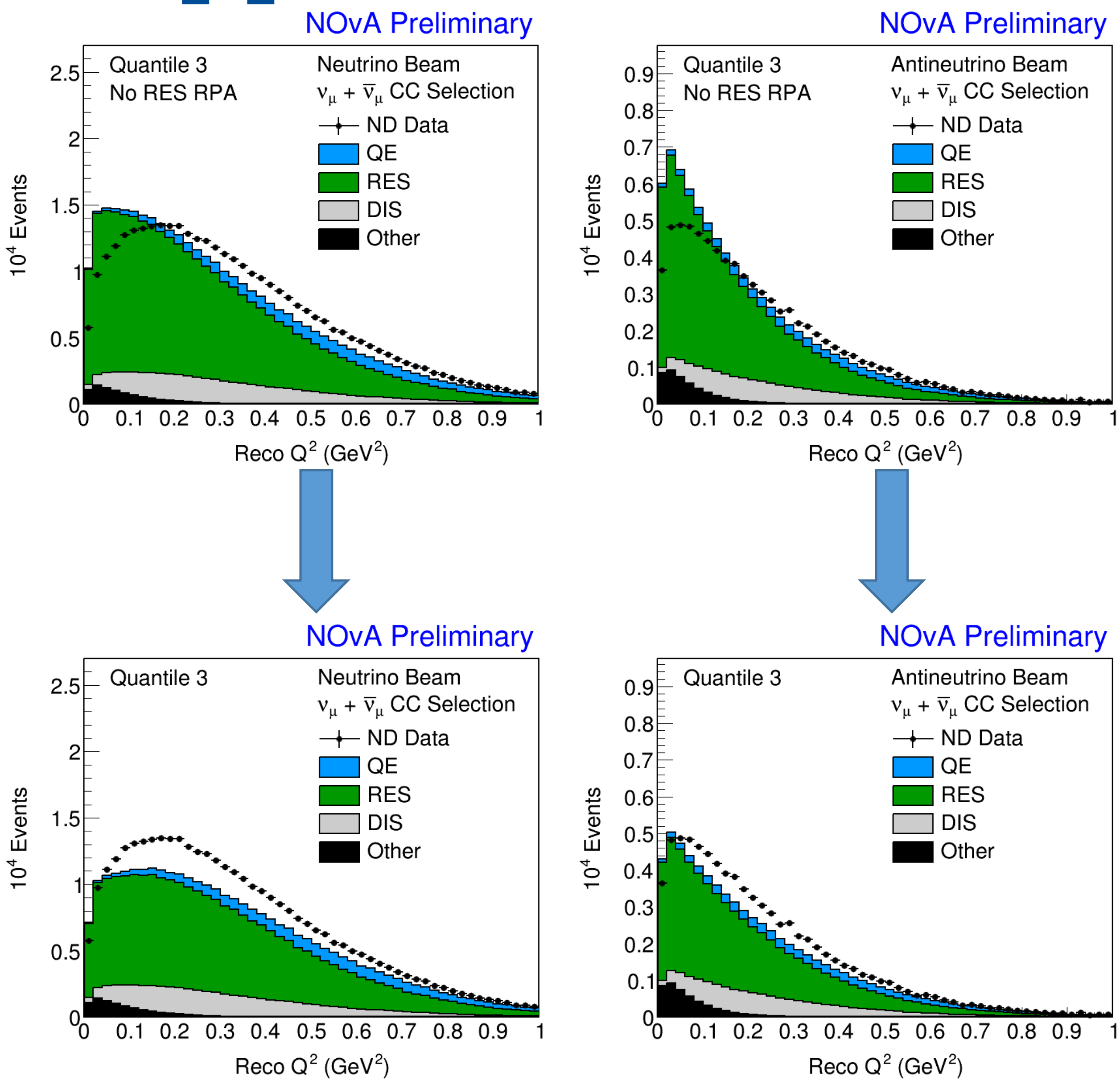
NOvA also observes less resonant events at lower Q^2 than predicted





