New Results from the NOvA Experiment

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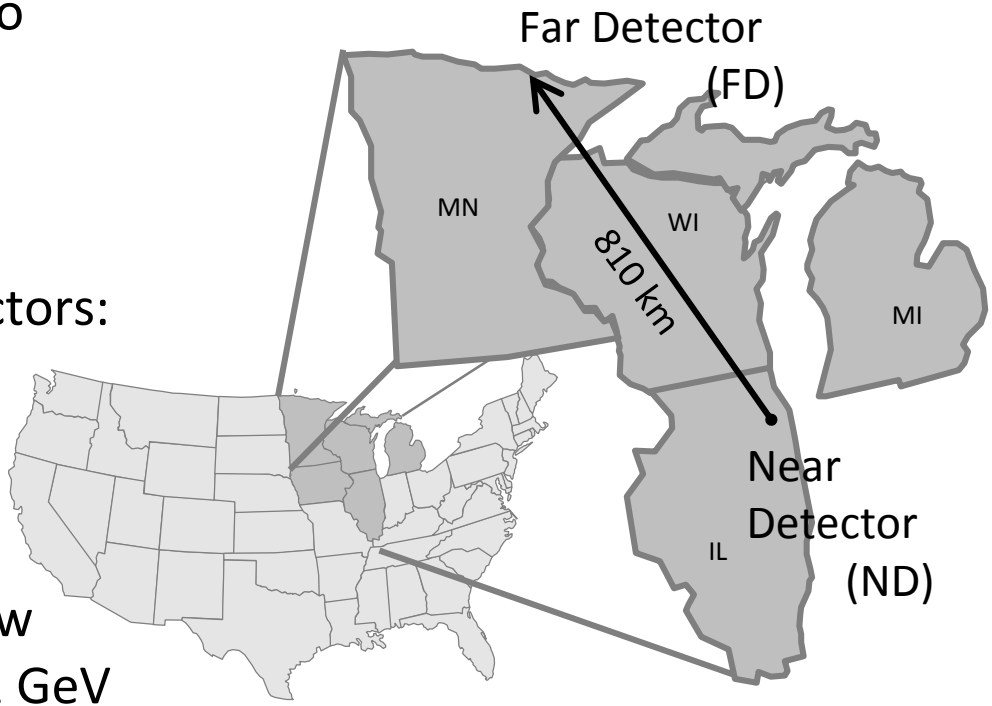
Indiana University

NuFACT 2019

August 26, 2019

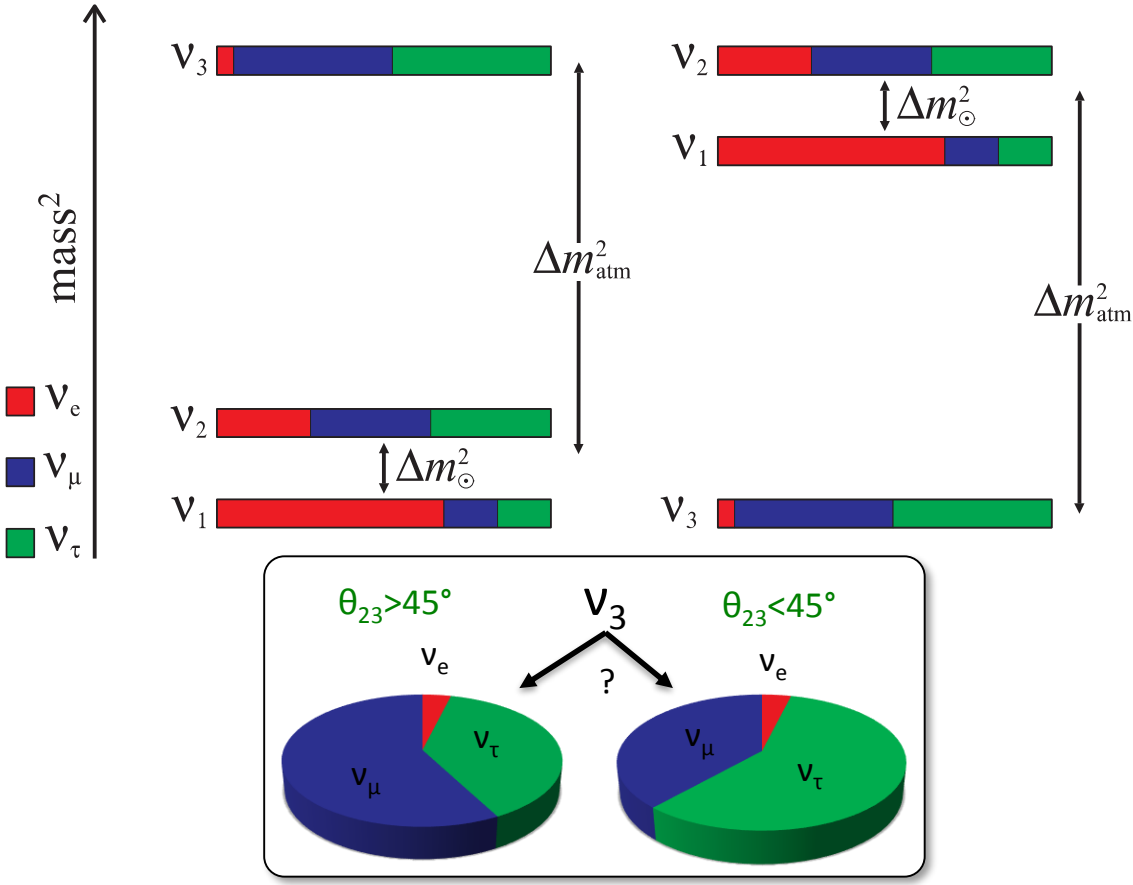
NOvA

- NOvA is a long-baseline neutrino oscillation experiment
- Study neutrinos from the NuMI beam at Fermilab
- Two functionally identical detectors:
  - Far Detector (FD)
    14 kton; on the surface
  - Near Detector (ND)
    0.3 kton; underground
- Off axis position provides narrow band beam that peaks around 2 GeV



Physics Goals

- What is the neutrino mass hierarchy?
- Is there a ν_μ-ν_τ symmetry?
  - Is the large mixing angle maximal, and if not, what is the octant?
- Is CP violated in the lepton sector?
- Are there other neutrinos beyond the three active flavors?



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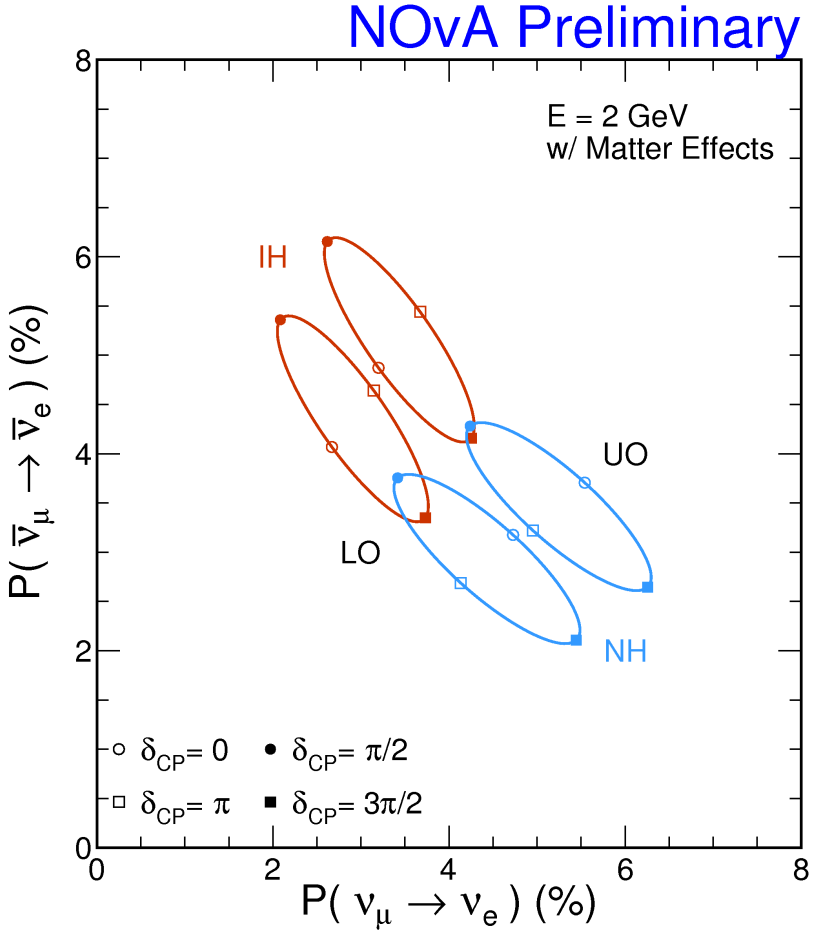
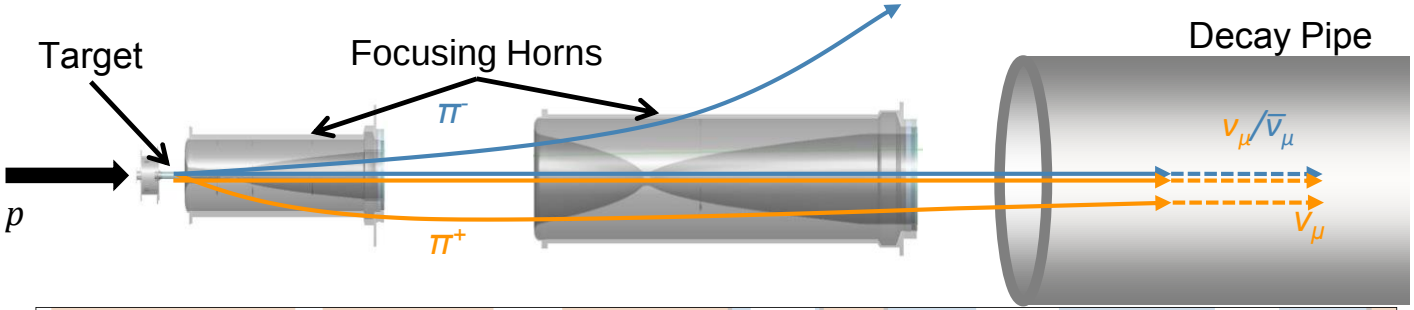
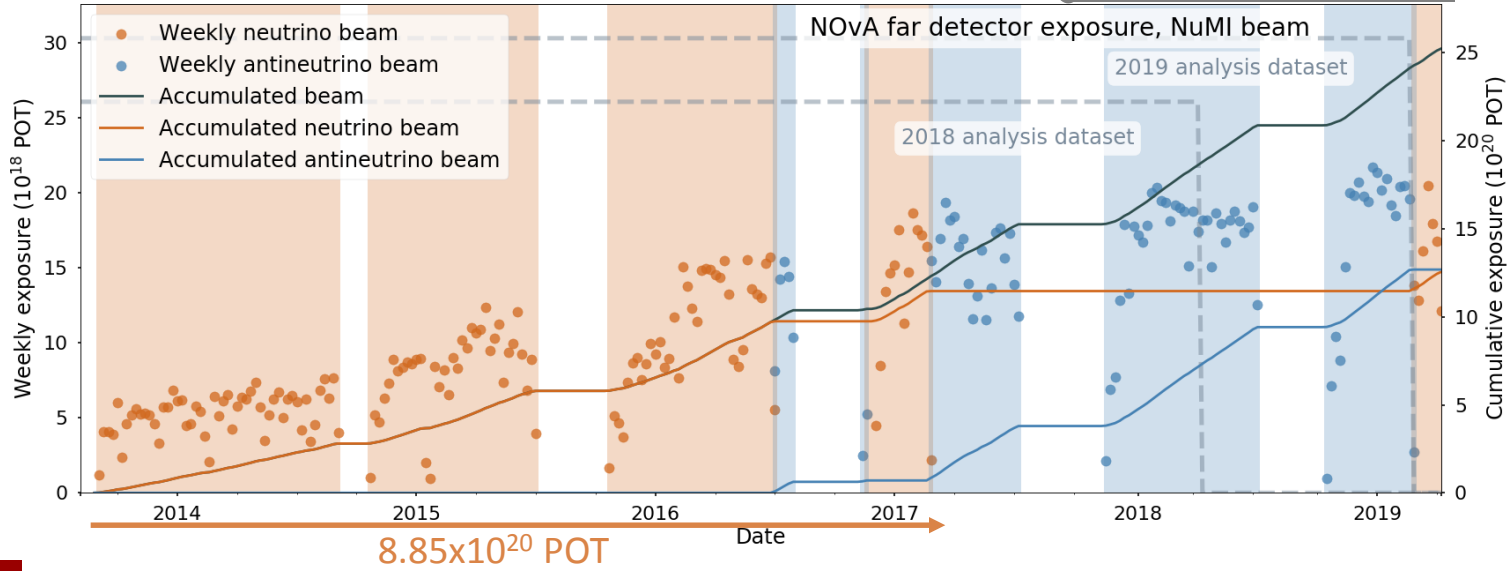


The NuMI Neutrino Beam



Flux 1-5 GeV
95% ν_μ
4% $\bar{\nu}_\mu$
1% ν_e



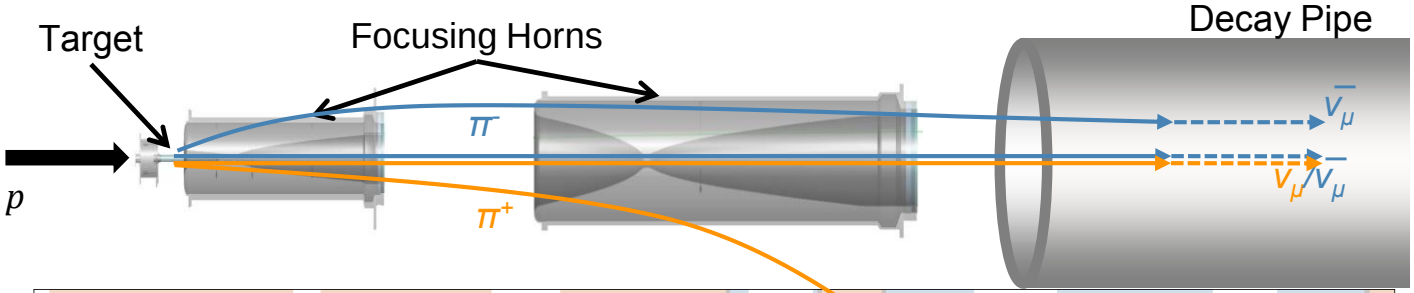
The NuMI Antineutrino beam

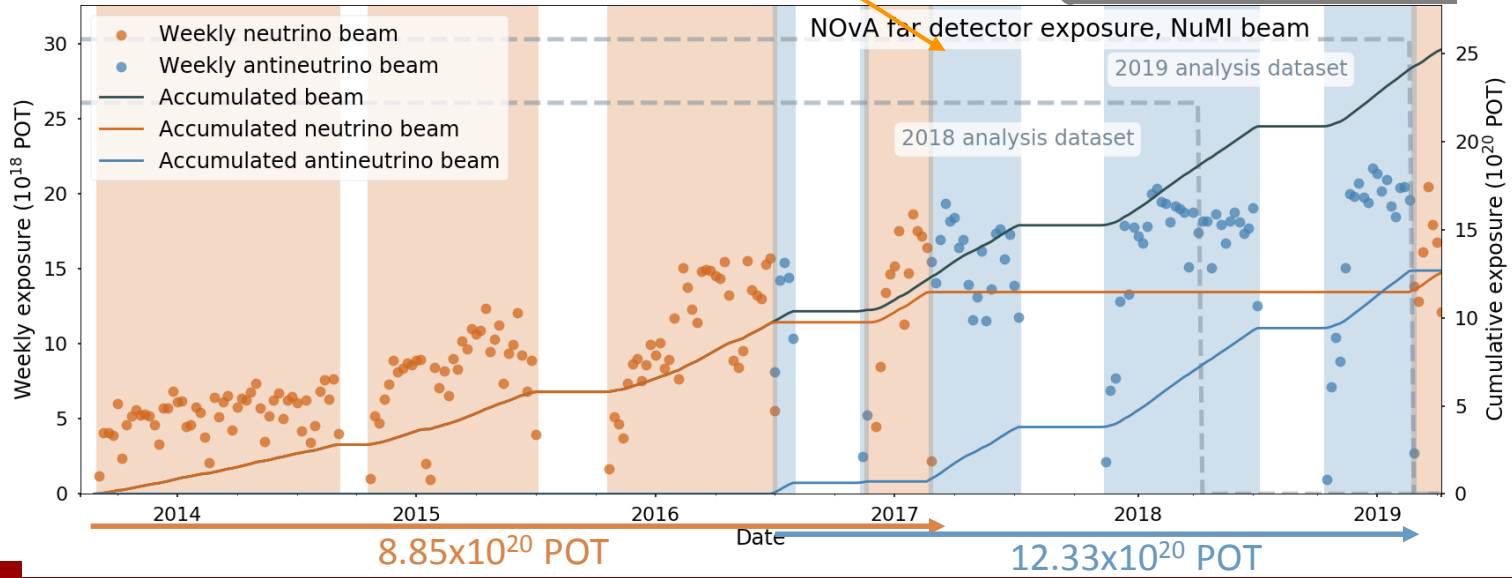
Flux 1-5 GeV

6% ν_μ

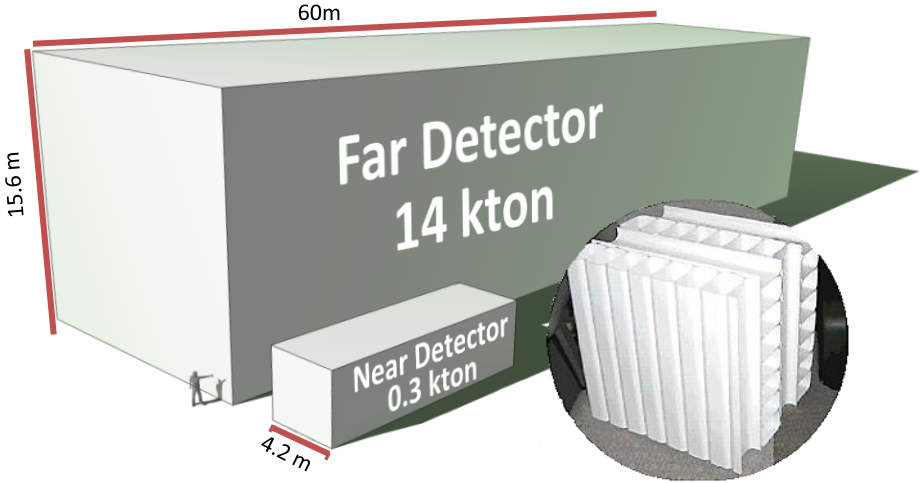
93% $\bar{\nu}_\mu$

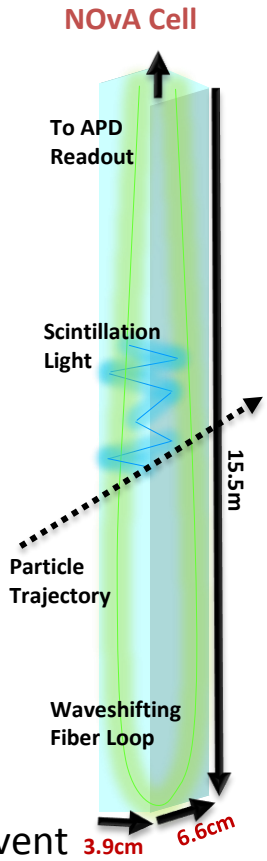
1% ν_e

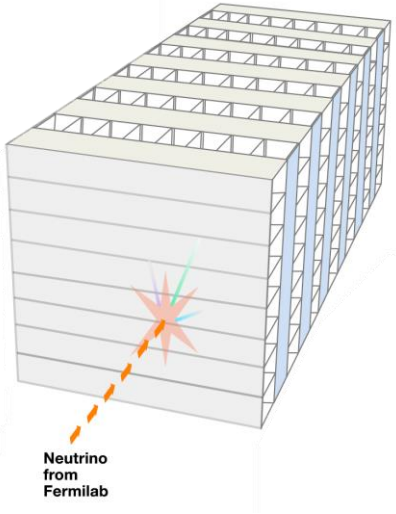


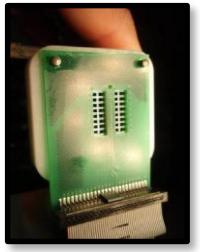


NOvA Detectors



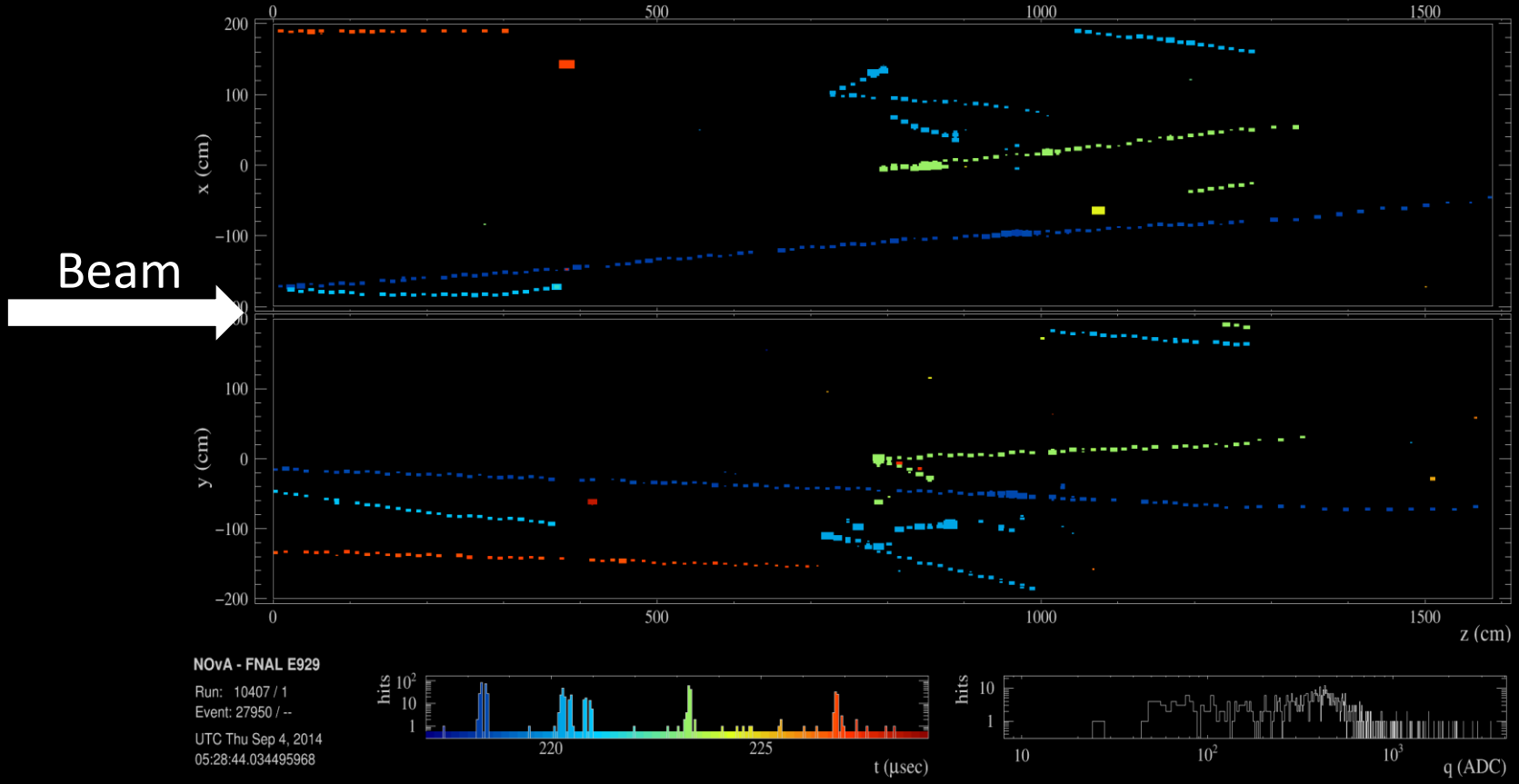






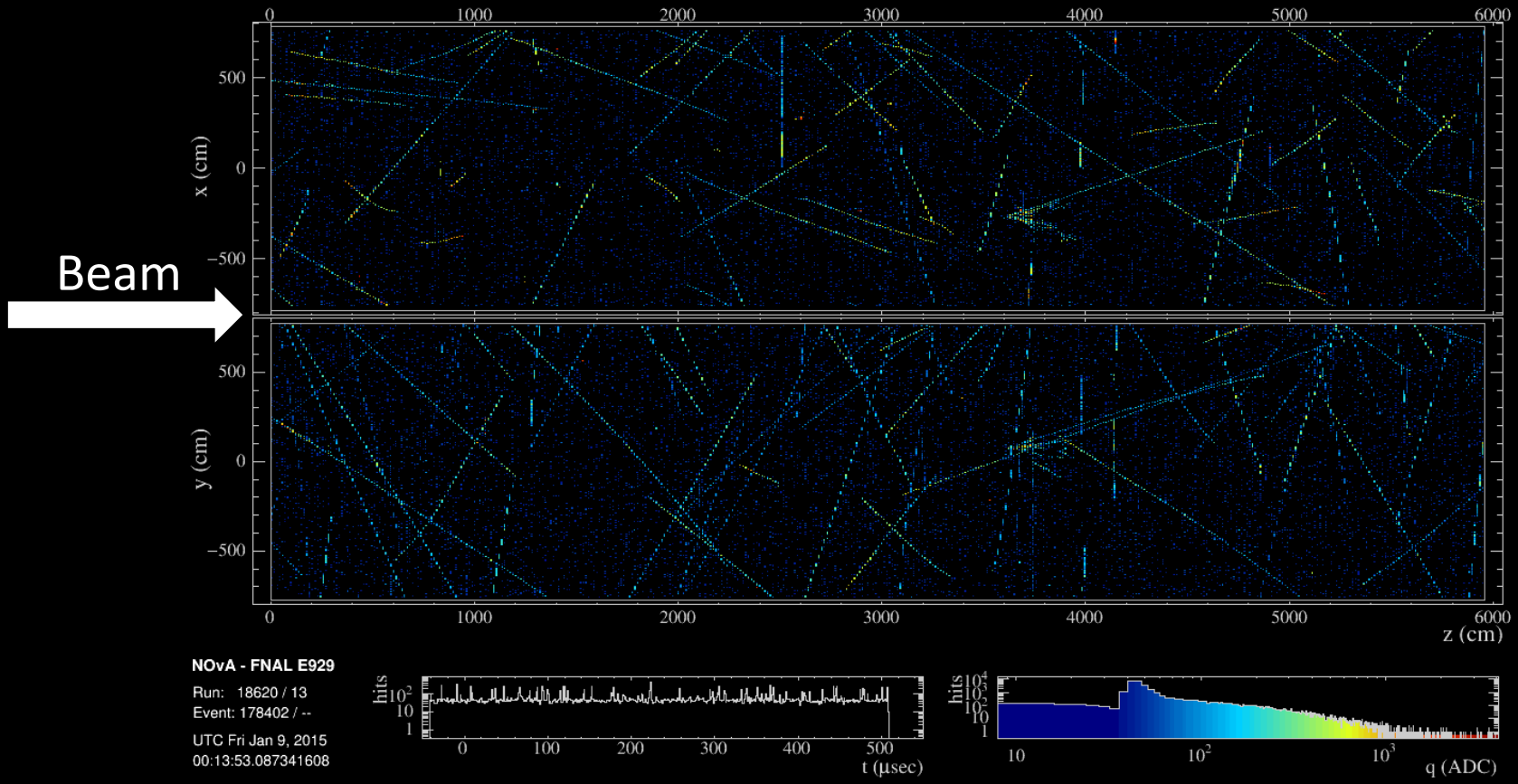
- Detectors are fine-grained, low-*Z*, highly-actively tracking calorimeters
- Cells are PVC, filled with liquid scintillator
- Read out via wavelength shifting fiber to APD
- Orthogonal layers of cells → top and side view for each event