NOvA – RES Suppression

NOvA also observes less resonant events at lower Q^2 than predicted

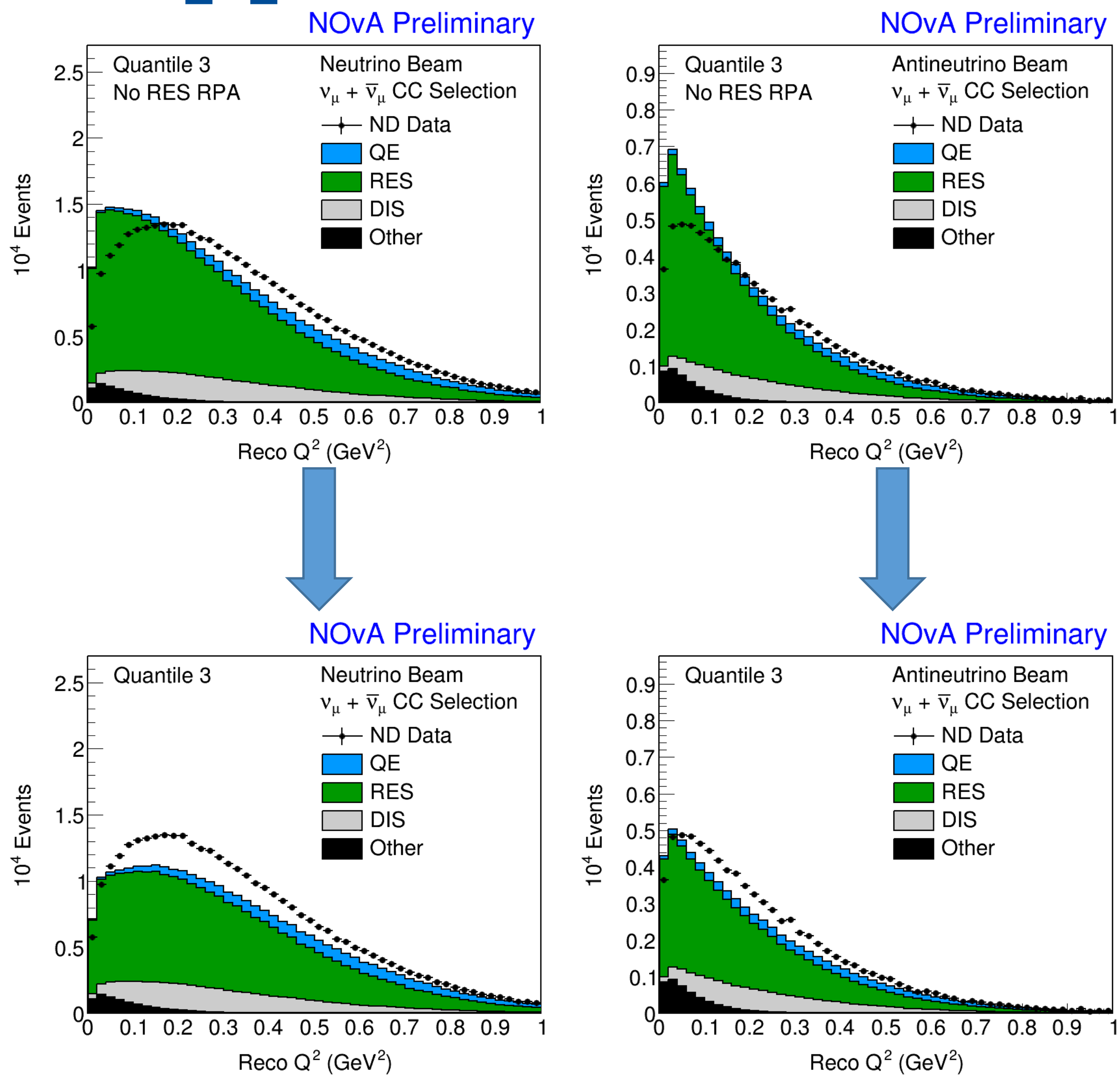


Applying Q^2 dependent suppression from Valencia QE RPA model