Near Detector Event Display



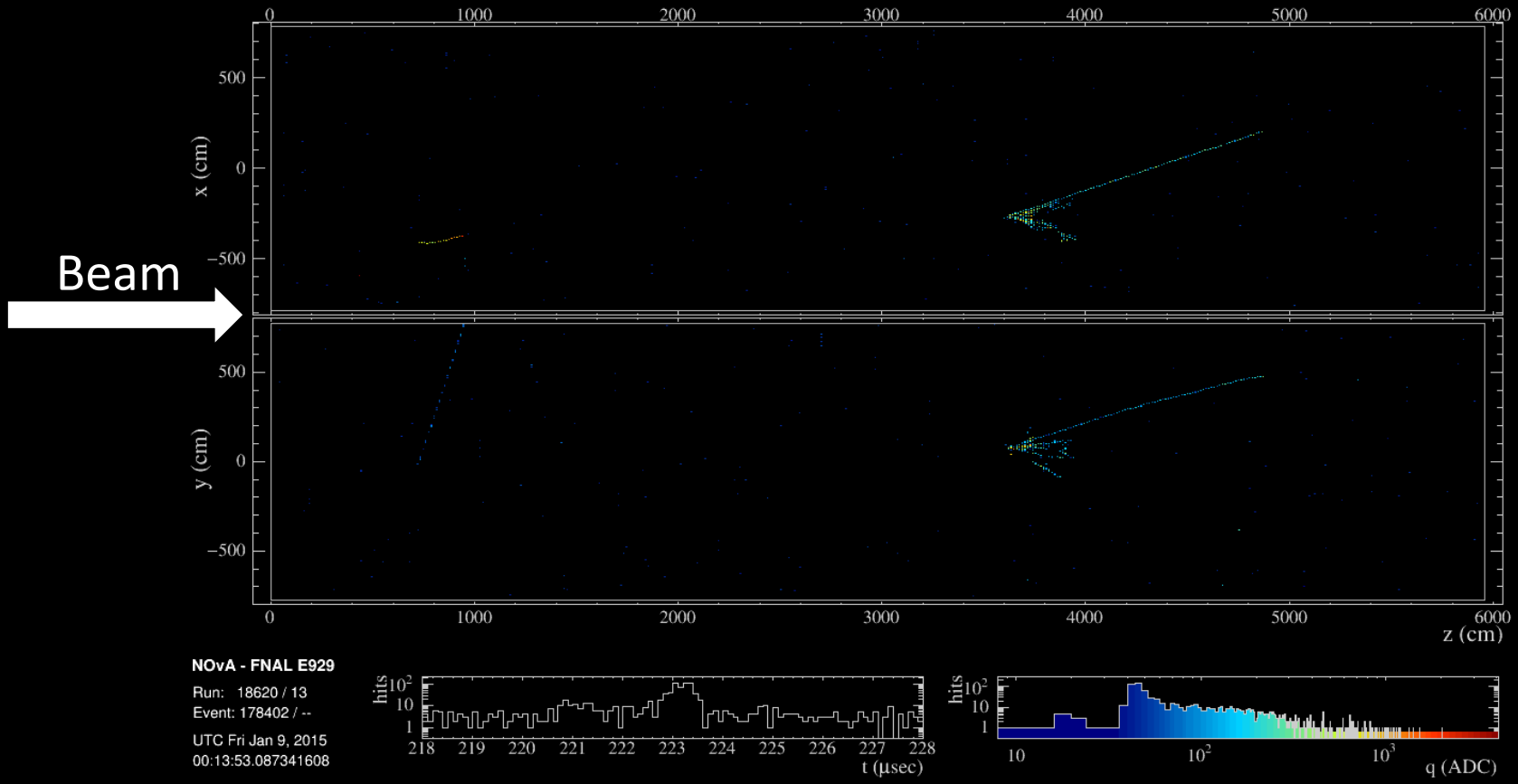
(colors show hit times)

Far Detector Event Display – 550 µs



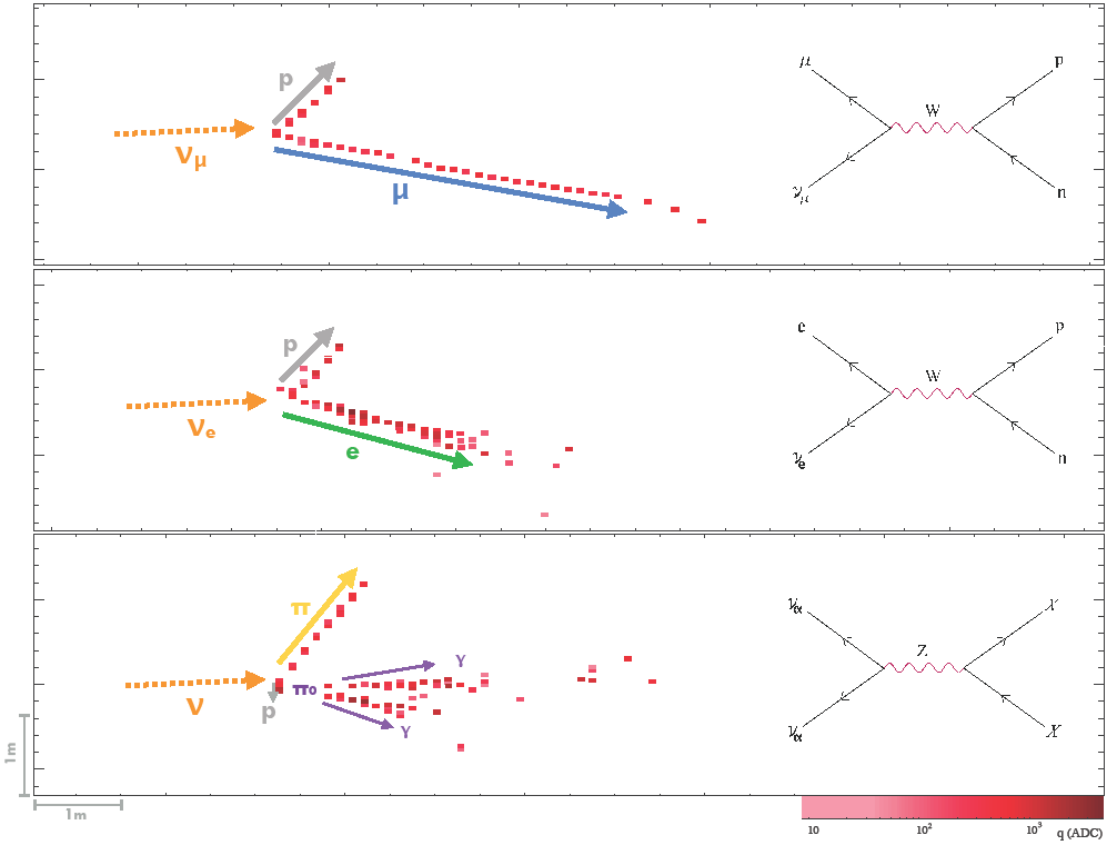
(colors show charge)

Far Detector Event Display – 10 µs



(colors show charge)

Selected Events from Near Detector Data



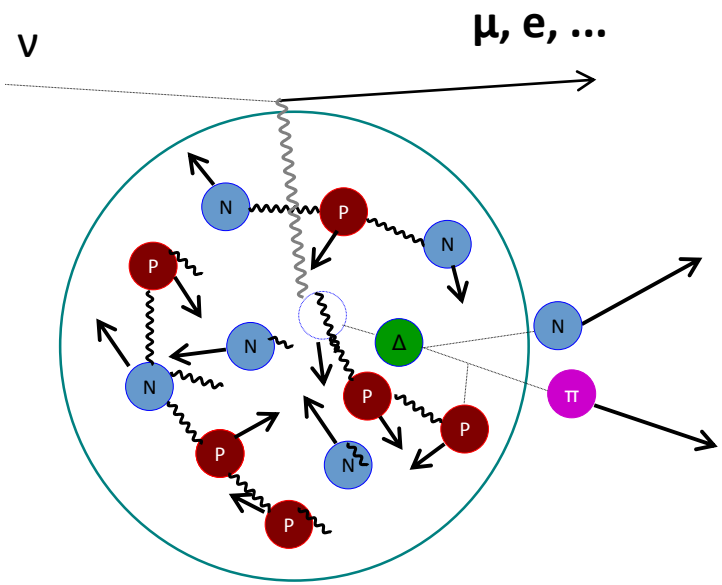
Cross section Measurements

How well do we understand neutrino interactions in our detector?

See talk: H. Duyang, WG2, Aug 27

Motivation

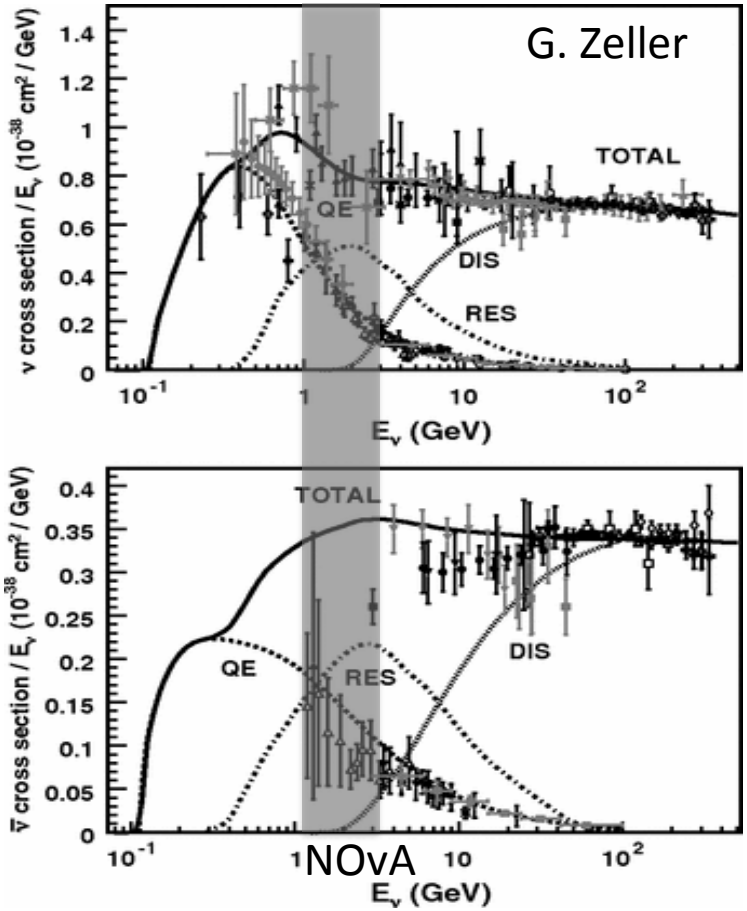
- High statistics datasets in our ND
- Cross section uncertainty is one of our largest systematics in the oscillation analyses
- Understanding nuclear effects is important to be able to reconstruct neutrino energy
  - i.e. do we model neutrino scattering well enough to be able to predict $E_{true} \rightarrow E_{reco}$



Measurements in Progress

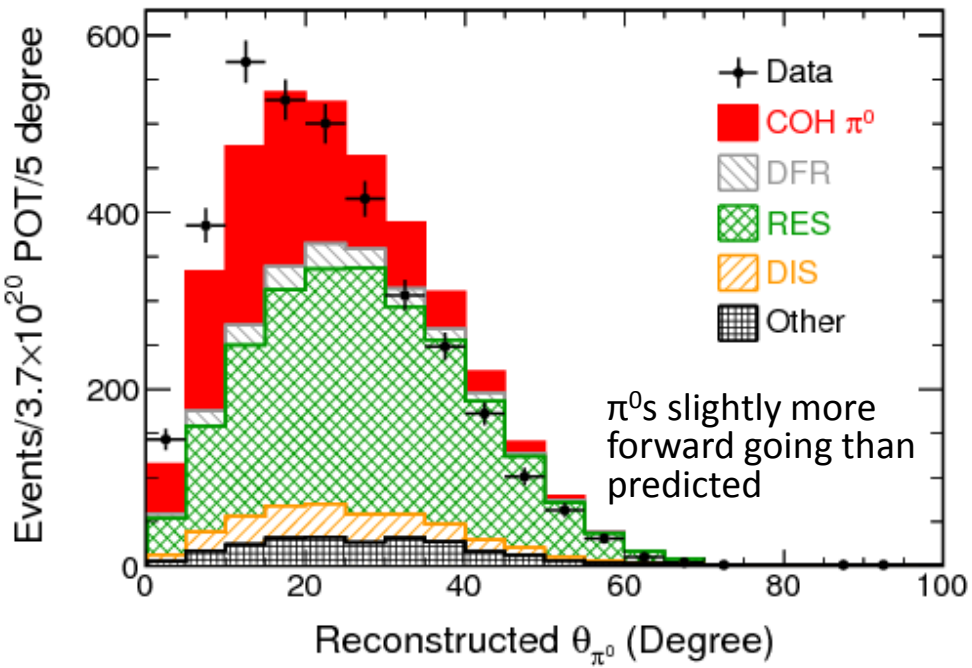
In neutrino and antineutrino modes –

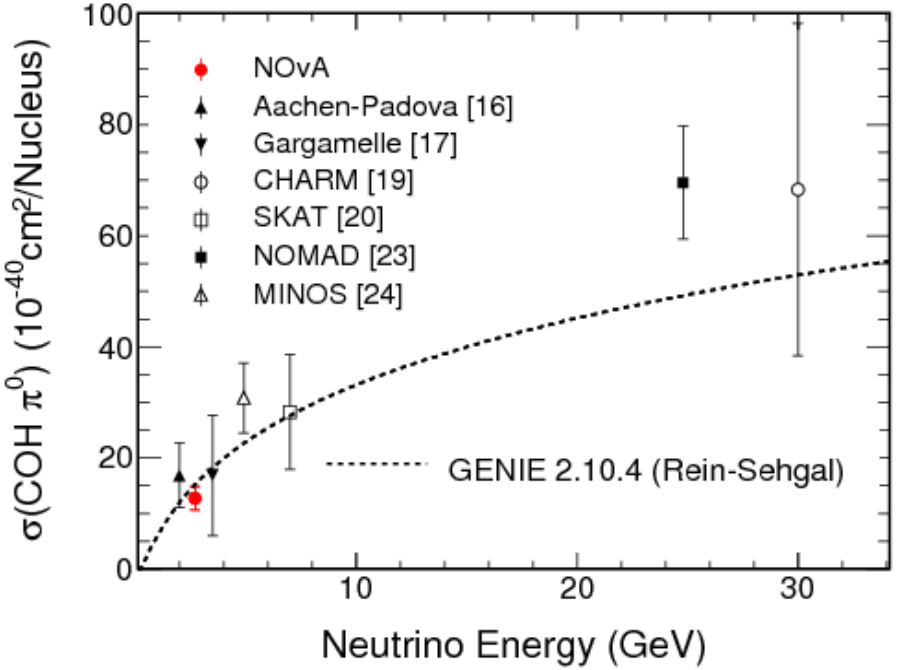
- Charged current measurements:
  - ν_μ CC 0π
  - **ν_μ CC π^0**
  - ν_μ CC $\pi^\pm$
  - **ν_μ CC inclusive**
  - ν_e CC inclusive
- Neutral current measurements:
  - **NC ν COH π^0**
  - NC ν π^0 semi-inclusive



NC Coherent π^0

arxiv:1902.00558, submitted to PRD





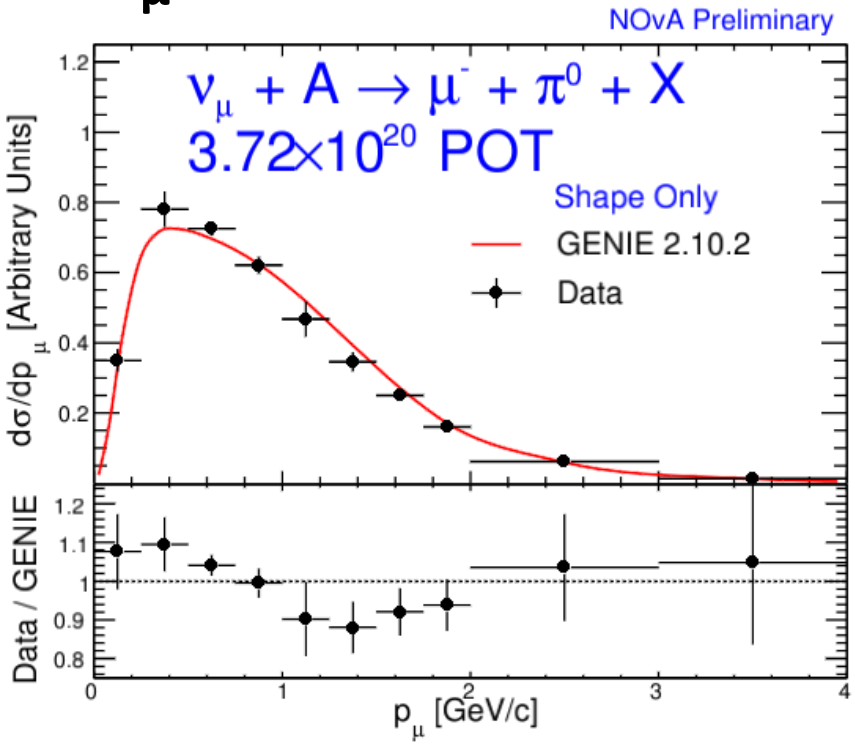
$\sigma = 14.0 \pm 0.9$ (stat.) ± 2.1 (syst.) $\times 10^{-40}$ cm^2 /nucleus

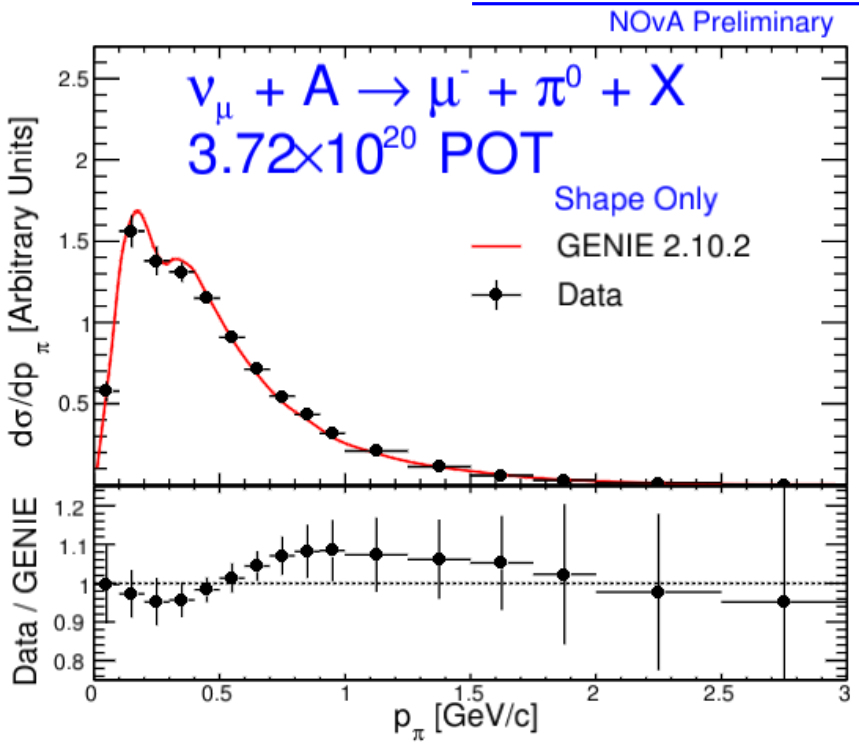
consistent with model prediction

ν_μCC Semi-inclusive π^0

Paper in preparation

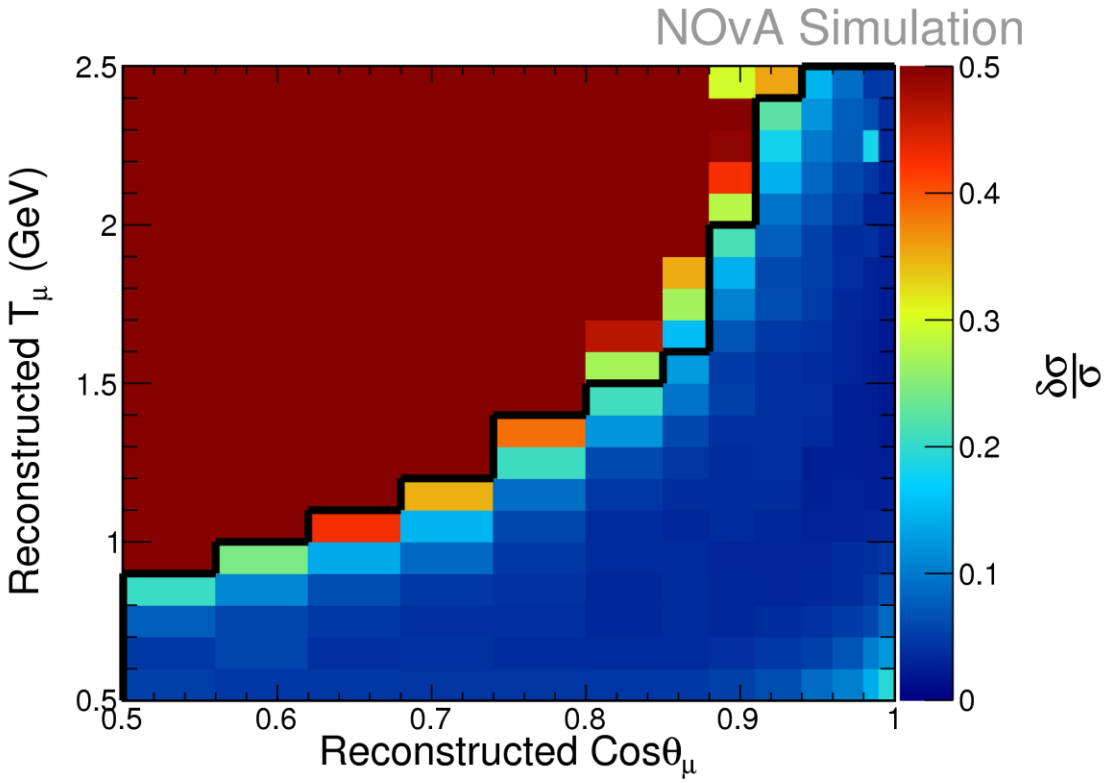
Fermilab JETP seminar

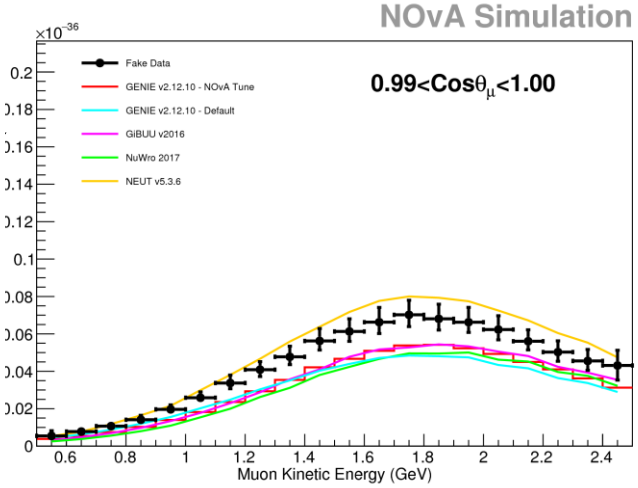




- Reporting result as differential cross section as a function of Q^2 and muon and pion kinematics
- Generally consistent with GENIE

ν_μCC Inclusive





- Double differential cross section as a function of muon kinematics
- Uncertainties driven by flux, energy scale
- Mock data study. Real data coming soon

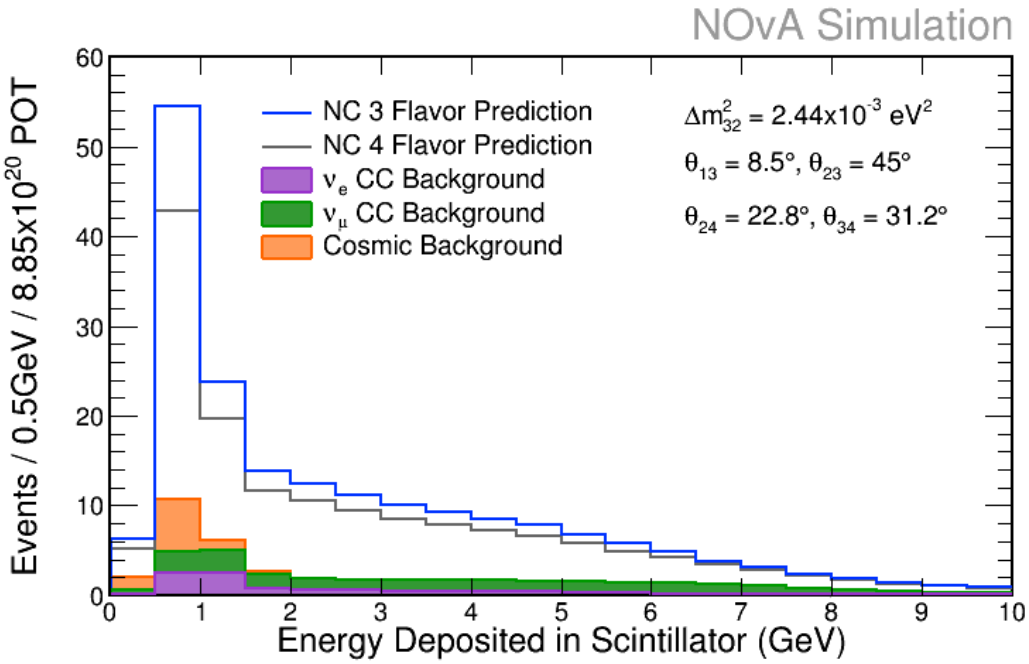
Neutral Current Analysis

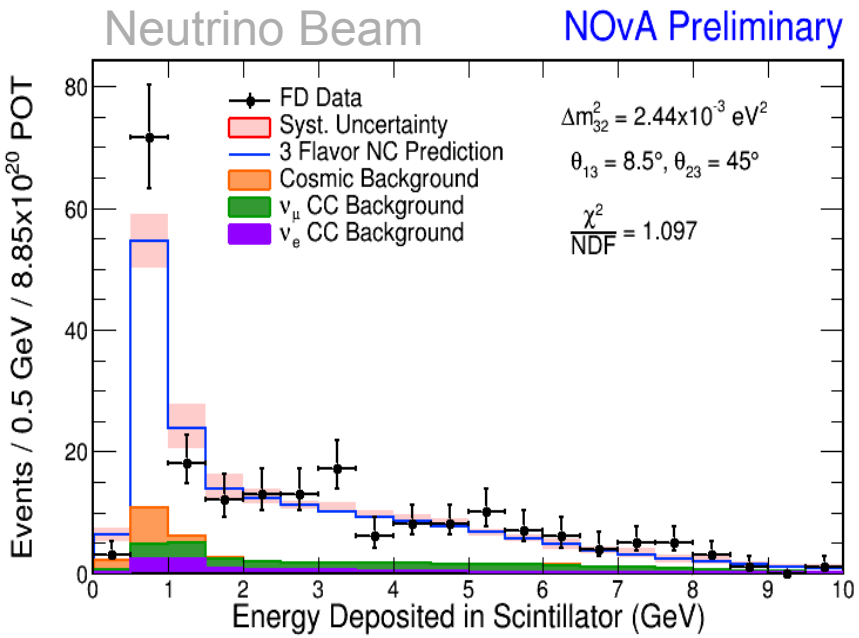
Are there other neutrinos beyond the three known active flavors?

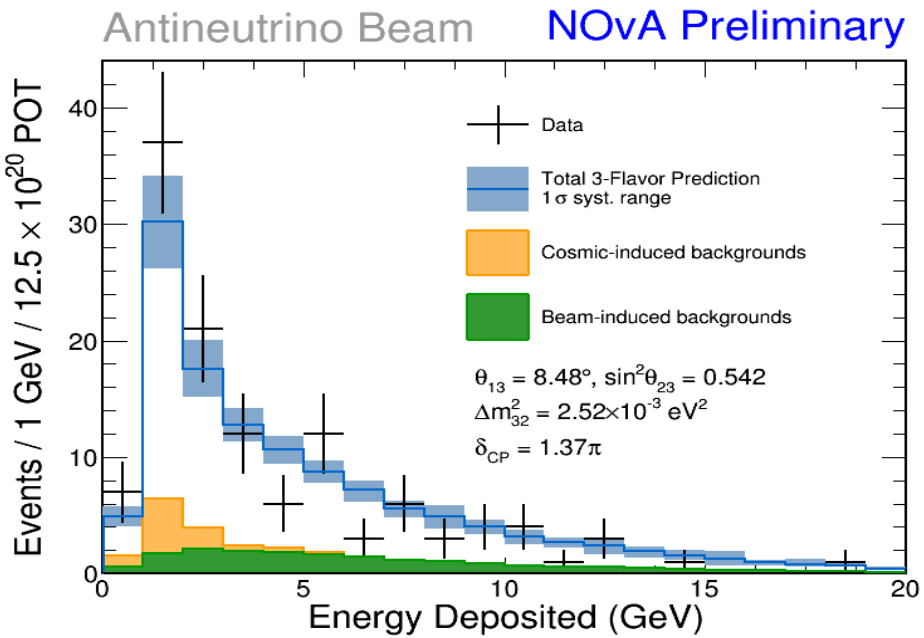
See talk: A. Aurisano, WG1+5, Aug 30

Long Baseline Neutral Current Disappearance

- NC interaction rate is the same for 3 active neutrino flavors – insensitive to 3 flavor oscillations
- Oscillations to sterile neutrino states will result in deficit in NC interaction rate
- Sensitive to mixing parameters θ_{24}, θ_{34}, Δm^2_{41}





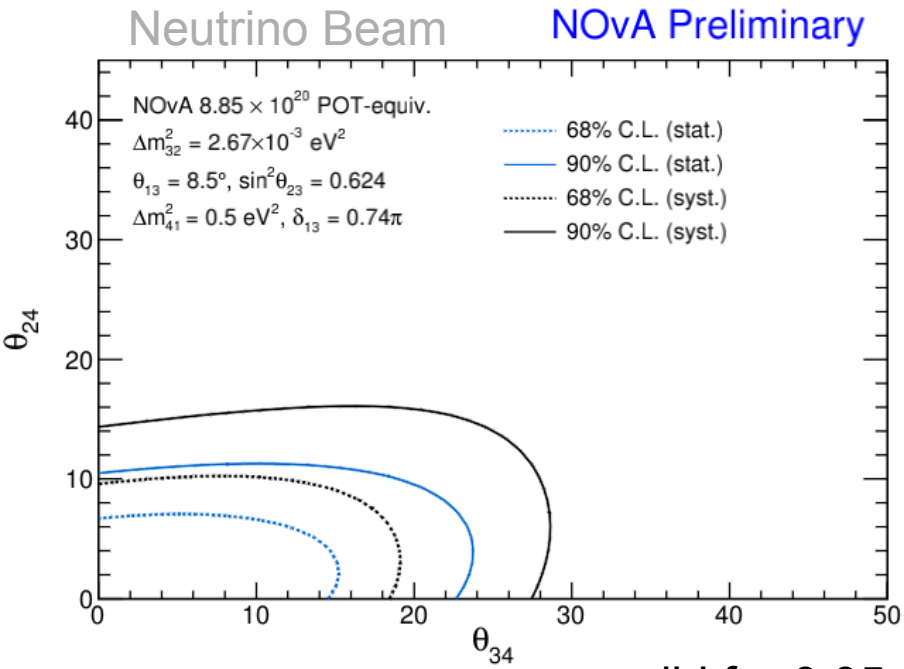


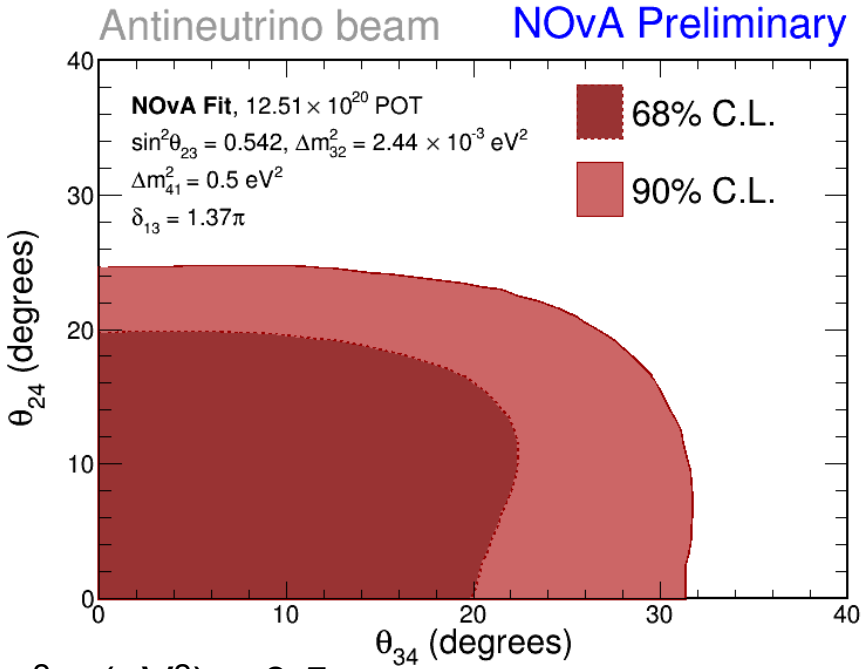
Predict 191.2 ± 13.8 (stat) ± 22.0 (syst) events
Observed 214

Predict 69 ± 8 (stat) ± 10 (syst) events
Observed 61

No evidence for NC disappearance

Limits





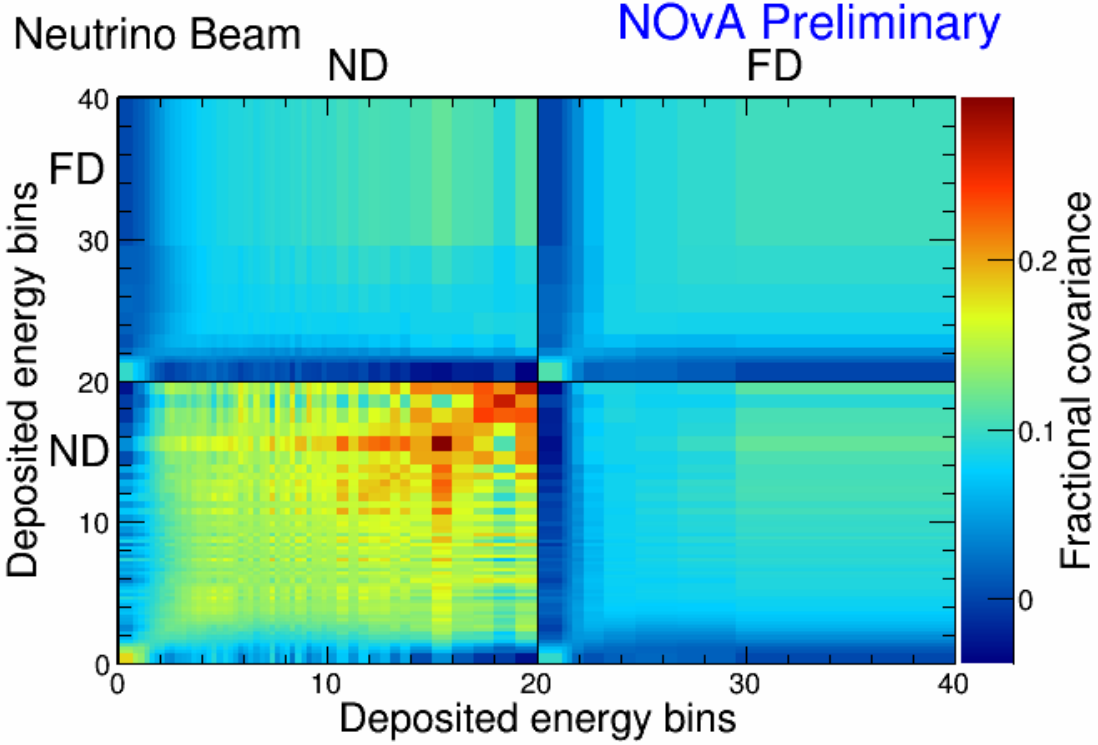
valid for $0.05 < \Delta m^2_{41}\ (eV^2) < 0.5$

$\theta_{24} < 16.2^o$, $\theta_{34} < 29.8^o$ (90%CL)

$\theta_{24} < 24.7^o$, $\theta_{34} < 31.7^o$ (90%CL)

Future

- Currently using data-driven near-to-far ratio approach which assumes no oscillations at the ND
- In the future, use covariance matrix technique to perform joint ND-FD fit to produce contours
  - Allows for oscillations in the ND
  - Extends reach to higher Δm^2_{41}
- Short baseline oscillation results from the ND



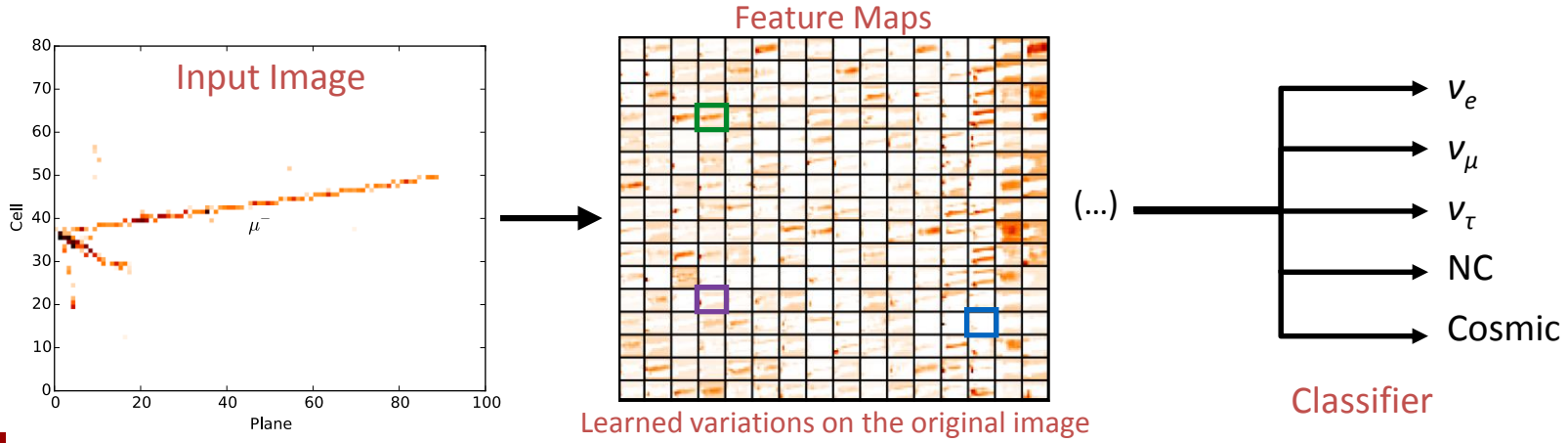
Three Flavor Analysis

Is there ν_μ-ν_τ symmetry?
What is the mass hierarchy?
Is CP violated in the lepton sector?

See talk: S. Calvez, WG1, Aug 29

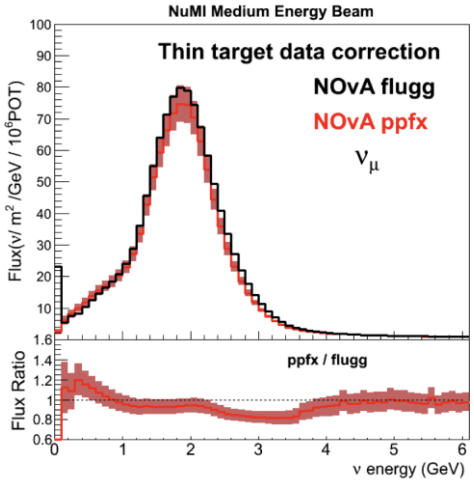
Event Identification

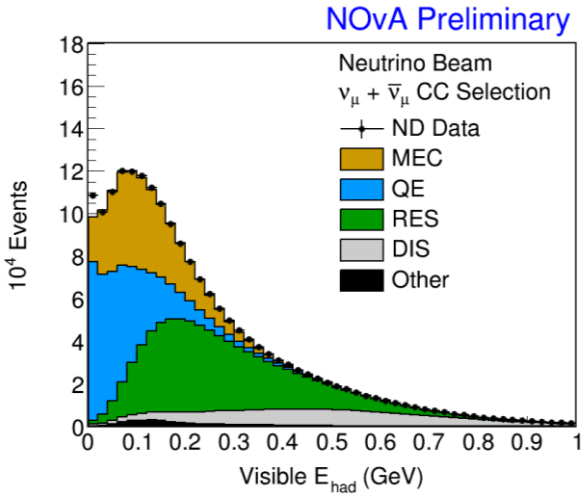
- Event ID is done by our CNN, called Convolutional Visual Network (CVN)
  - Employs a deep convolutional network in the “image recognition” style
  - Trained on two dimensional views of the event’s calibrated hits
  - Information of each view is combined in the final layer of the network
- Trained separately on neutrinos and antineutrinos
- Effective exposure increase of 30% for ν_e selection (JINST 11, P09001)



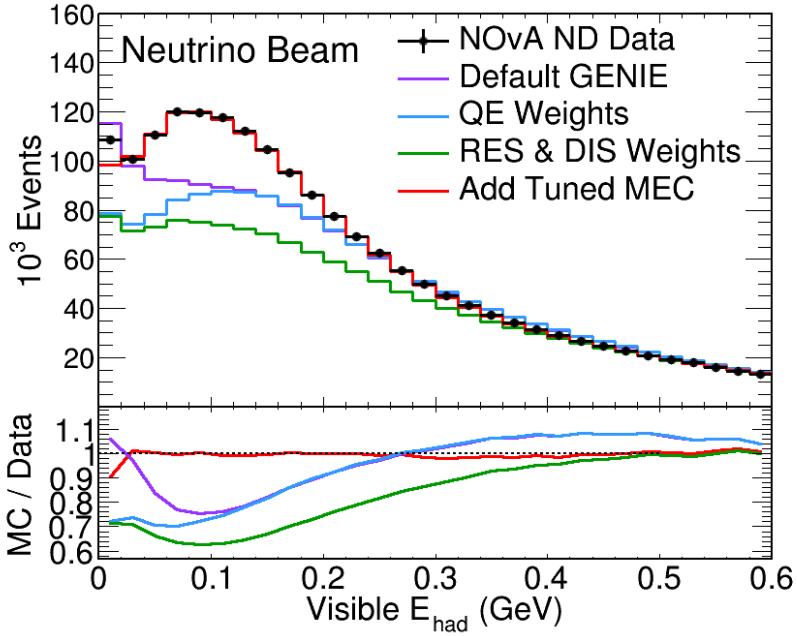
Simulation Tuning

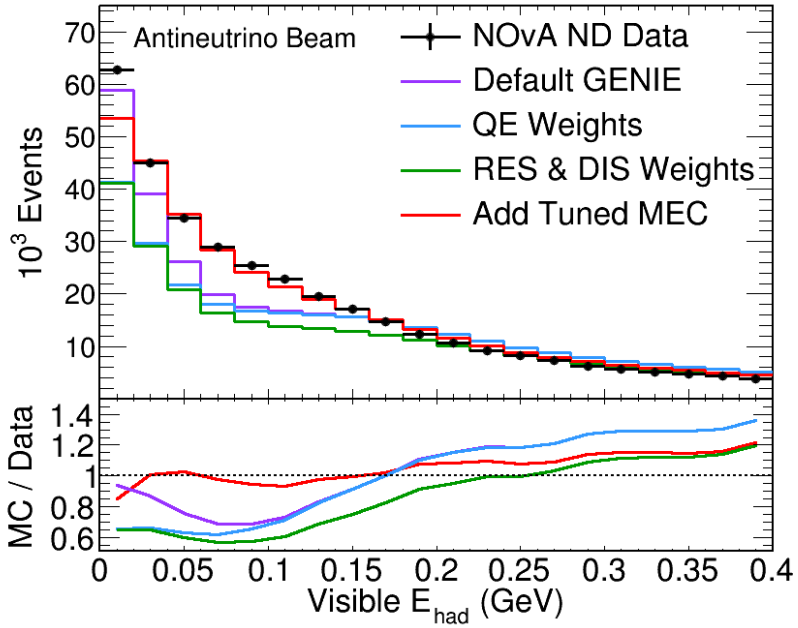
- Beam flux is tuned using the Package to Predict the FluX using external data
  - Minerva, Phys. Rev. D 94, 092005 (2016)
- We tune our cross-section model primarily to account for nuclear effects
  - First apply corrections based on external theory and/or data
  - Use ND data to constrain remaining pieces





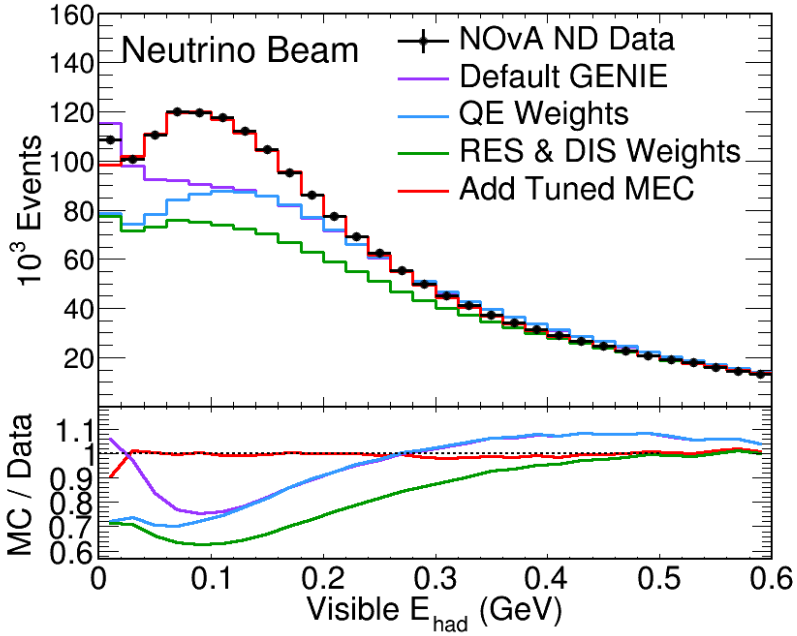
Cross Section Tuning

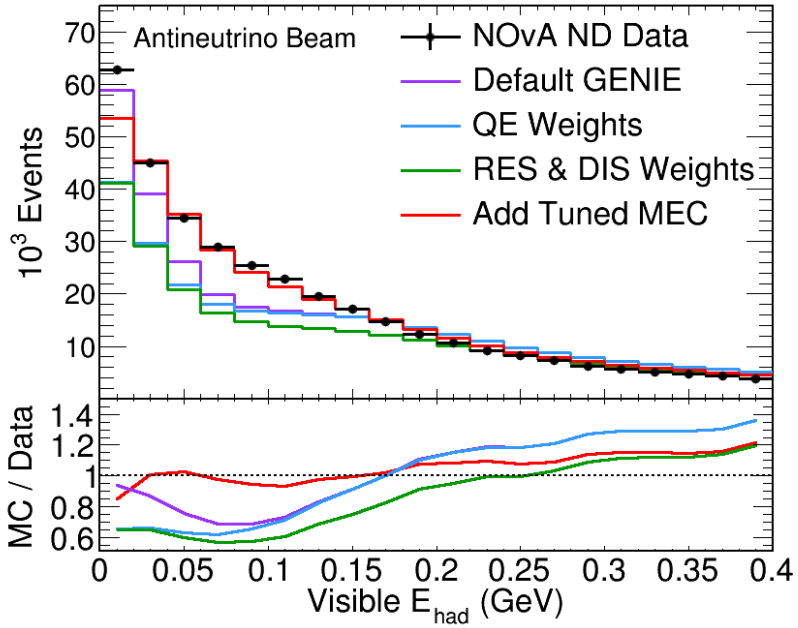




Correct QE component to account for effect of long-range nuclear correlations using model of València group via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]