Take correction as new CV with 100% uncertainty

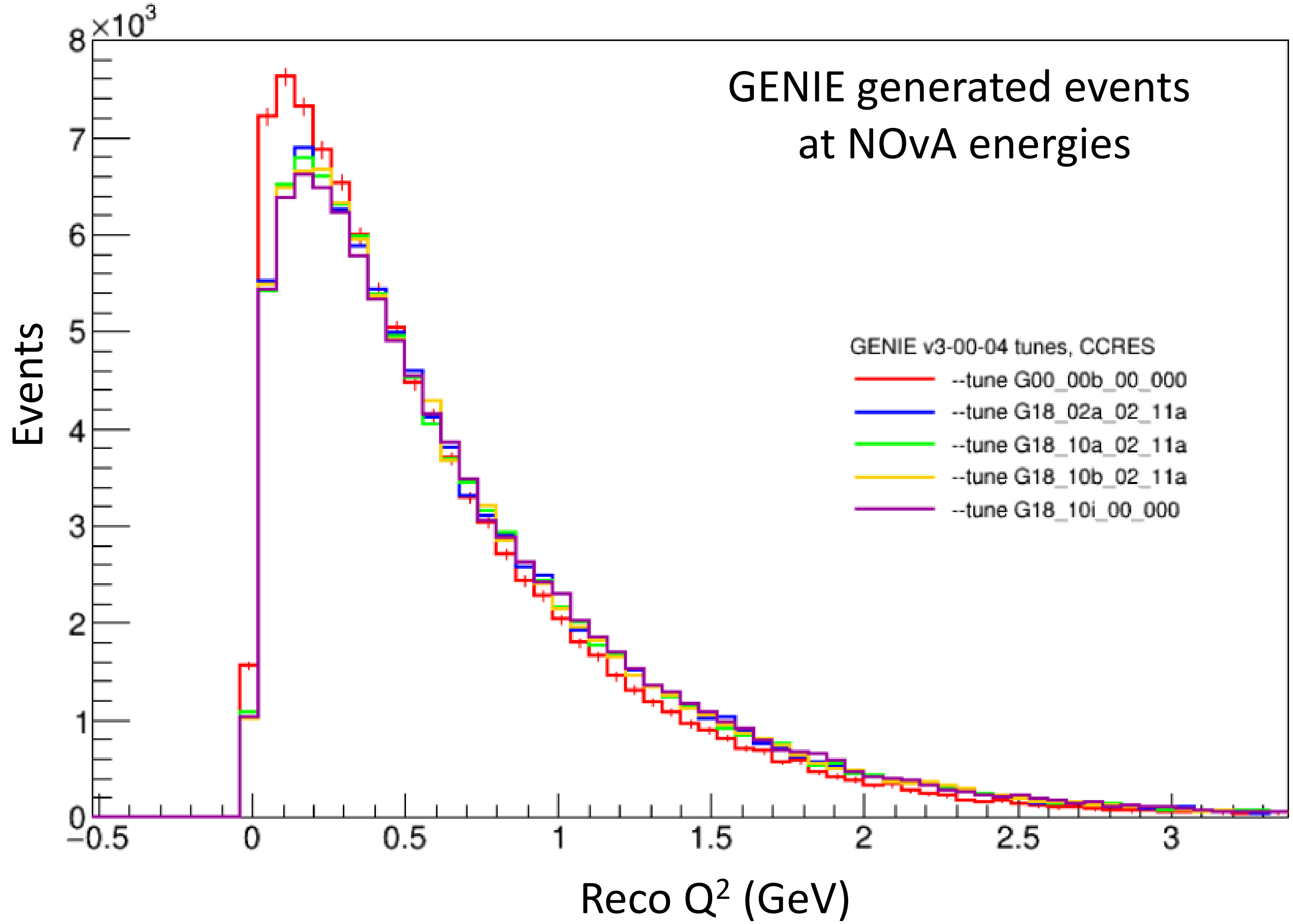
NOvA – RES Suppression

NOvA is studying effect of MINOS (iron) and Minerva (hydrocarbon) empirical weights