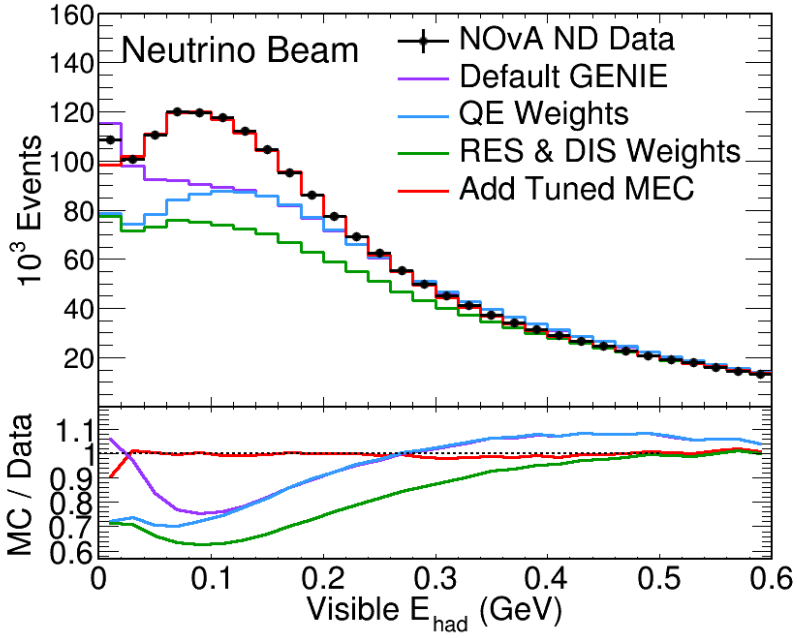
Cross Section Tuning

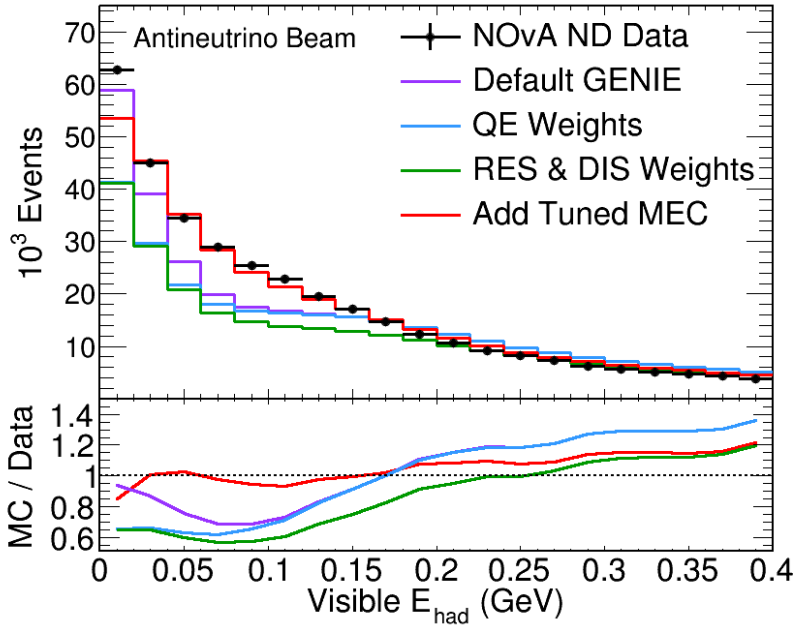




Apply same long-range effect as for QE to resonant (RES) baryon production as a stand-in for nuclear effects we see at low Q^2 - difference between modified and unmodified as uncertainty

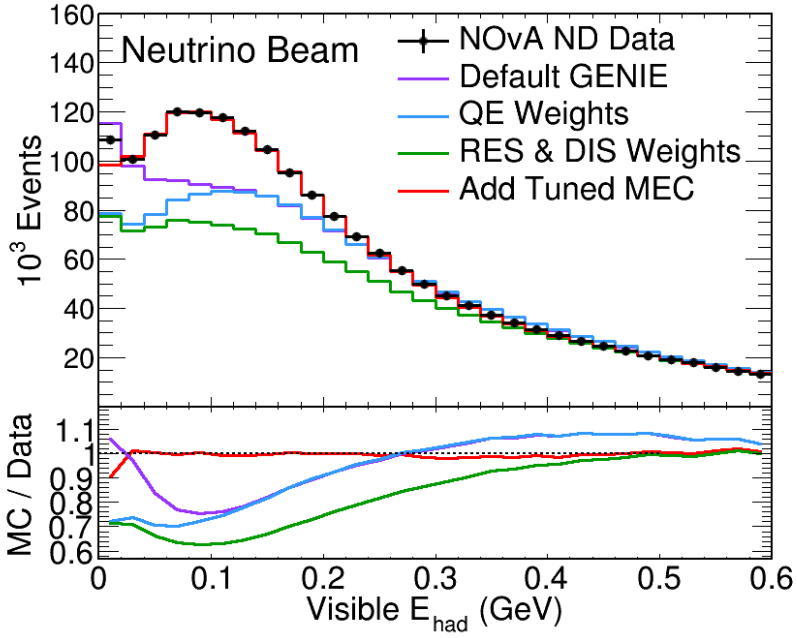
Cross Section Tuning

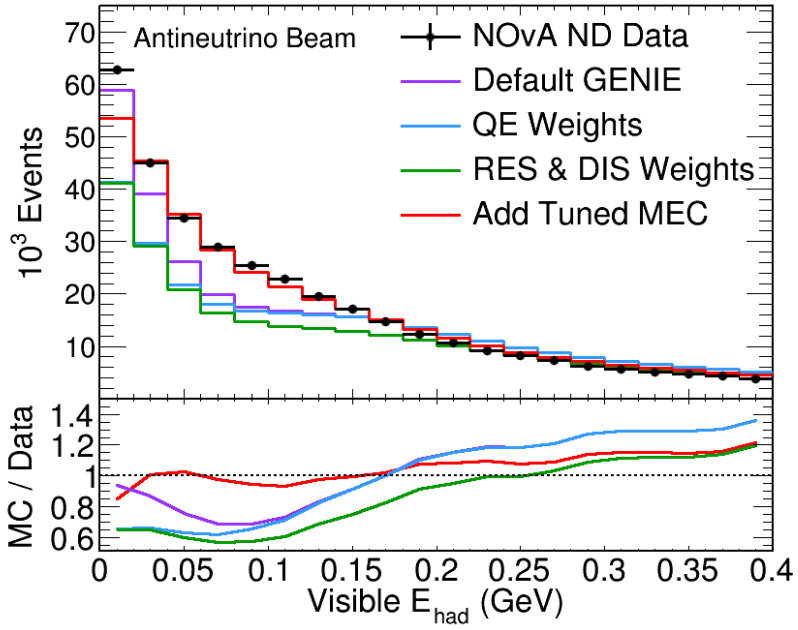




Nonresonant inelastic scattering (DIS) at high invariant mass ($W>1.7$ GeV/c^2) weighted up 10% based on NOvA data.

Cross Section Tuning

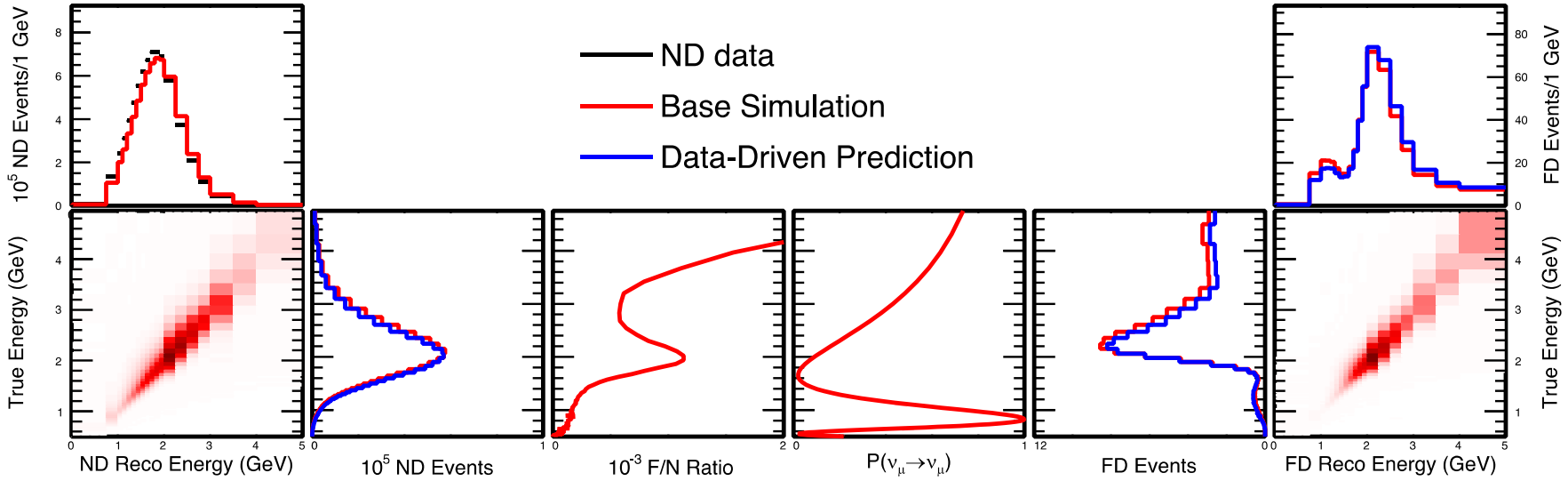




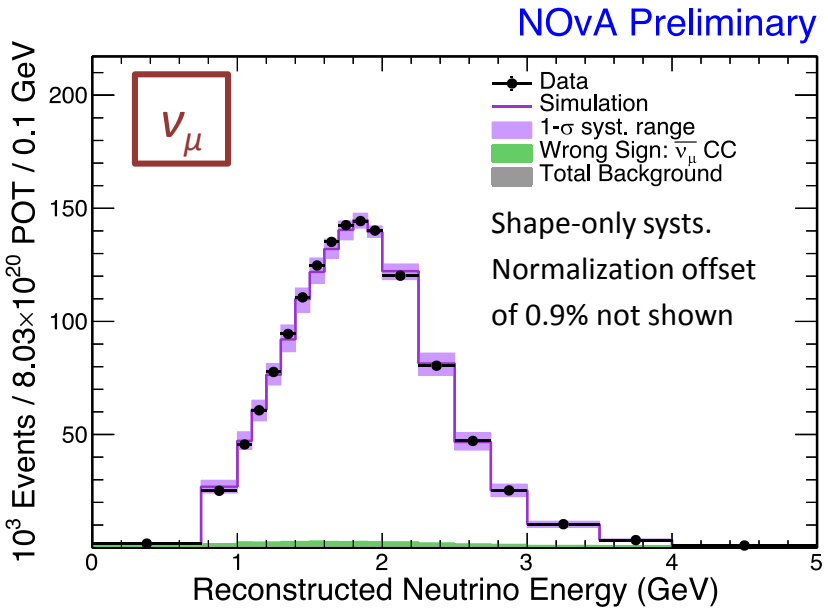
Tune weights for empirical MEC in true 4-momentum transfer to get agreement with ND data in reconstructed 4-momentum transfer

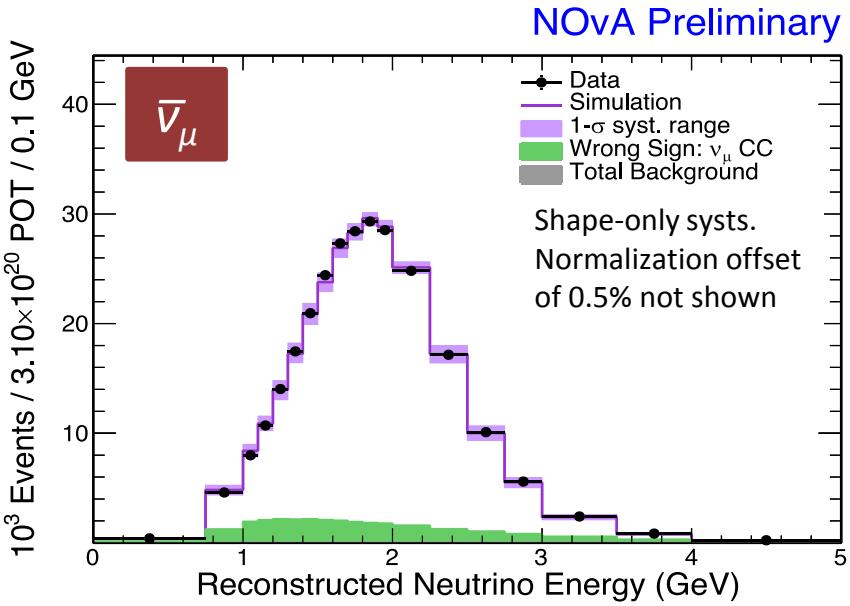
Constraints from ND Data

- Use reco-to-true migration for signal extrapolation
- ν_e backgrounds use the Far/Near ratio in bins of reconstructed energy
- Other (small) beam backgrounds are taken from simulation



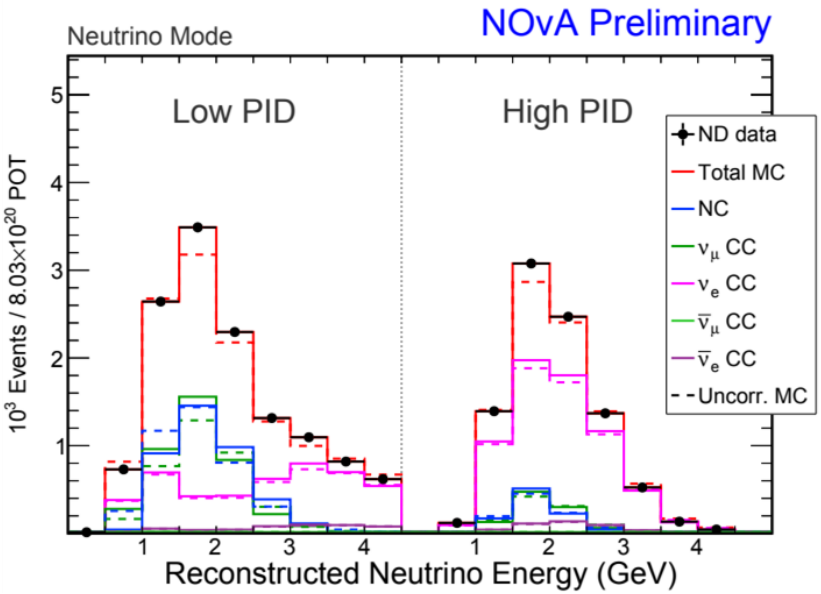
Muon Neutrinos at the ND

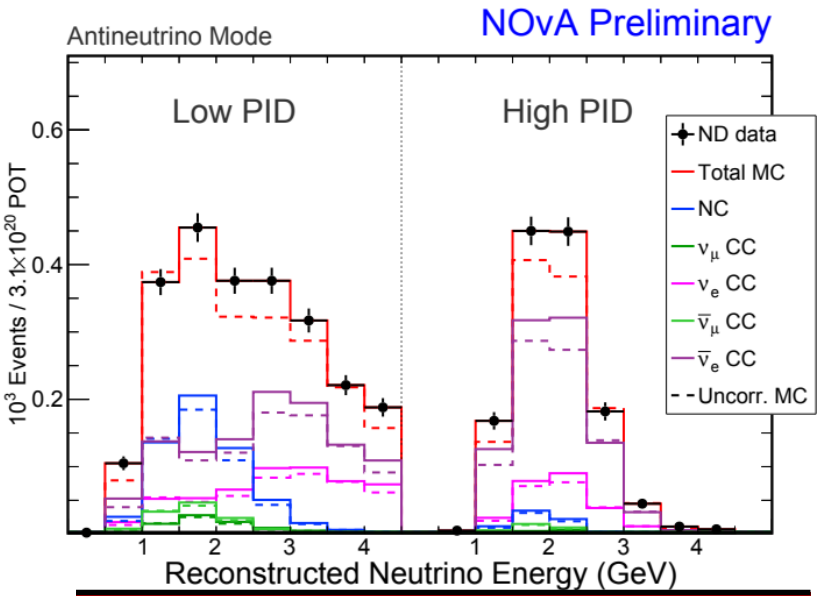




- Selected muon neutrino and antineutrino charged current interactions in ND.
- Used in the signal extrapolation
- Wrong sign contamination is estimated to be 3% (11%) for neutrino (antineutrino) beam.

Electron Neutrinos at the ND

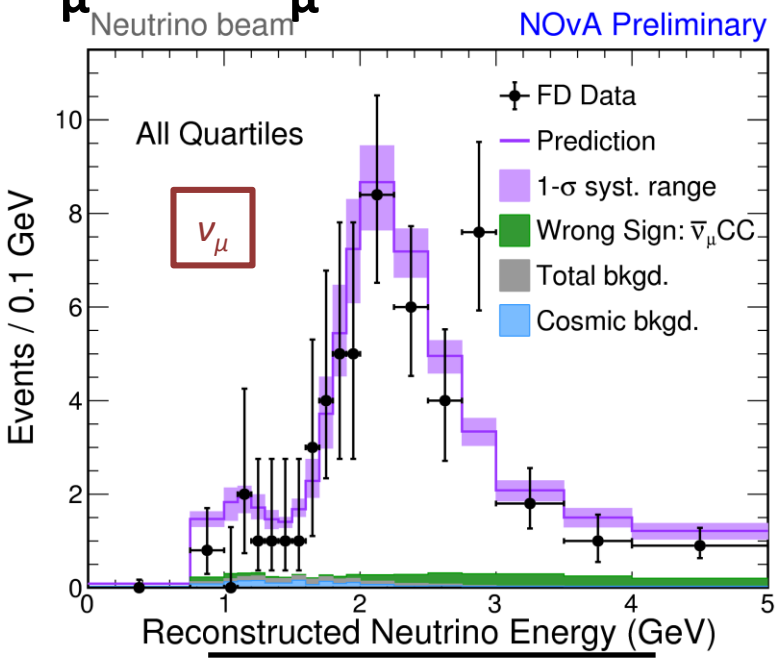




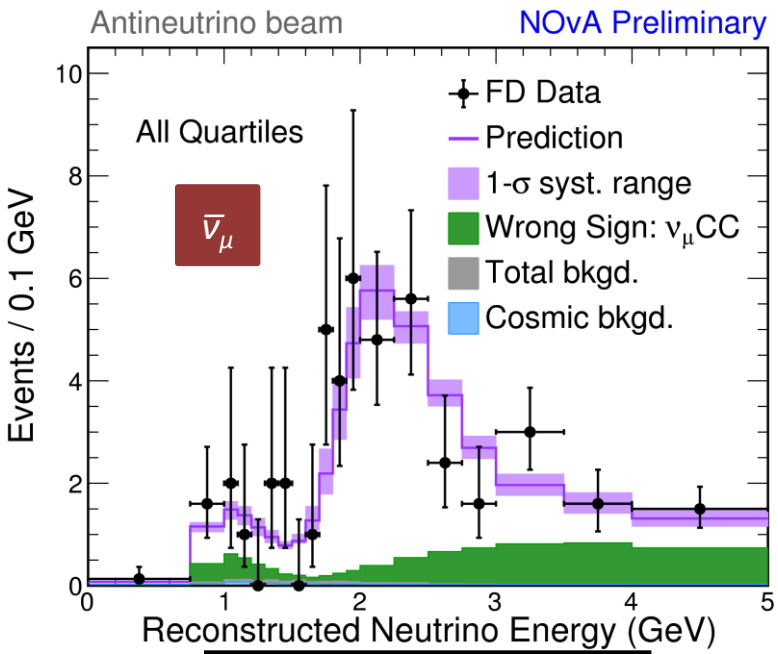
- ND ν_e-like sample has no appearance – all background
- To constrain backgrounds in the neutrino beam we use two data-driven techniques
- For the antineutrino beam we scale all components proportionally

	Neutrino	Antineutrino
Beam $\nu_e/\bar{\nu}_e$	55%	76%
NC	24%	17%
CC $\nu_\mu/\bar{\nu}_\mu$	21%	7%

ν_μ and $\bar{\nu}_\mu$ data at the Far Detector

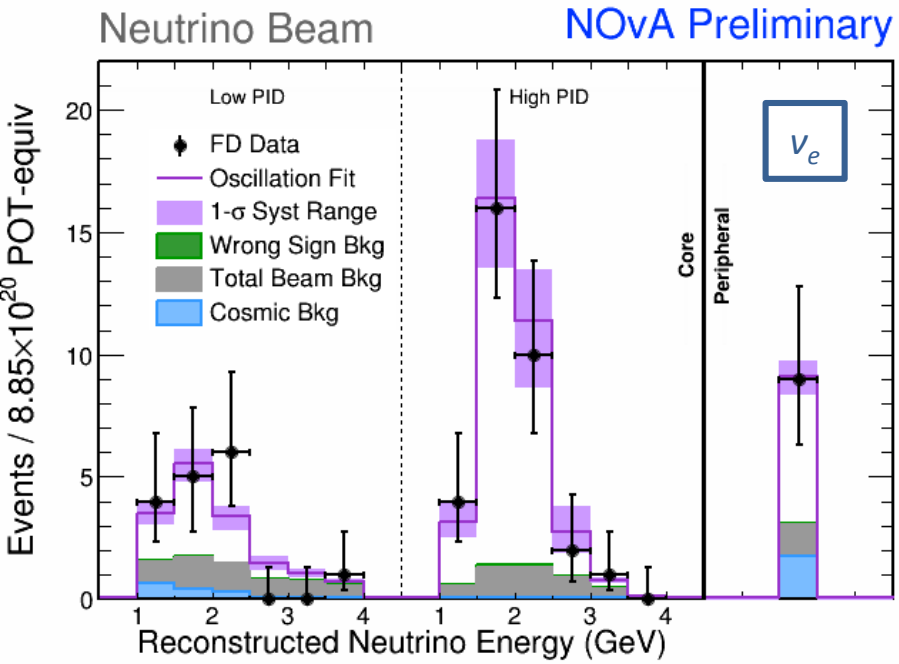


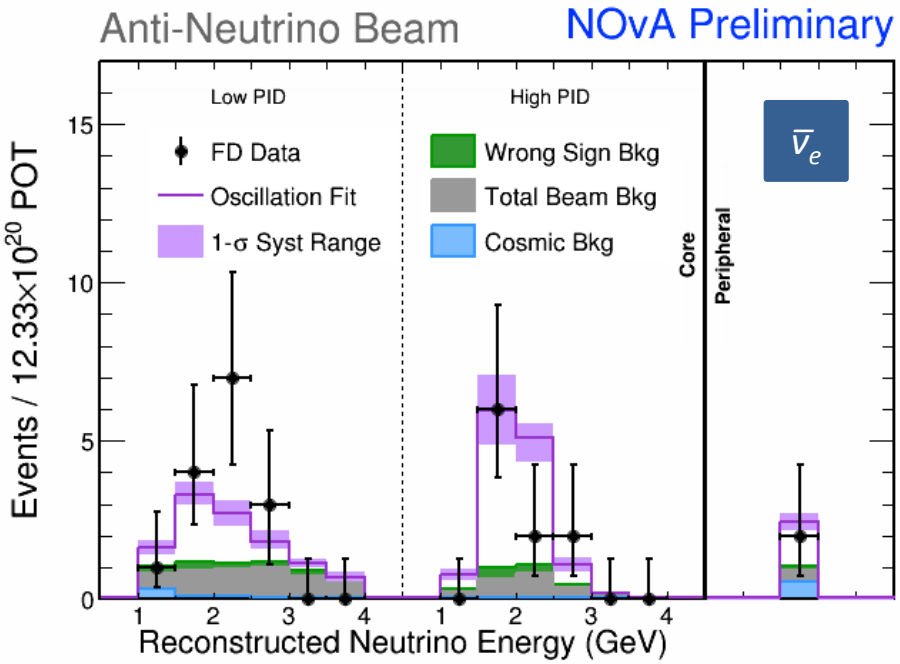
Total Observed	113
Best fit prediction	124
Cosmic Bkgd.	2.1
Beam Bkgd.	2.1



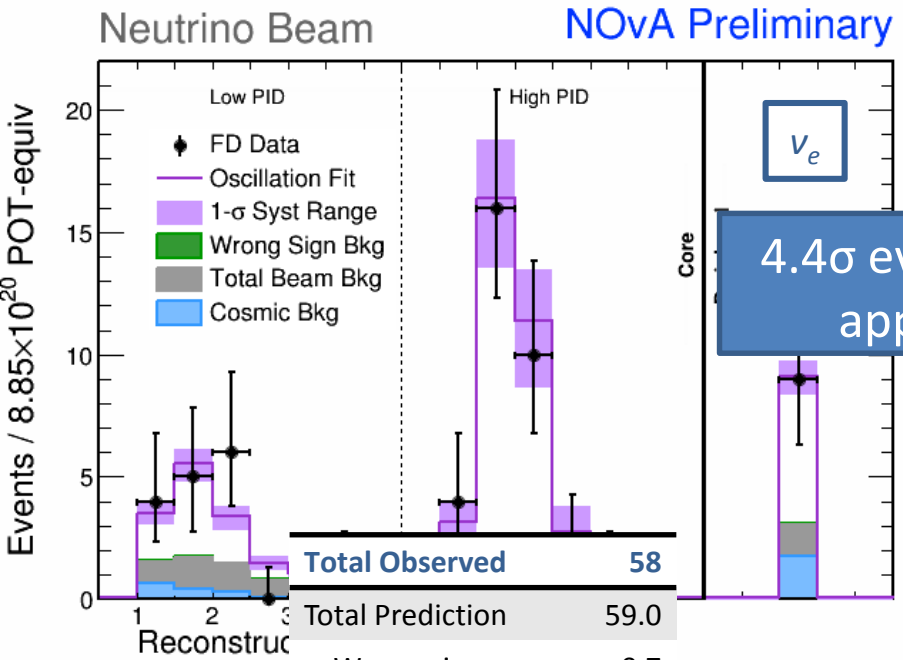
Total Observed	102
Best fit prediction	96
Cosmic Bkgd.	0.8
Beam Bkgd.	1.4

ν_e and $\bar{\nu}_e$ data at the Far Detector

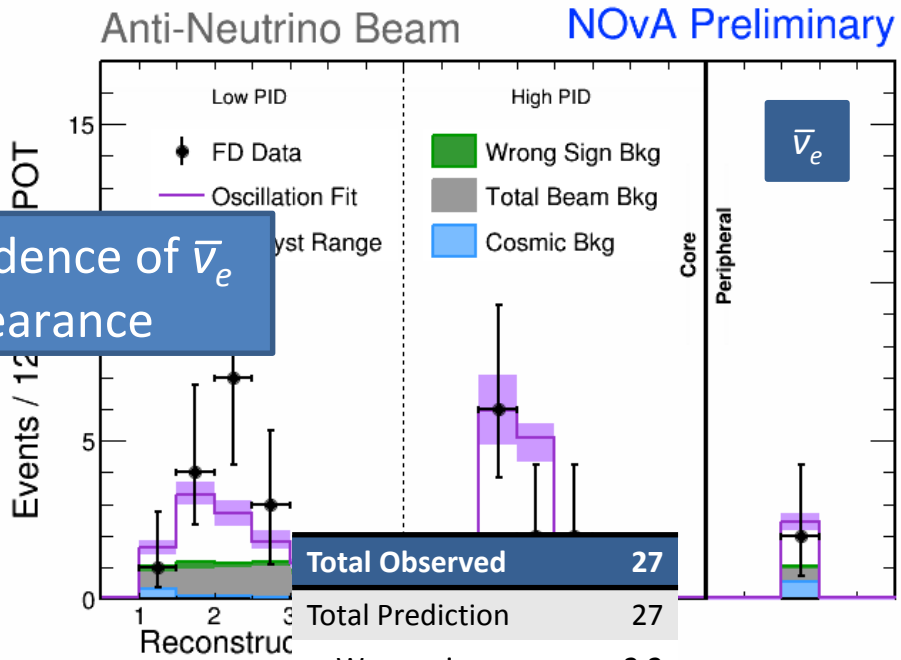




ν_e and $\bar{\nu}_e$ data at the Far Detector



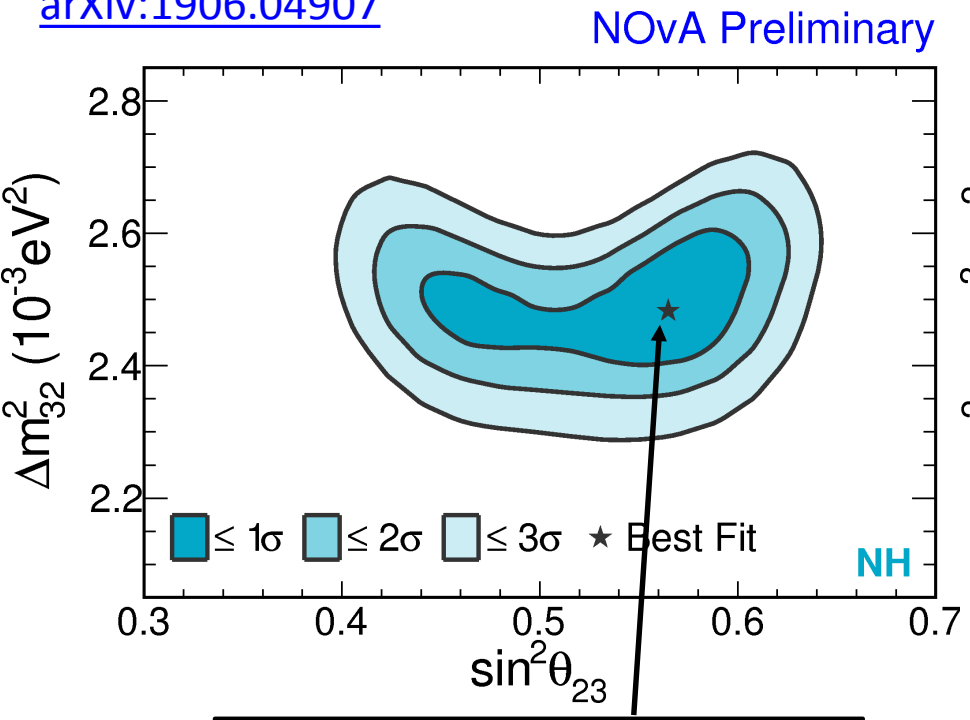
Total Observed	**58**
Total Prediction	59.0
Wrong-sign	0.7
Beam Bkgd.	11.1
Cosmic Bkgd.	3.3
Total Bkgd.	15.1

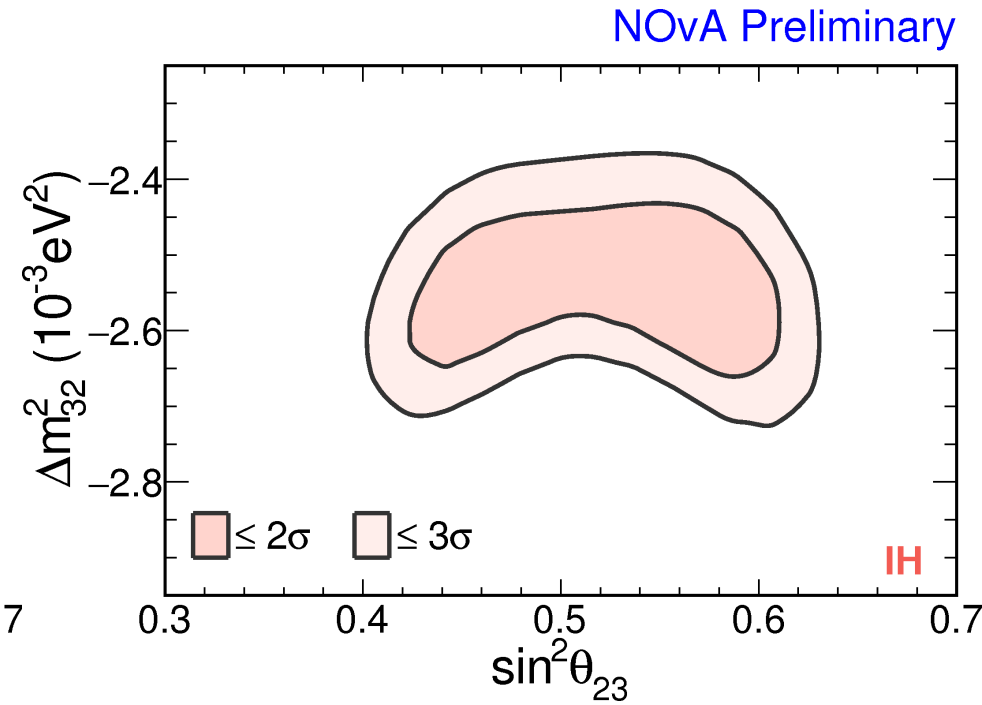


Total Observed	**27**
Total Prediction	27
Wrong-sign	2.2
Beam Bkgd.	7.0
Cosmic Bkgd.	1.1
Total Bkgd.	10.3

4.4σ evidence of $\bar{\nu}_e$ appearance

arXiv:1906.04907





Best Fit

$\Delta m^2_{32} = (2.48^{+0.11}_{-0.06}) \times 10^{-3}$ eV^2

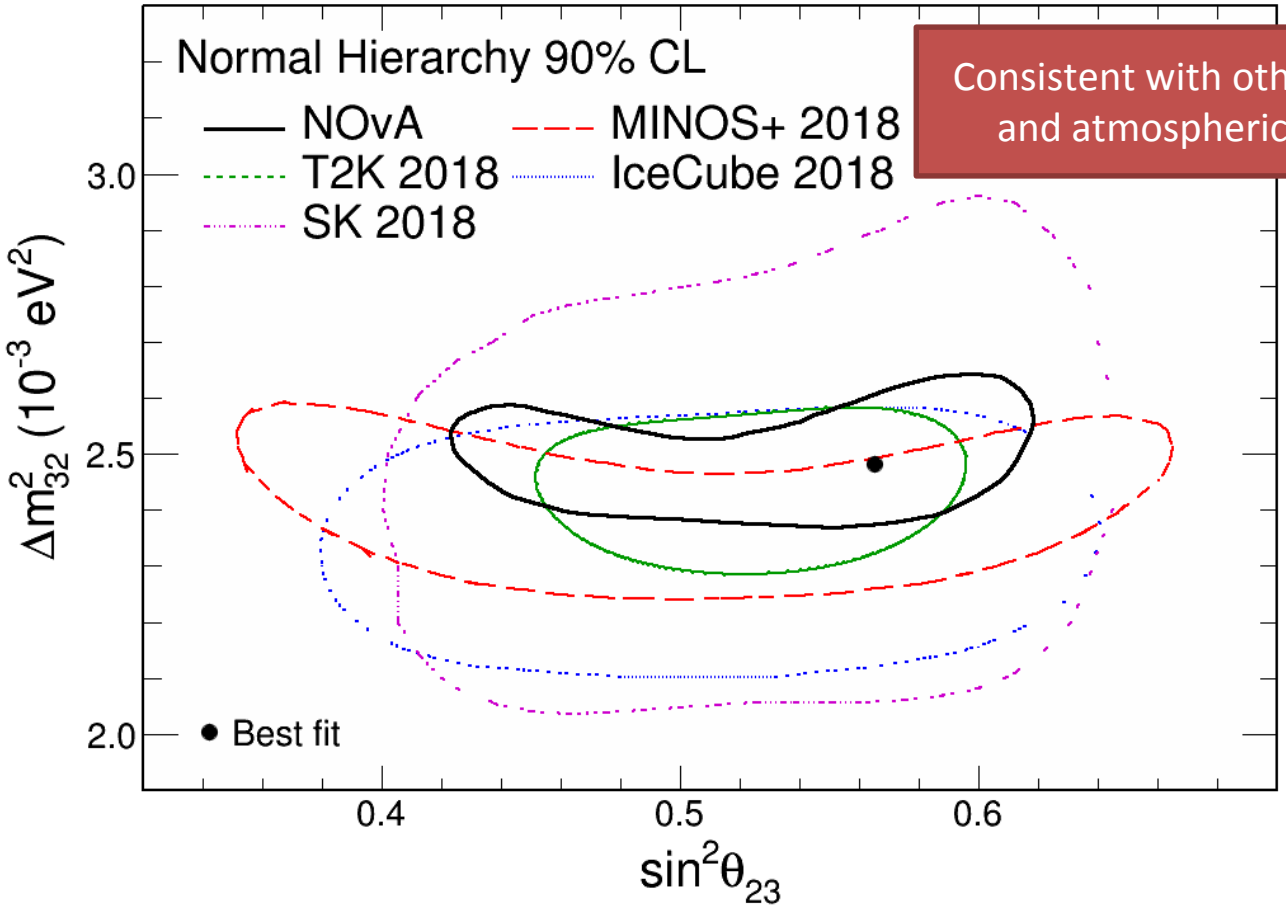
$\sin^2\vartheta_{23} = 0.56^{+0.04}_{-0.03}$

Maximal mixing disfavored at **1.2σ**.

Lower octant disfavored at 1.6**σ..**

arXiv:1906.04907

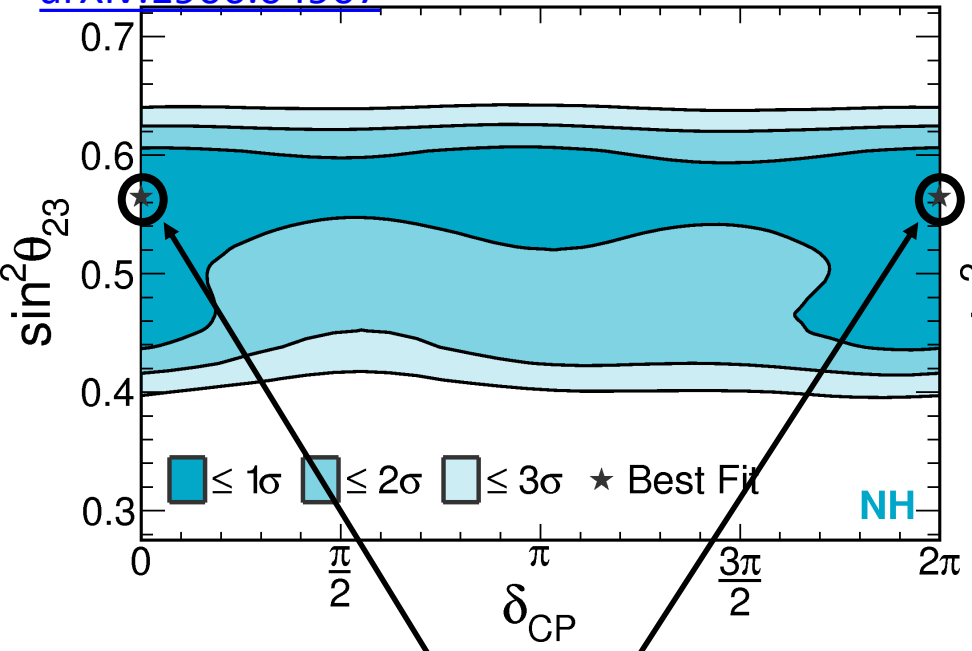
NOvA Preliminary



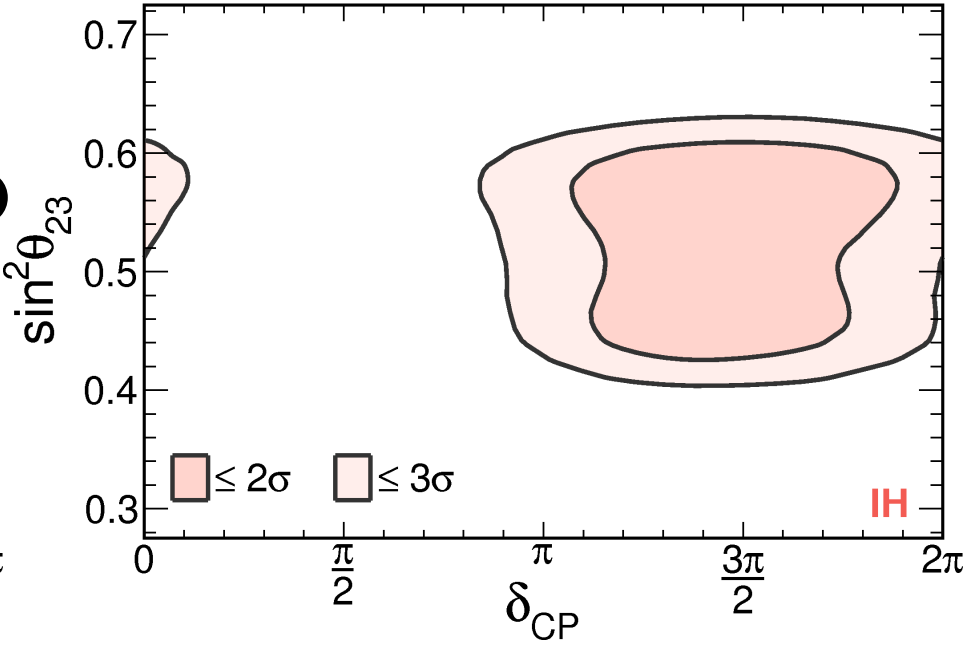
Consistent with other long-baseline and atmospheric experiments.

arXiv:1906.04907

NOvA Preliminary



NOvA Preliminary



Best Fit

$\Delta m^2 = (2.48^{+0.11}_{-0.06})\times10^{-3}$ eV^2

$\sin^2\vartheta_{23} = 0.56^{+0.04}_{-0.03}$

$\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi$

NHUO: All values of δ ruled out at 1.1σ.

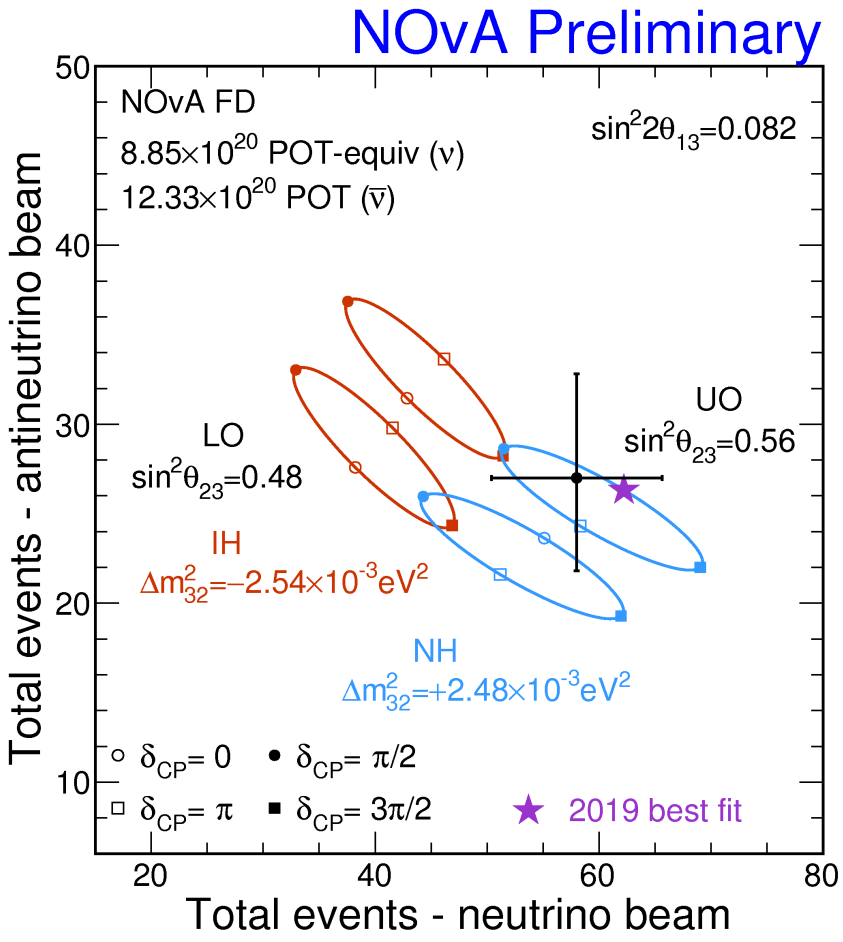
IH: δ = π/2 ruled out > 4σ.

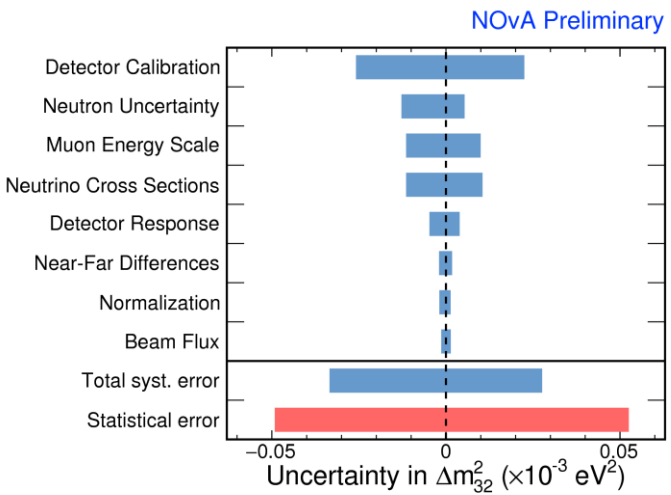
arXiv:1906.04907

	LO Disfavored 1.6σ	
IH Disfavored 1.9σ	IH LO Disfavored 2.0σ	IH UO Disfavored 1.8σ
	NH LO Disfavored 1.6σ	**NH UO Best fit**

NH preferred at 1.9σ

Feldman-Cousins corrected significances





- Calibration and energy scale are two of the largest systematic uncertainties
- Will be reduced with the test beam program
- Beam run in fall 2019

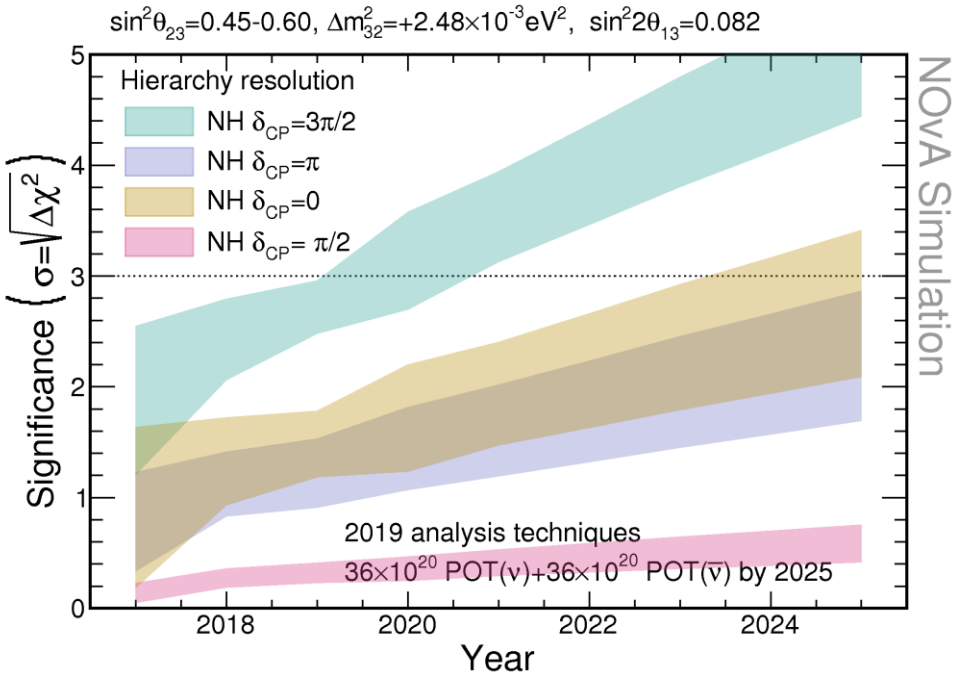
Future

- Expected to run through 2025
- Run plan: 50-50 neutrinos/antineutrinos

- Potential 3-5σ sensitivity to hierarchy
- Possible > 2σ sensitivity to CP violation

- Proposed accelerator improvements and test beam program enhance NOvA's reach
- Improvements in simulation will improve analysis robustness

- Joint T2K-NOvA analysis coming soon



Summary

- Cross section program:
  - Dedicated measurements using ND data
  - Integration of new measurements and theoretical work from the community

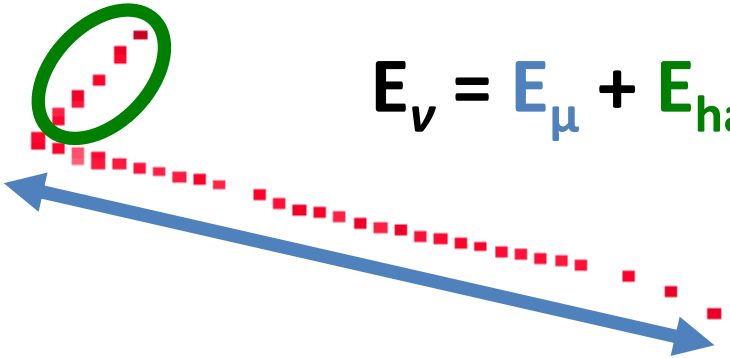
- Consistent with three flavor picture:
  - No evidence for NC disappearance

- Constraints on three flavor oscillation parameters:
  - 4.4σ evidence for electron antineutrino appearance in a muon antineutrino beam
  - 1.9σ preference for the Normal Hierarchy
  - 1.6σ preference for θ_{23} in the Upper Octant (maximal mixing disfavored at 1.2σ)

Thank you!