RES Q^2 Shape

GENIE 3 Berger-Seghal Models vs GENIE historical configuration



Summary

Resonance modelling is a large cross-section uncertainty

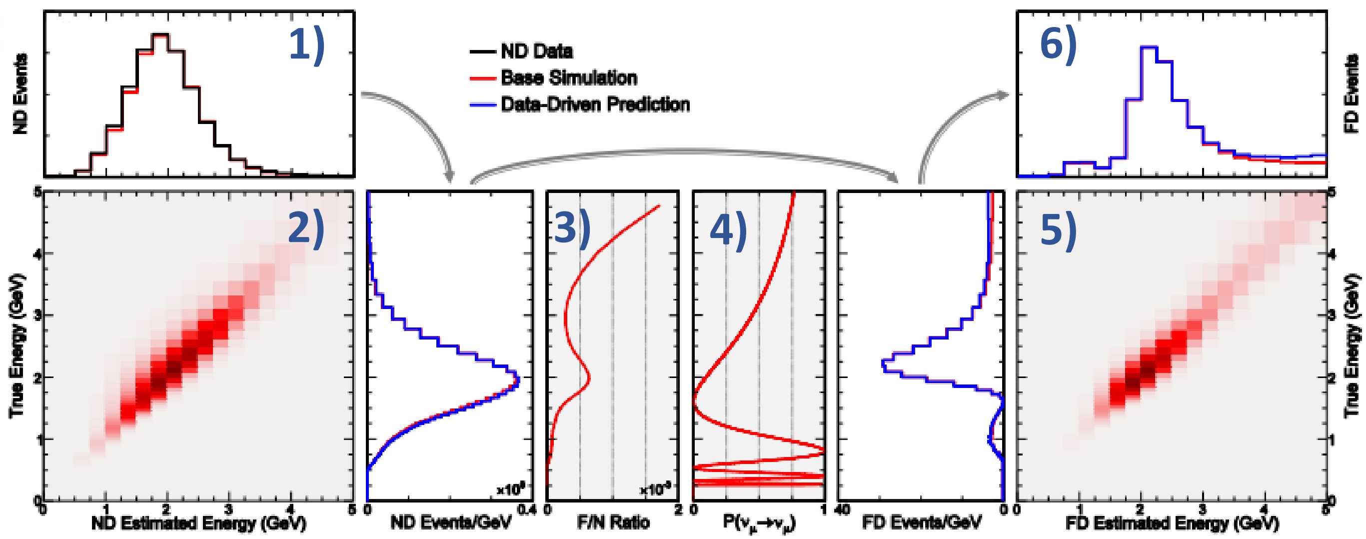
- Effect is important for predicting event yields
- Conservative uncertainties currently do not limit the oscillation analyses

Empirical modeling of low Q2 suppression

- How do we use MINOS vs Minerva?
- How do we go from NUEGEN, GENIE 2 to GENIE 3?
- What is an acceptable systematic for this effect?
  - Systematic knobs have assume some correlated effects

Extrapolation

1) Select events in ND (use data)
2) Map ND reco E to true E (use simulation)
3) Apply ratio of FD events to ND events in bins of true E (use simulation)
   Takes into account differences between two detectors
4) Apply oscillation probability on FD true E events (use simulation)
5) Map FD true E to reco E (use simulation)
6) Oscillated FD prediction



Don't need to separately measure flux, cross-section, efficiencies, etc in ND

Systematics accounted for by altering simulation at steps 2, 3, 4, and 5