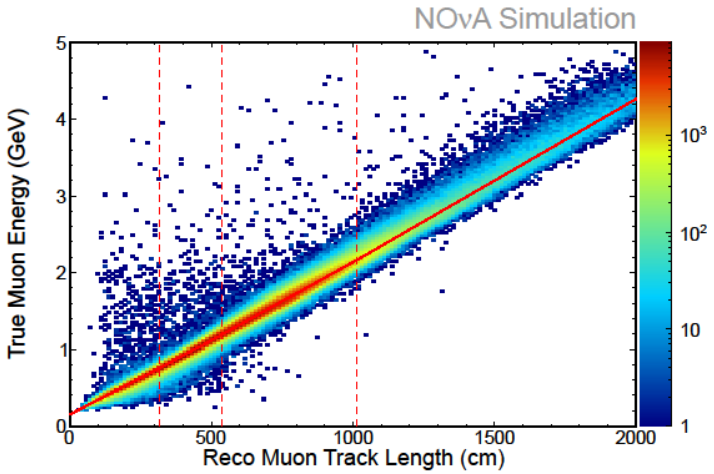
Backups

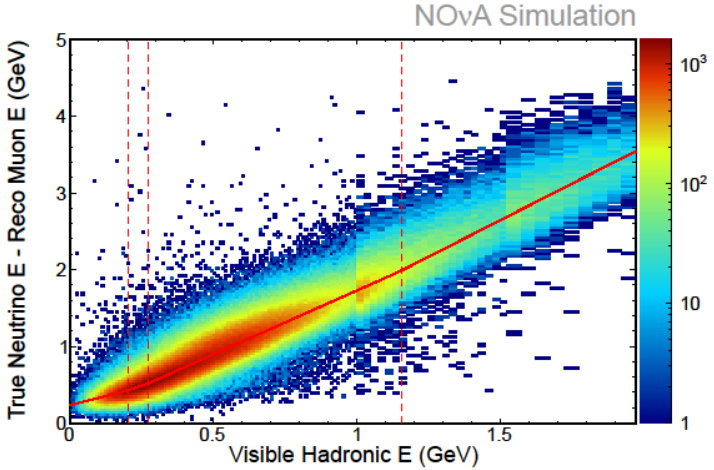
Muon Neutrino Energy



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

- Muon energy is calculated with a conversion from track length.
- Hadronic energy is the summed calorimetric energy of the non-muon hits, converted to true energy.
- Muon energy resolution (3%) is much better than hadronic energy resolution (30%).



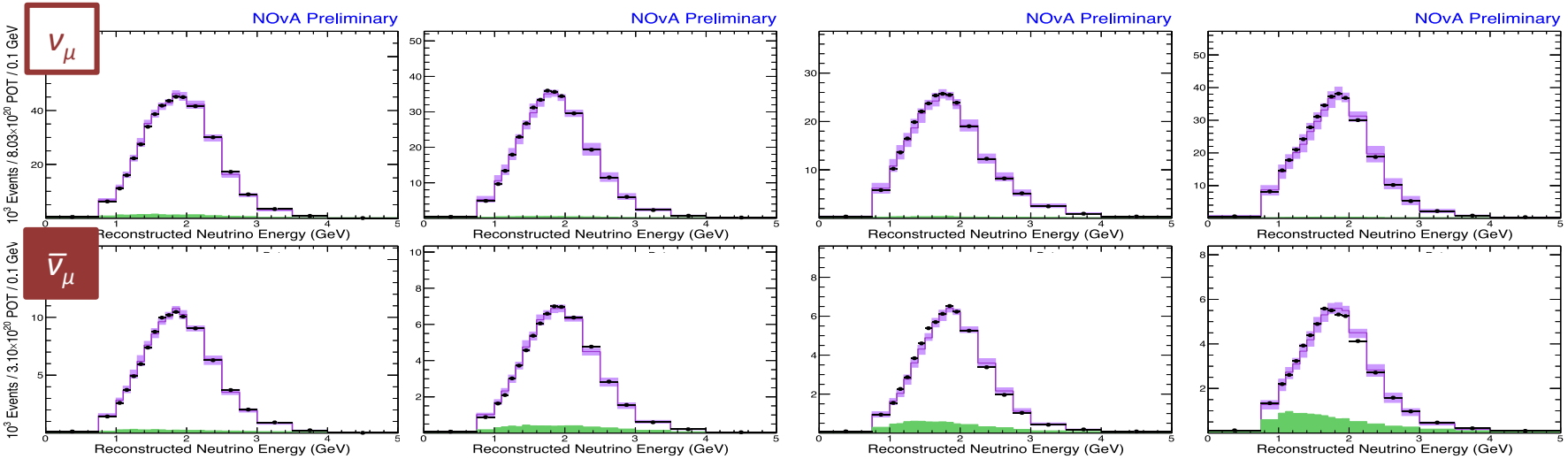


Muon Neutrinos at the ND

Data
Area-normalized MC
Shape-only systematics
Wrong-sign

Quartile 1
Best Resolution ~6%

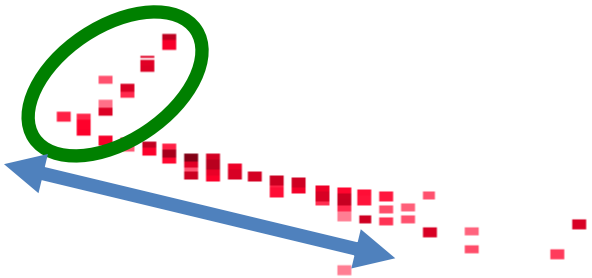
Quartile 4
Worst Resolution ~12%



Muon neutrino sample divided into four quartiles based on hadronic energy fraction.

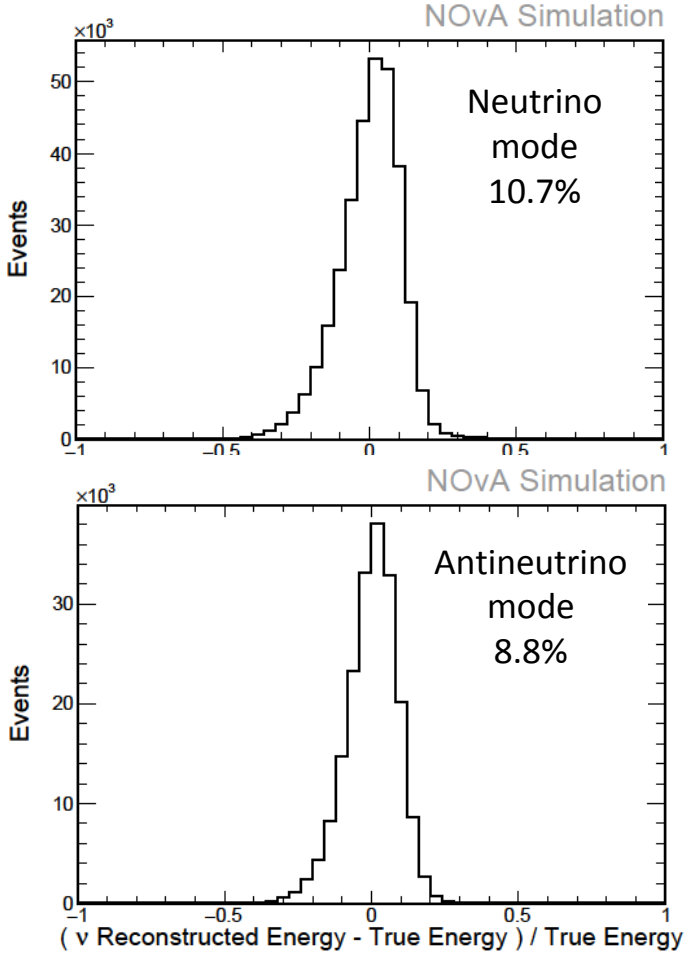
Each quartile extrapolated separately to the FD.

Electron Neutrino Energy



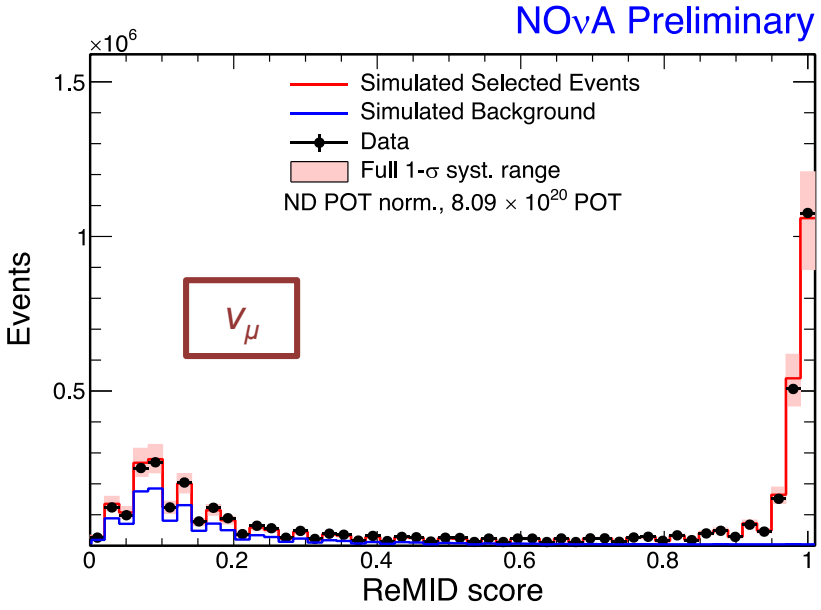
$$E_\nu = A*E_{EM} + B*E_{had} + C*E_{EM}^2 + D*E_{had}^2$$

- Detector response is different for EM energy and hadronic energy
- To take this into account we separate the EM and hadronic depositions with a CVN variant

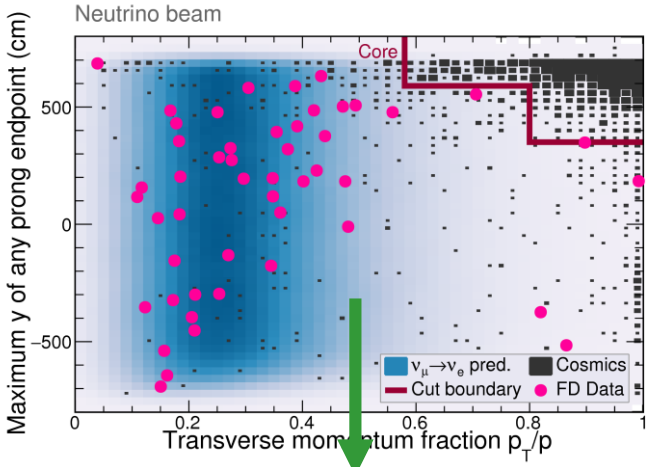


Other Selections

- Some basic additional cuts:
  - Contained, fiducial events, well-reconstructed, reasonable energy range
- An additional **ν_μ requirement: a track identified as a muon**.
  - CVN identifies events with a muon, but it does not identify the muon track.
  - Identify muons in reconstructed tracks using a kNN
    - Track length, dE/dx, scattering, fraction of track-only planes



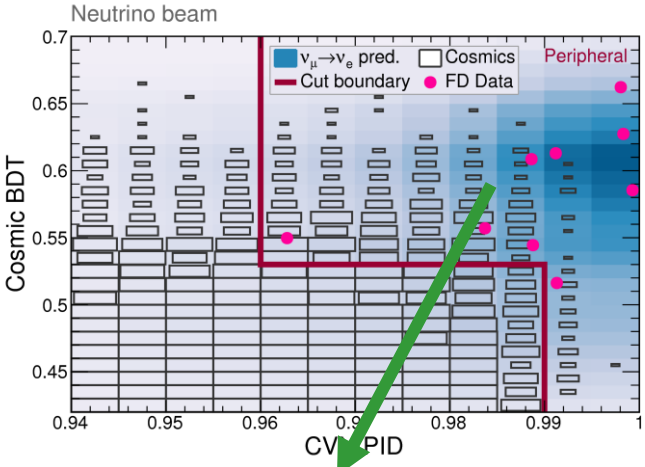
- Additional cosmic rejection needed at the Far Detector.
  - 11 billion cosmic rays/day in the Far Detector on the surface.
  - 10^7 rejection power required *after* timing cuts are applied.
- The ***ν_μ* sample** uses a BDT based on:
  - Track length and direction, distance from the top/sides, fraction of hits in the muon, and CVN.
- Cosmic rejection for the ***ν_e* sample** is in 2 stages:
  - **Core sample**: require contained events, beam-directed events, away from the detector top
  - **Peripheral sample**: events failing the core selection can pass a BDT cut plus a tight CVN cut.
    - Different BDT from ν_μ based on the same containment variables used for cuts in the core sample.



Core Sample

ν_e

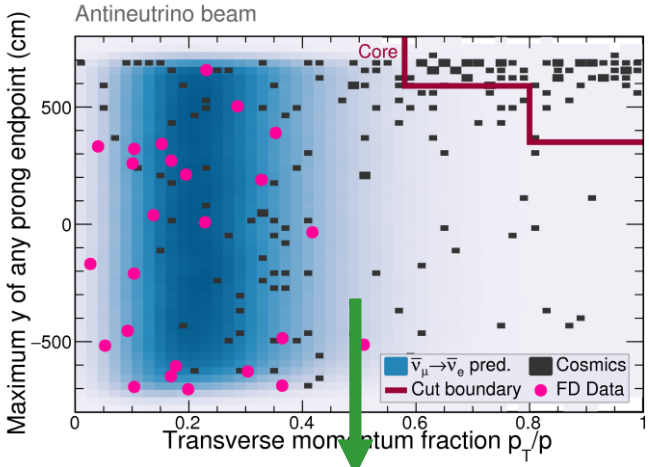
Black – Cosmic data
Color – ν_e Signal MC



Peripheral Sample

- Additional cosmic rejection needed at the Far Detector.
  - 11 billion cosmic rays/day in the Far Detector on the surface.
  - 10^7 rejection power required *after* timing cuts are applied.
- The ν_μ **sample** uses a BDT based on:
  - Track length and direction, distance from the top/sides, fraction of hits in the muon, and CVN.

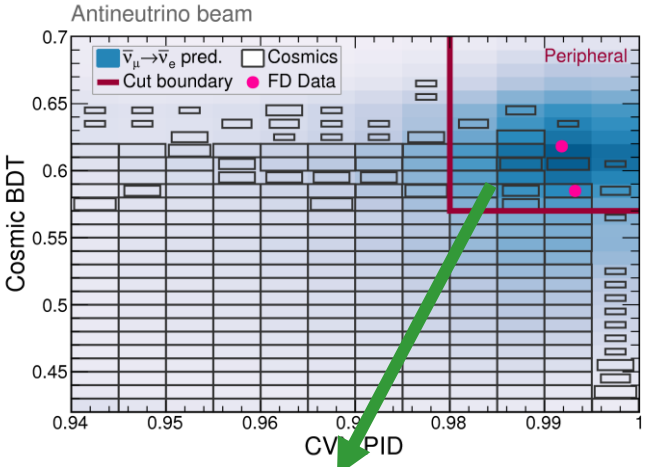
- Cosmic rejection for the ν_e **sample** is in 2 stages:
  - **Core sample**: require contained events, beam-directed events, away from the detector top
  - **Peripheral sample**: events failing the core selection can pass a BDT cut plus a tight CVN cut.
    - Different BDT from ν_μ based on the same containment variables used for cuts in the core sample.



Core Sample

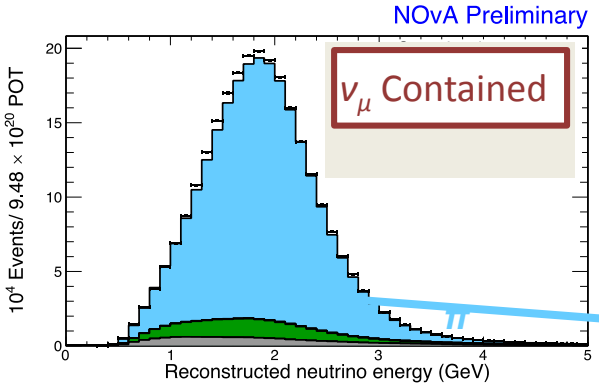
$\bar{\nu}_e$

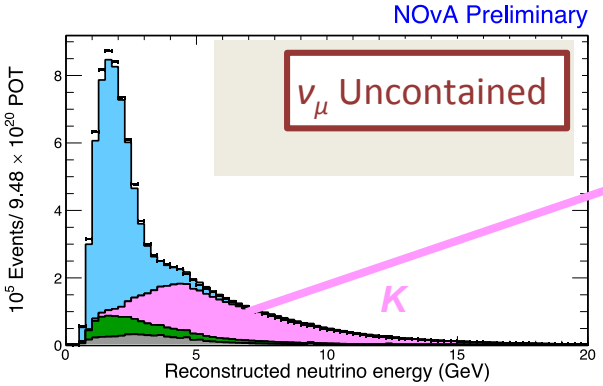
Black – Cosmic data
Color – ν_e Signal MC

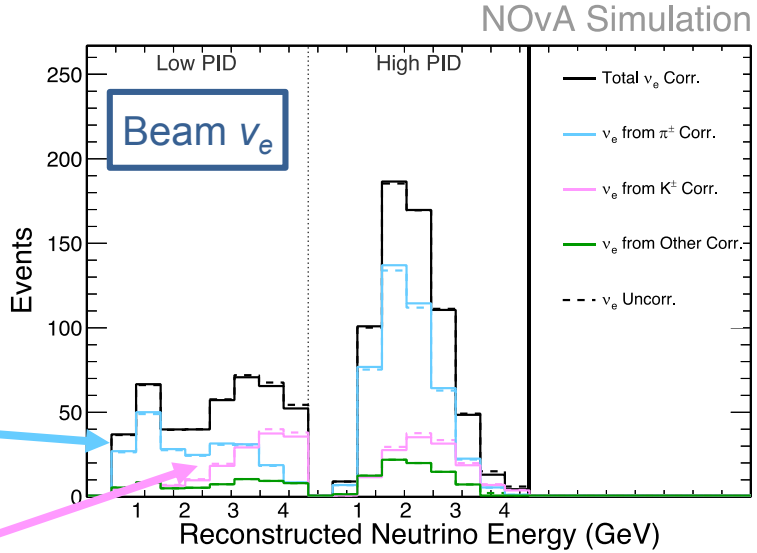


Peripheral Sample

ν_e Decomposition





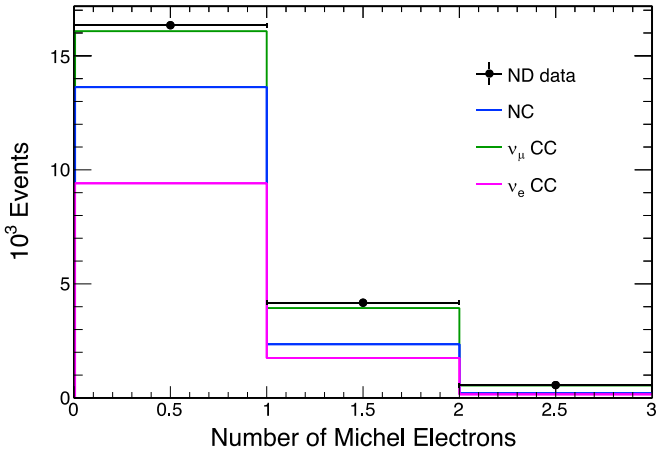


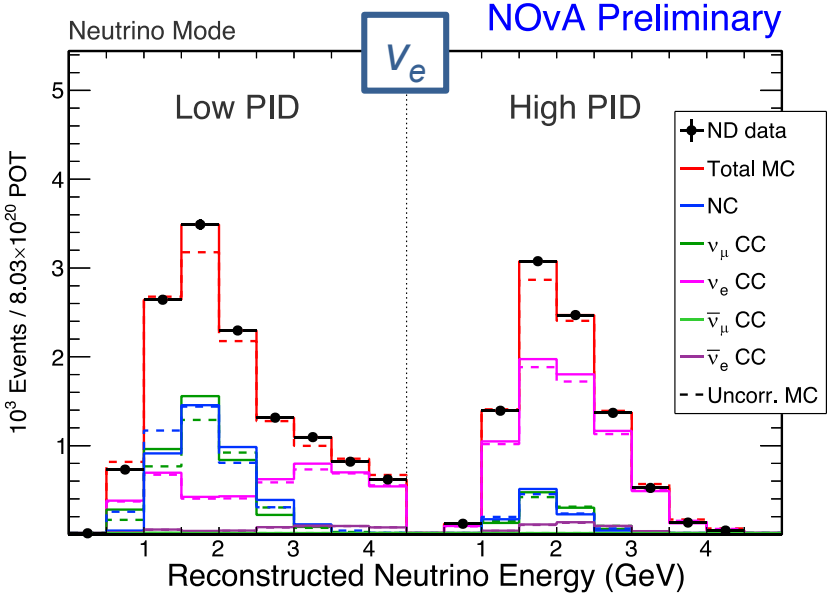
- ν_e and ν_μ events come from the same parents:
  - Lower energy neutrinos come primarily from ***π*** decay.
  - Higher energy neutrinos come primarily from ***K*** decay.
- Use contained ν_μ data to constrain the ***π* flux**
- Use higher energy uncontained events to constraint the ***K* flux**.

ν_e Decomposition

The CC/NC constrained using the number of observed Michel electrons.

- Determine the fraction of the two components in each analysis bin.





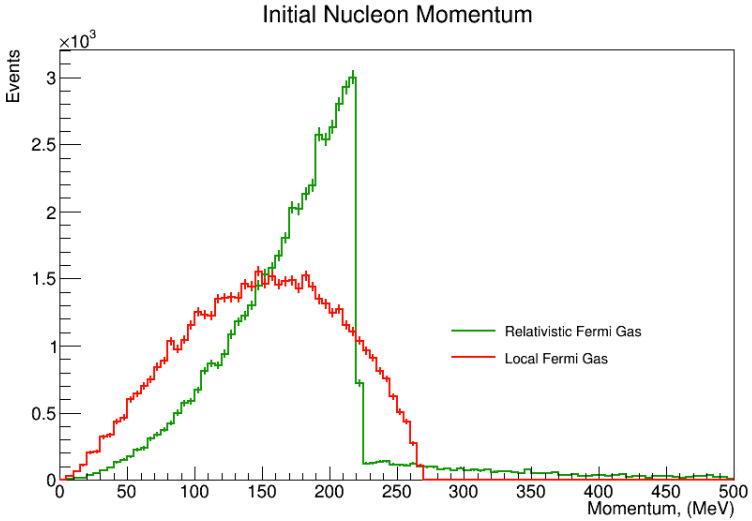
Change in Total	
ν_e CC	+3%
ν_μ CC	+7%
NC	-4%

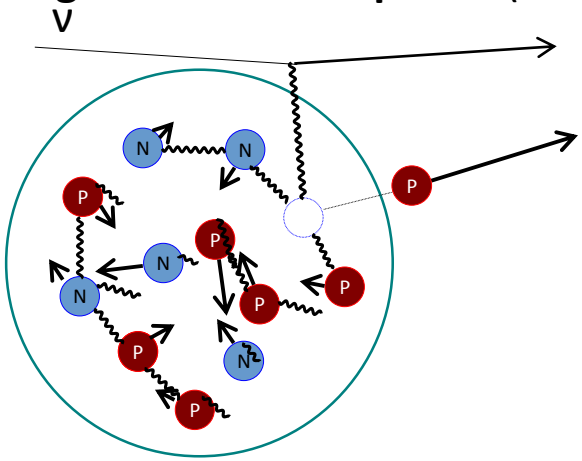
Cross Section Tuning - QE

GENIE 2.12 default:
global relativistic Fermi gas
(+ “Bodek-Ritchie tail”)

→

Local Fermi gas
+
Nuclear polarization / long-range collective response (“RPA”)





Supported by eA data;
MINERvA νA data (PRD 116, 071802; PRL 121, 022504),
T2K νA data (PRD 98, 032003), ...

Cross Section Tuning - QE

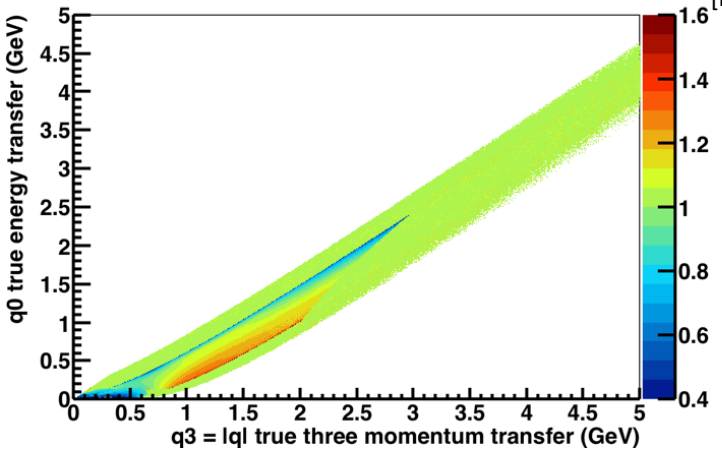
GENIE 2.12 default:
global relativistic Fermi gas
(+ “Bodek-Ritchie tail”)

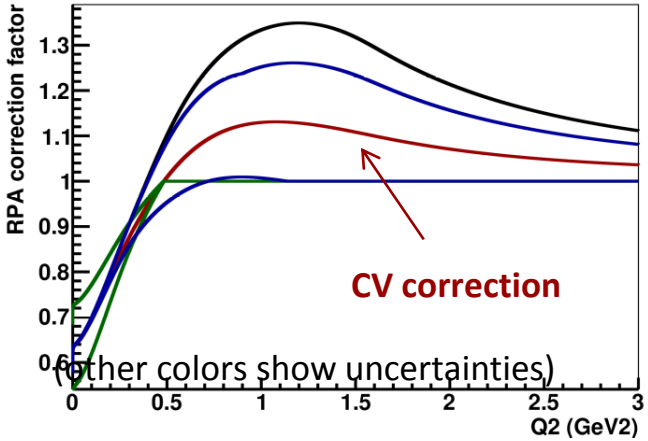
→

Local Fermi gas
+
Nuclear polarization / long-range collective response (“RPA”)

Apply IFIC València group's calculation (LFG + RPA)
via reweights for GENIE by R. Gran (MINERvA)

[R. Gran, arXiv:1705.02932]

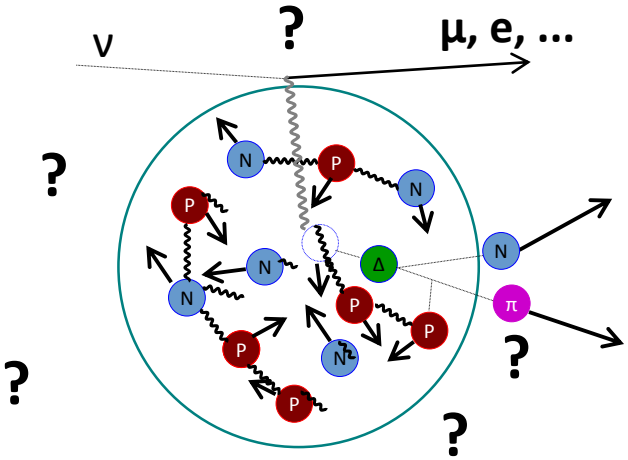


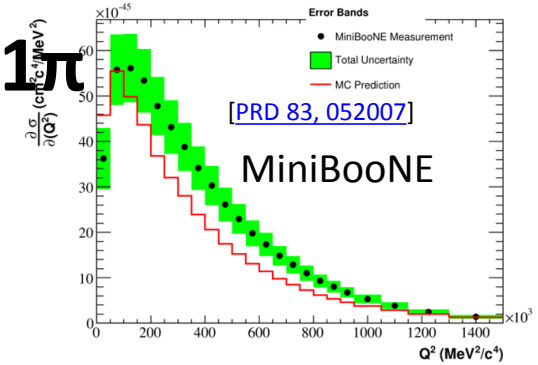


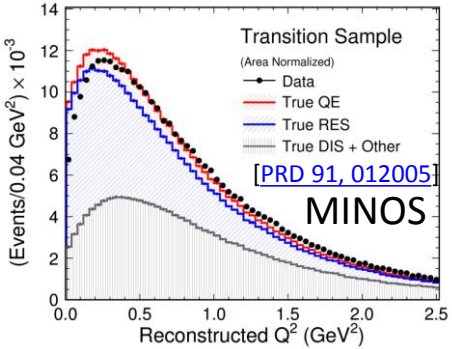
Cross Section Tuning – 1π

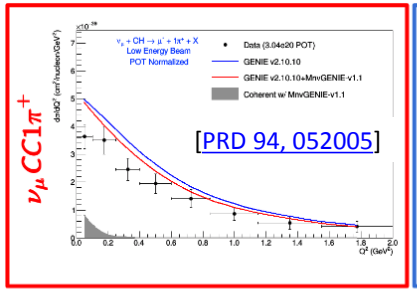
Apparent **suppression at low momentum transfer (Q^2)** relative to model...
(except in νA → $\mu^+\pi^-$?...)

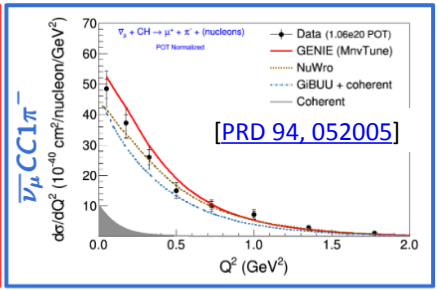
No theory guidance here.
Reminiscent of LFG+RPA correction in elastic though....

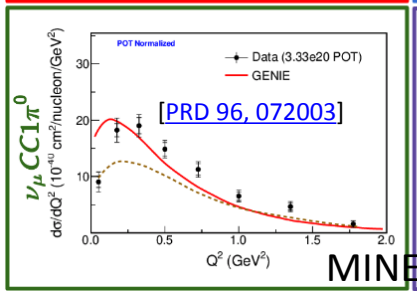


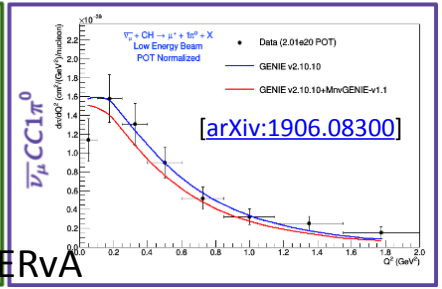












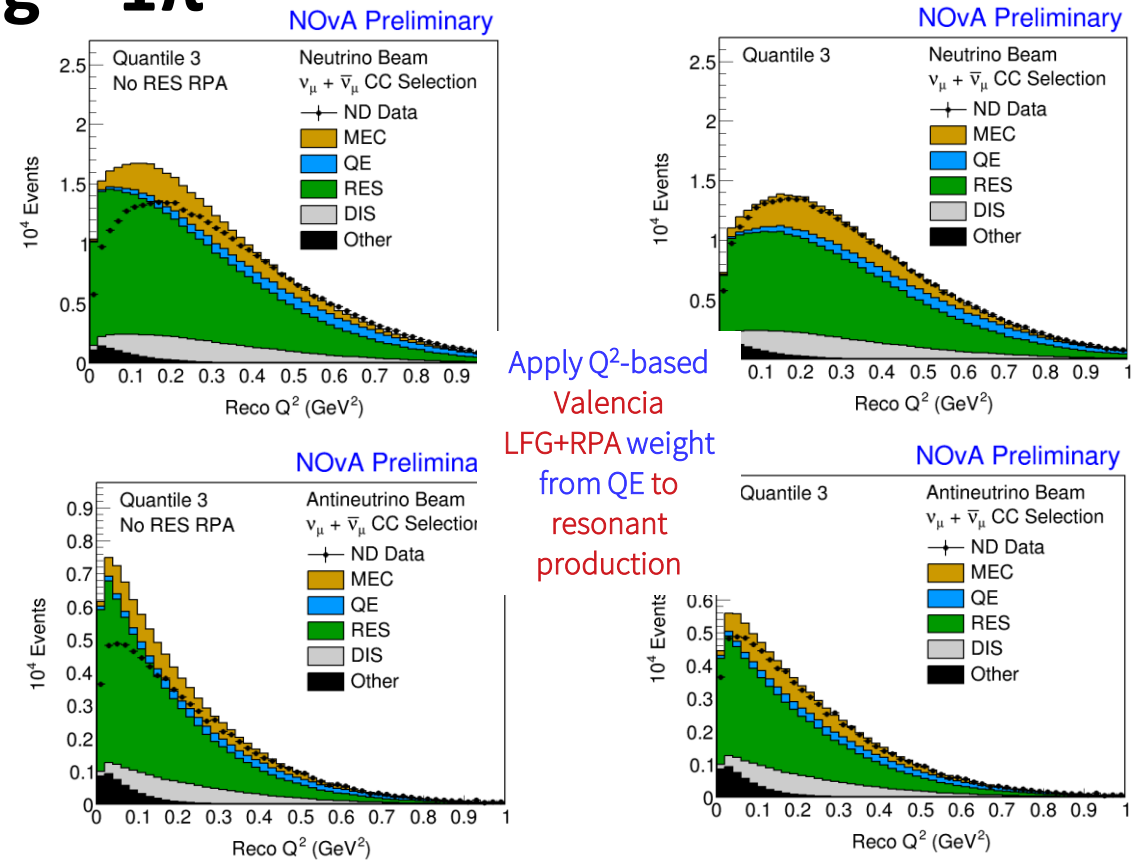
MINERvA

Cross Section Tuning – 1π

Adapt elastic long-range correlation model ("RPA")

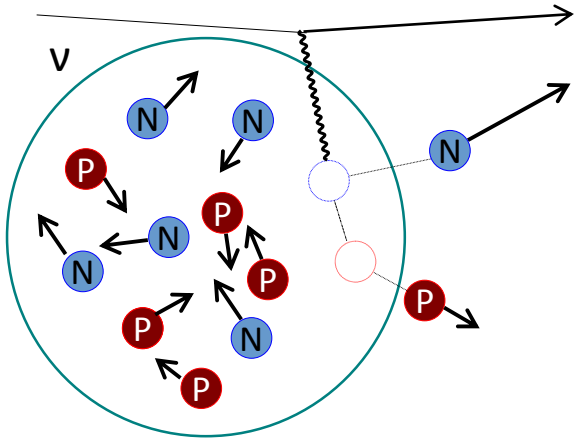
Use difference between modified and unmodified as uncertainty

MINERvA [studies in pion production] suggest alternate empirical correction we may consider in future



Apply Q^2-based Valencia LFG+RPA weight from QE to resonant production

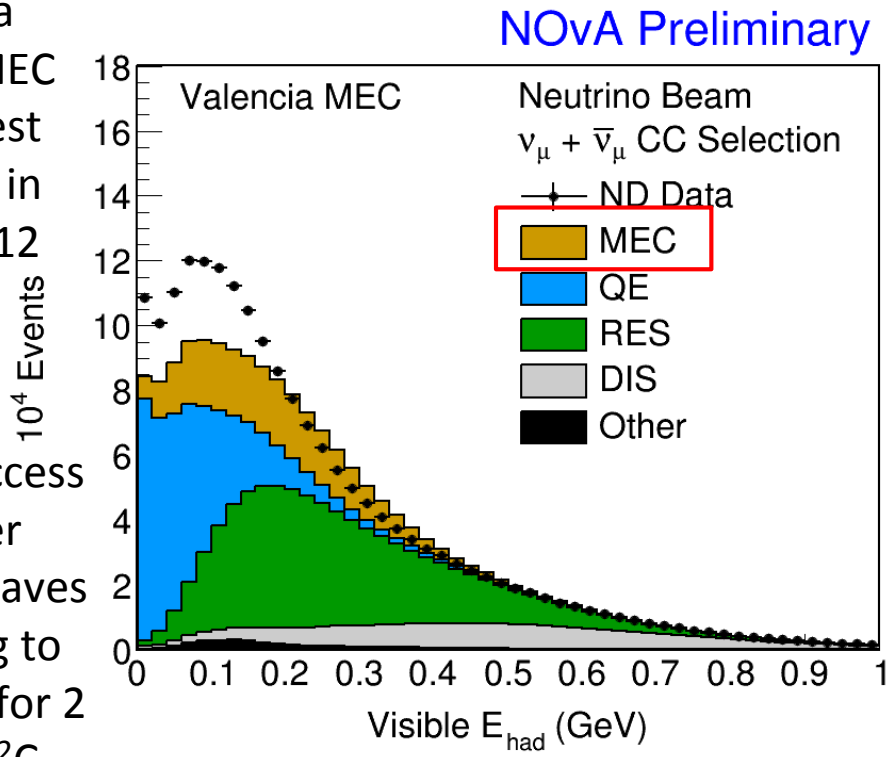
Cross Section Tuning – 2p2h



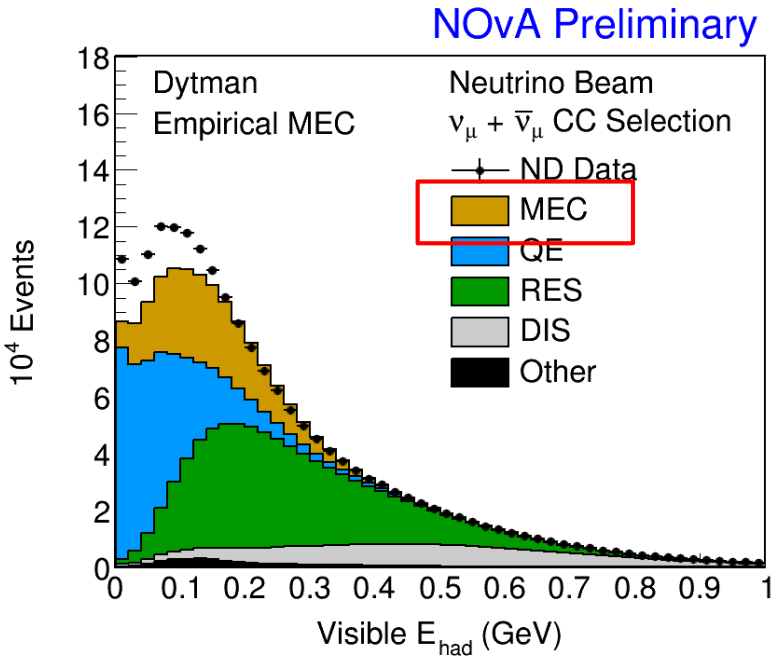
"2p2h"
Knock out two nucleons with an elastic-like interaction

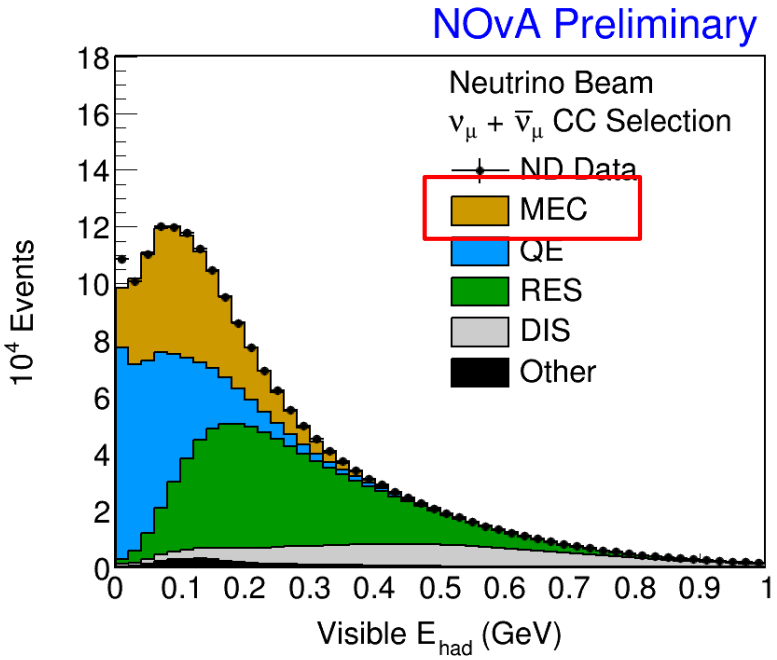
València group's MEC model best available in GENIE 2.12

Despite success for lower energies, leaves something to be desired for 2 GeV on ^{12}C



Cross Section Tuning – 2p2h

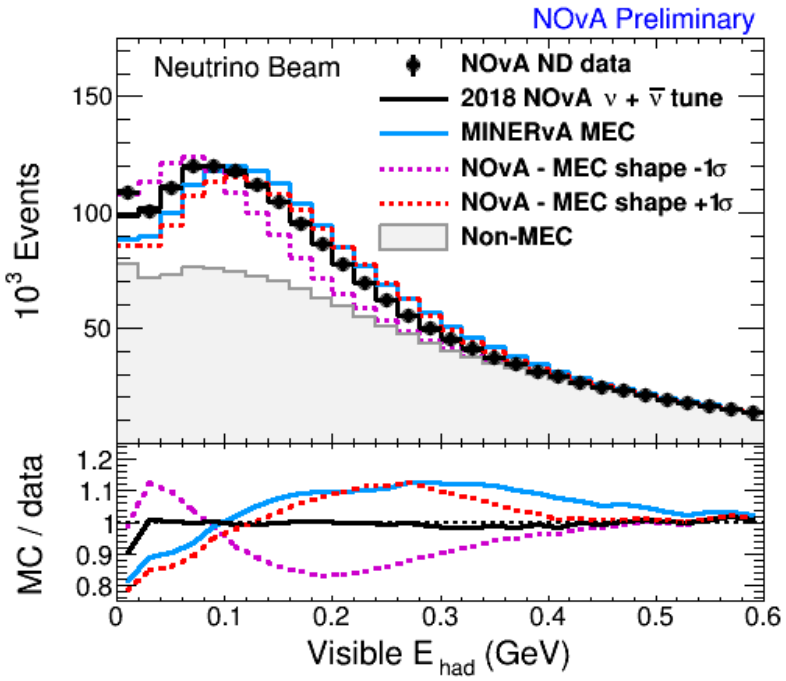


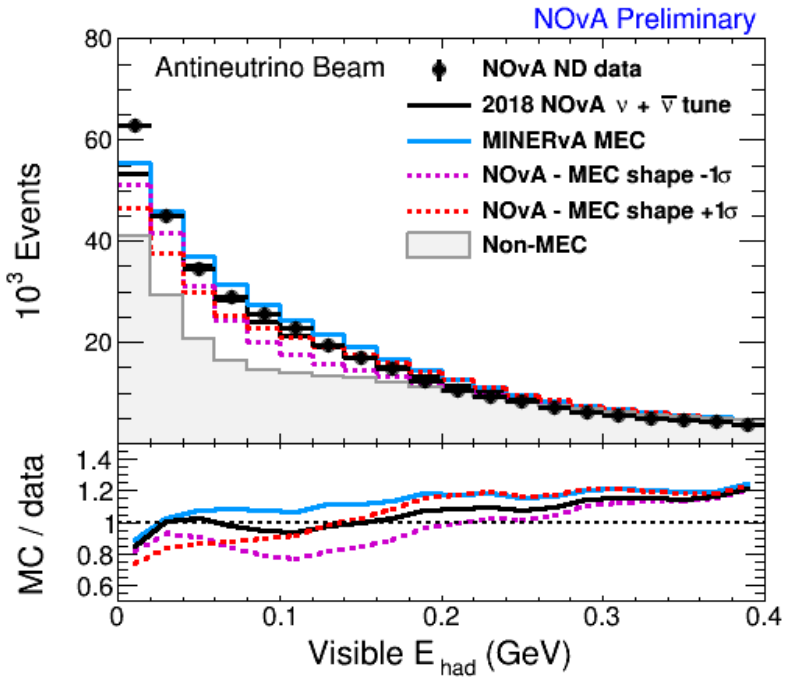


Refit empirical "model"* to ND data

*T. Katori, NuInt12 Proceedings, arXiv:1304.6014

Cross Section Tuning – 2p2h



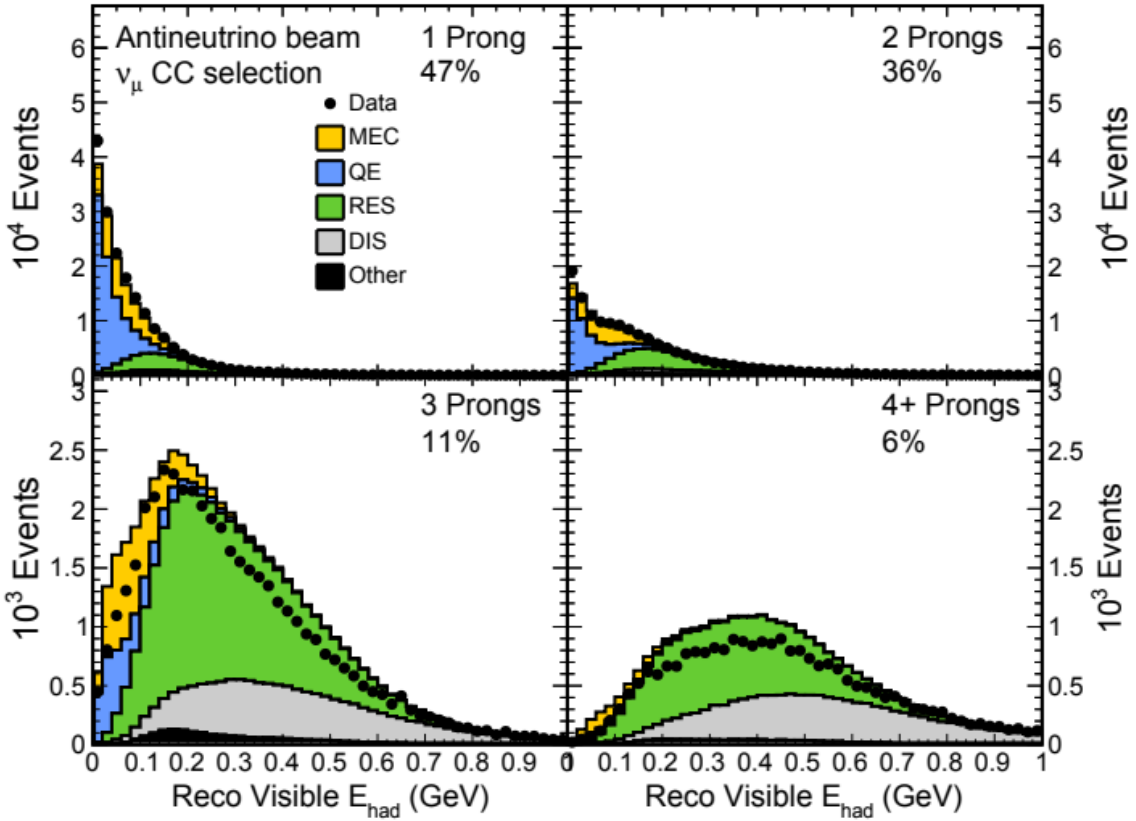


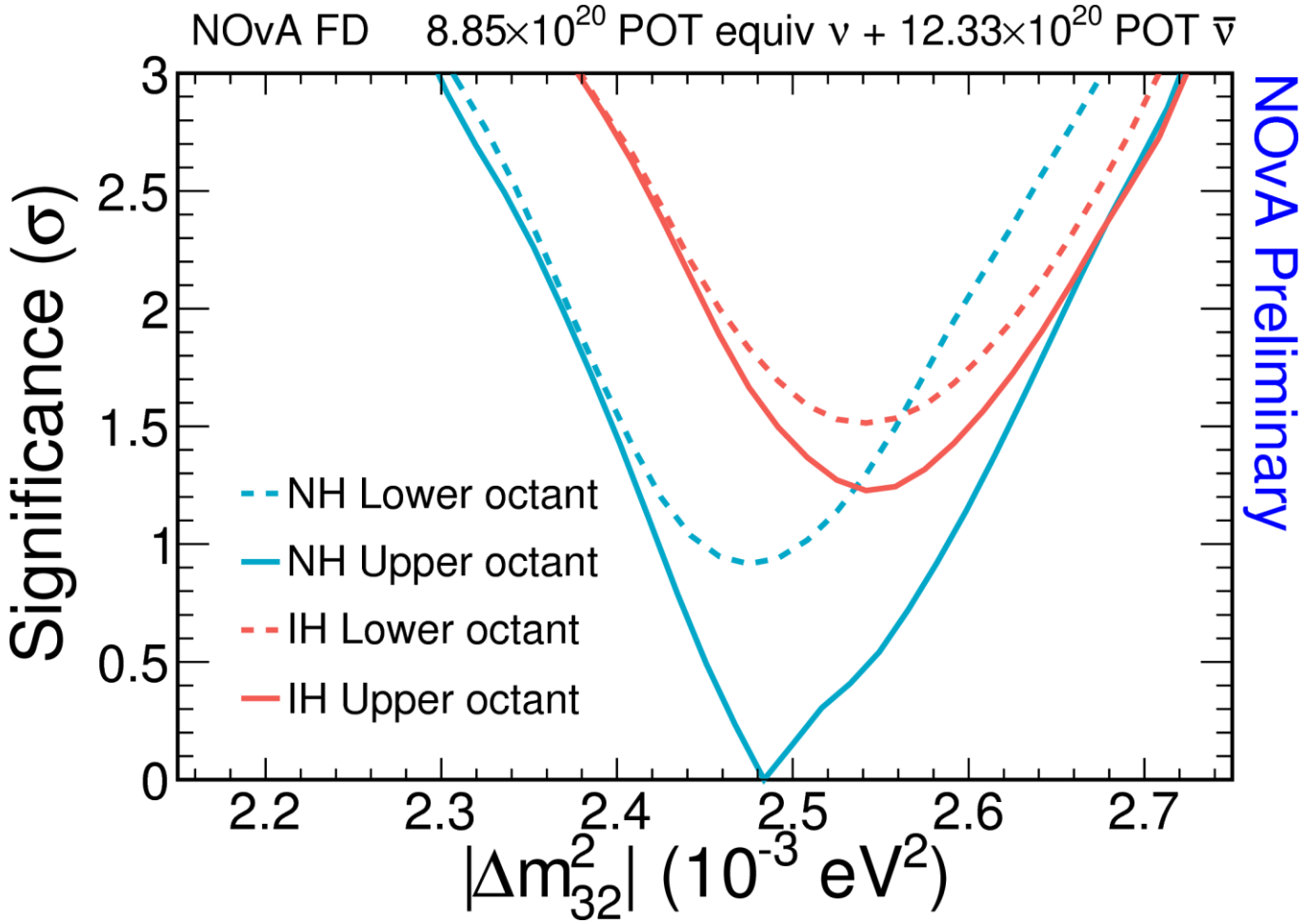
Re-perform fitting procedure with alternate non-MEC model (shifts within uncertainties) to establish uncertainty bounds for MEC fit

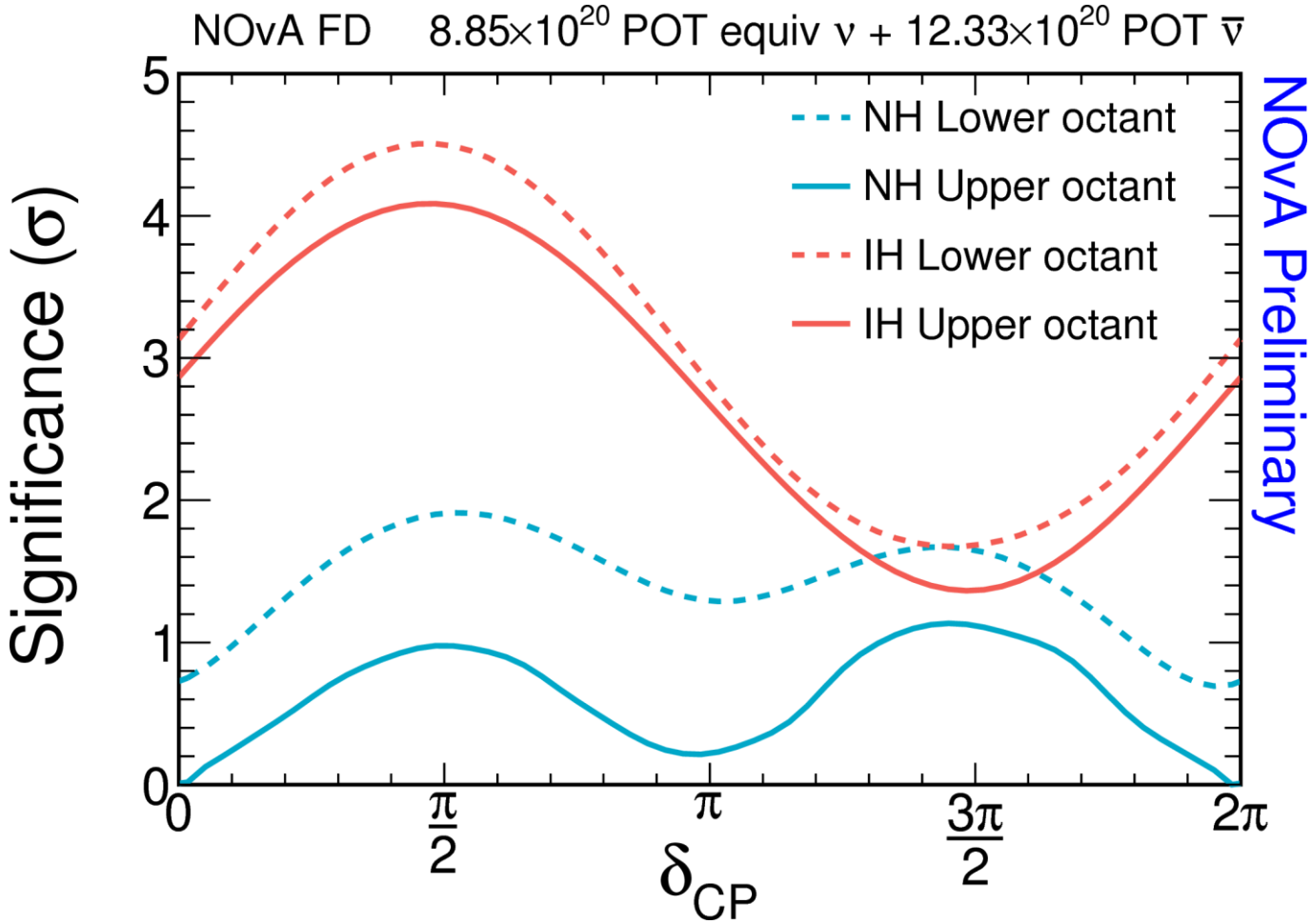
Cross Section Tuning - Future

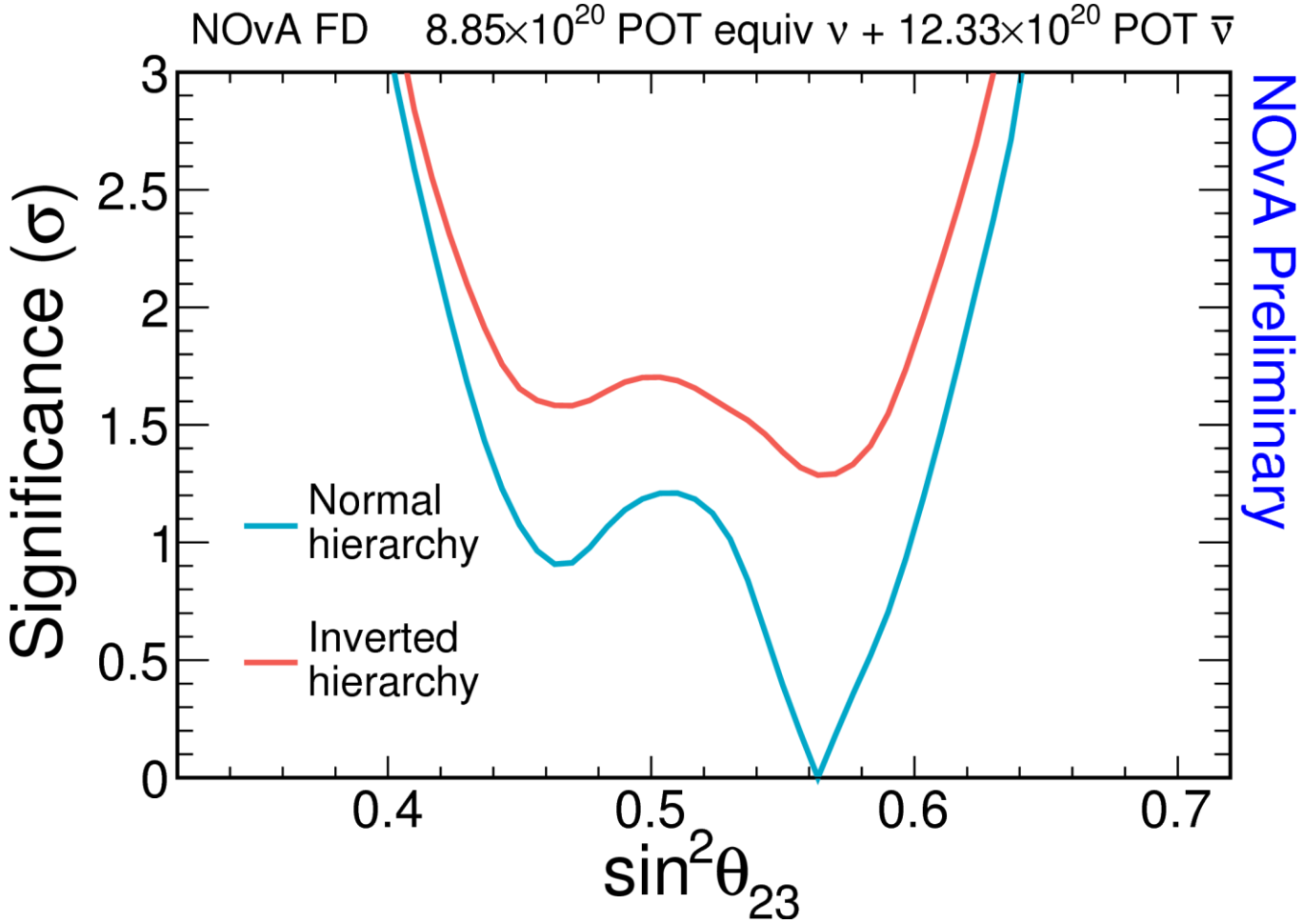
NOvA Preliminary

Topological selections give us other windows into the performance of our model

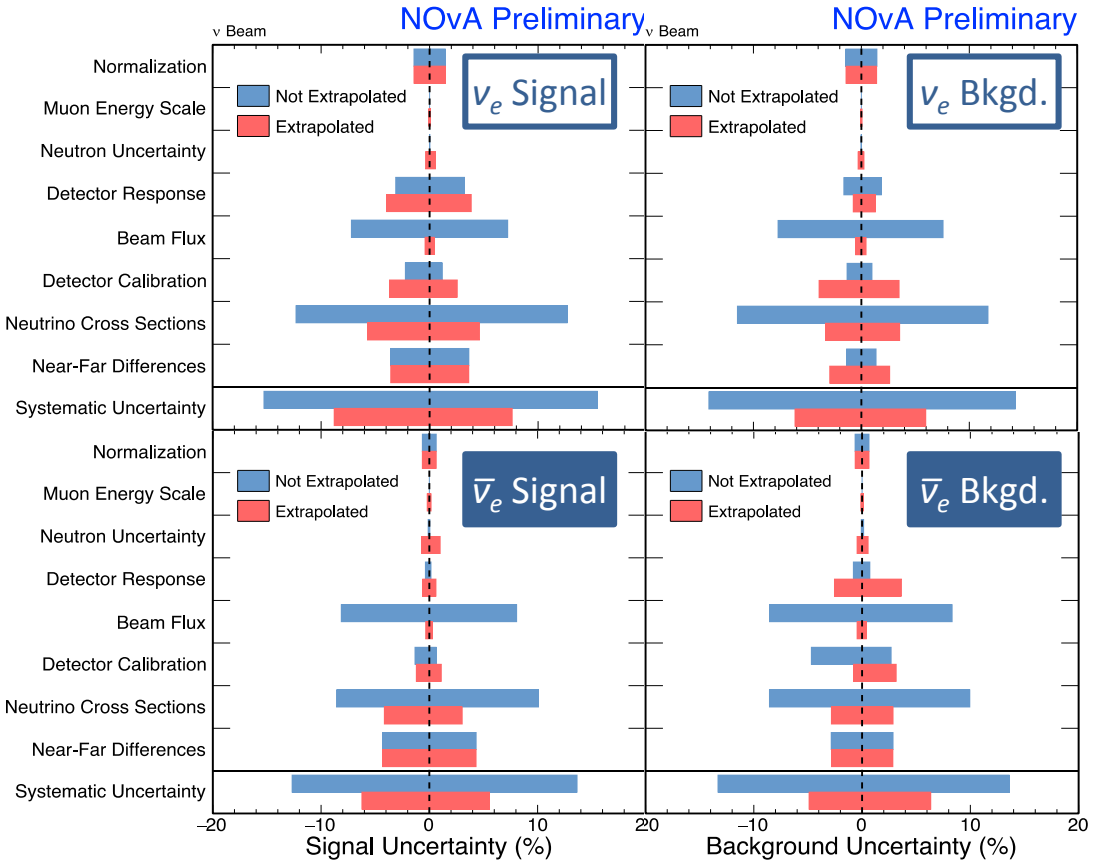



NOvA FD 8.85×10^20 POT equiv ν + 12.33×10^20 POT ν̄
Significance (σ)
|Δm²32| (10^-3 eV²)
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
NOvA Preliminary
0
0.5
1
1.5
2
2.5
3
2.2
2.3
2.4
2.5
2.6
2.7

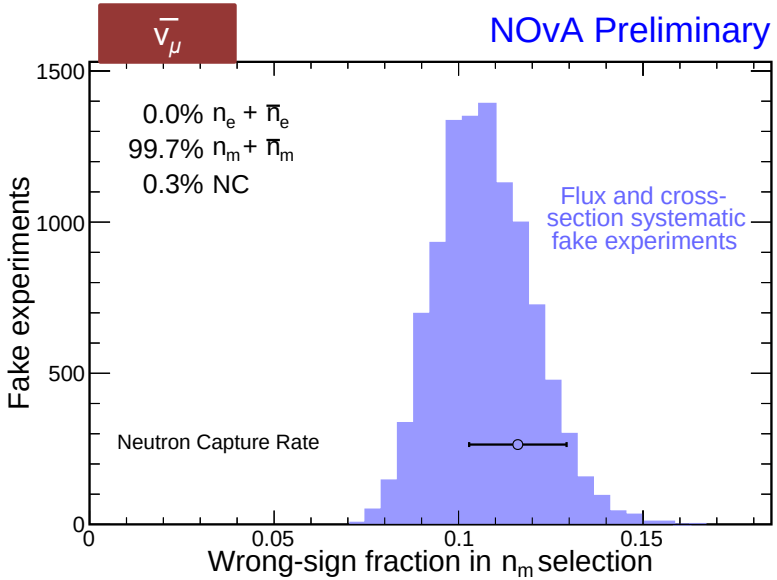

NOvA FD 8.85×10^20 POT equiv ν + 12.33×10^20 POT ν̄
Significance (σ)
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
NOvA Preliminary
0
1
2
3
4
5
0
π/2
π
3π/2
2π
δCP

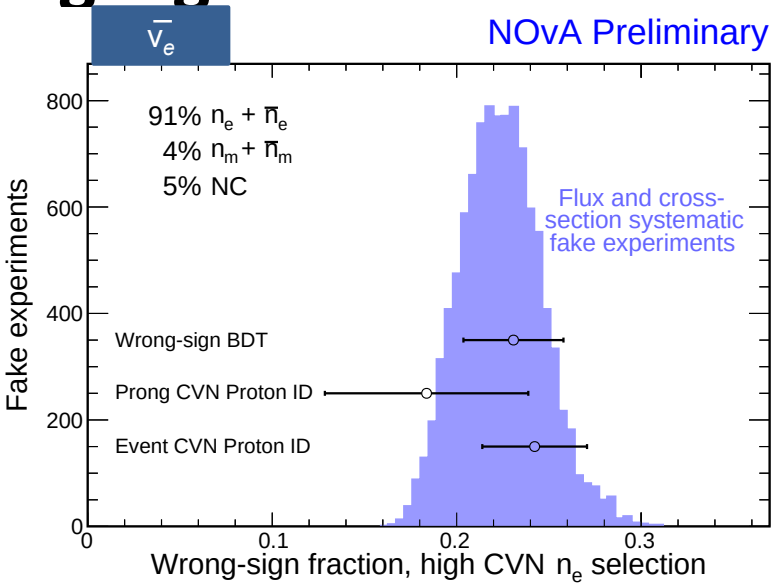

NOvA FD 8.85×10^20 POT equiv ν + 12.33×10^20 POT ν̄
Significance (σ)
3
2.5
2
1.5
1
0.5
0
0.4
0.5
0.6
0.7
sin²θ23
Normal hierarchy
Inverted hierarchy
NOvA Preliminary

Systematics Reduced with Extrapolation



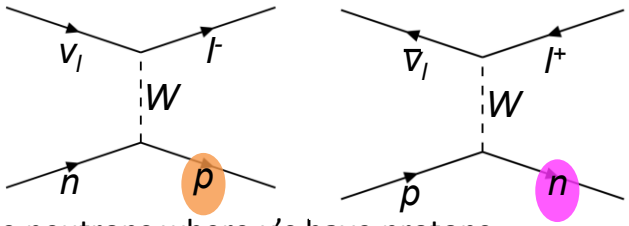
What's new with $\bar{\nu}$'s? Wrong-sign contamination



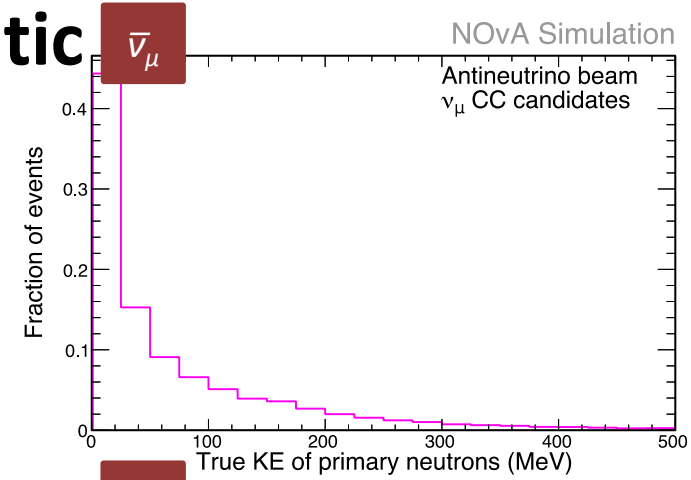


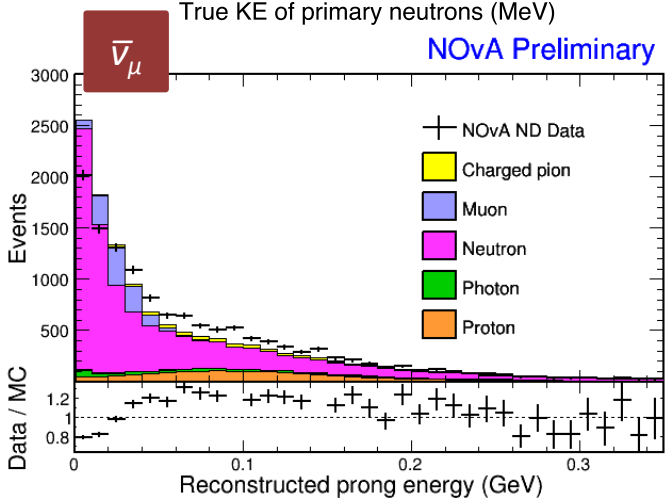
- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Does not include uncertainties from detector effects.
- Confirm using data-driven cross-checks
  - 11% WS in the ν_μ sample checked using neutron captures.
  - 22% WS in beam ν_e checked using identified protons and event kinematics.

New neutron response systematic

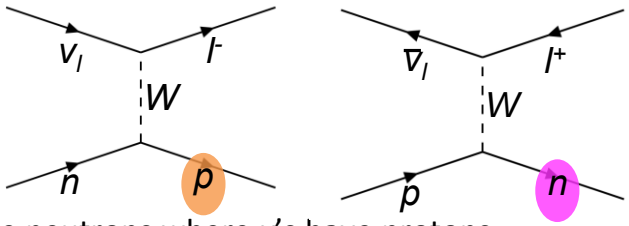


- $\bar{\nu}$'s have neutrons where ν's have protons.
  - Often several hundred MeV of energy.
  - Modeling these fast neutrons is known to be challenging.
- See some discrepancies in an enriched sample of neutron-like prongs.
- New systematic introduced:
  - Scales the amount of deposited energy of some neutrons to cover the low-energy discrepancy.
- Shifts the mean ν_μ energy by 1% in the antineutrino beam and 0.5% in the neutrino beam.
  - Negligible impact was seen on selection efficiencies.





New neutron response systematic



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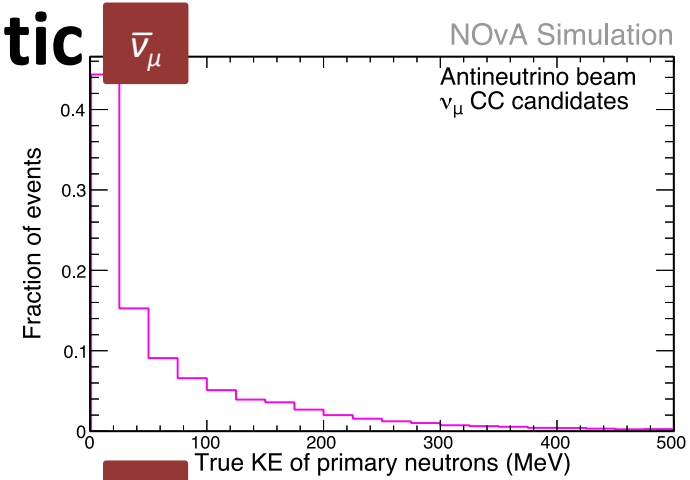
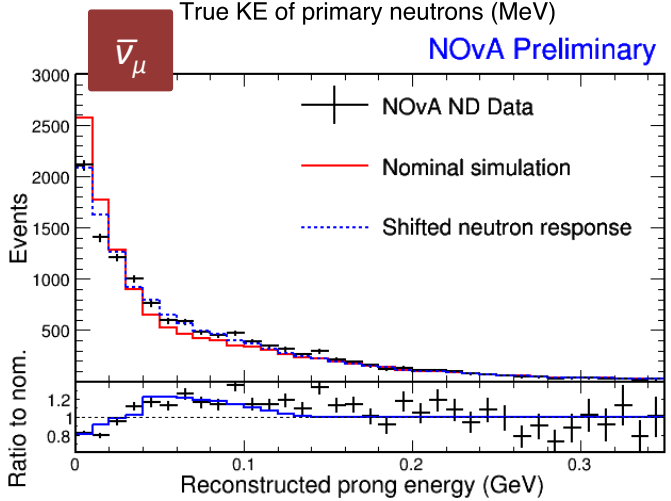
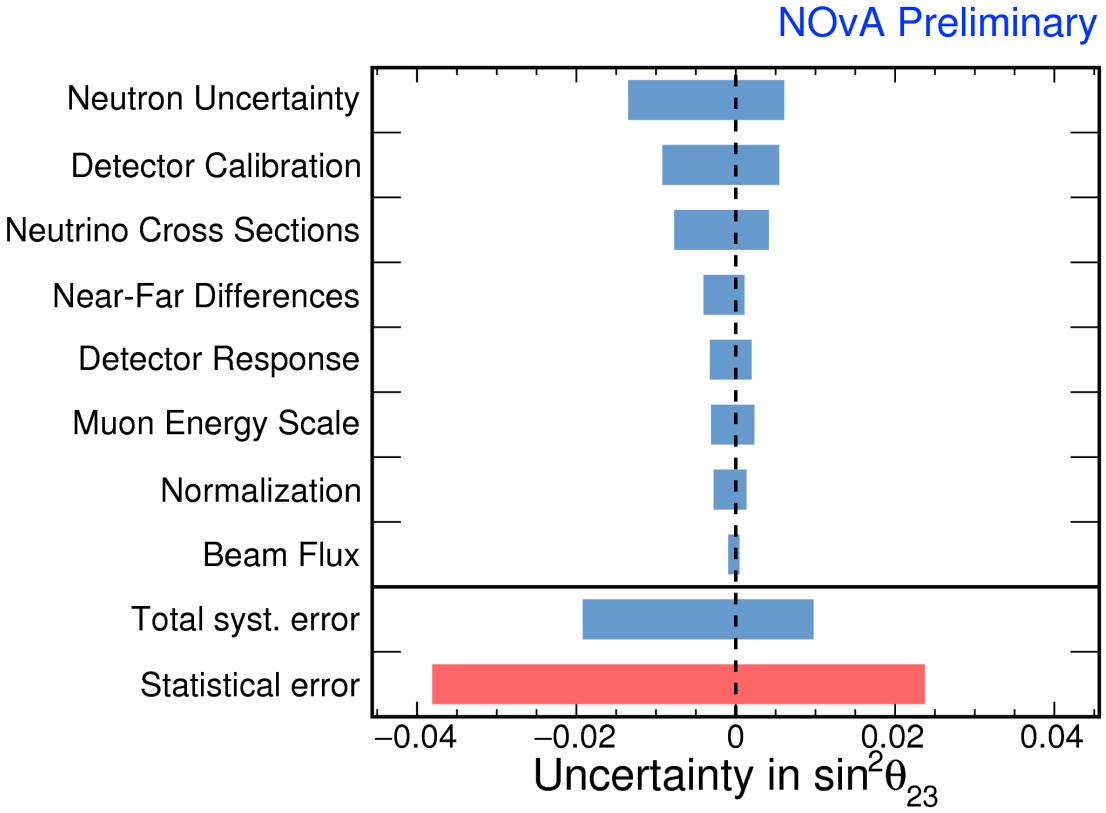
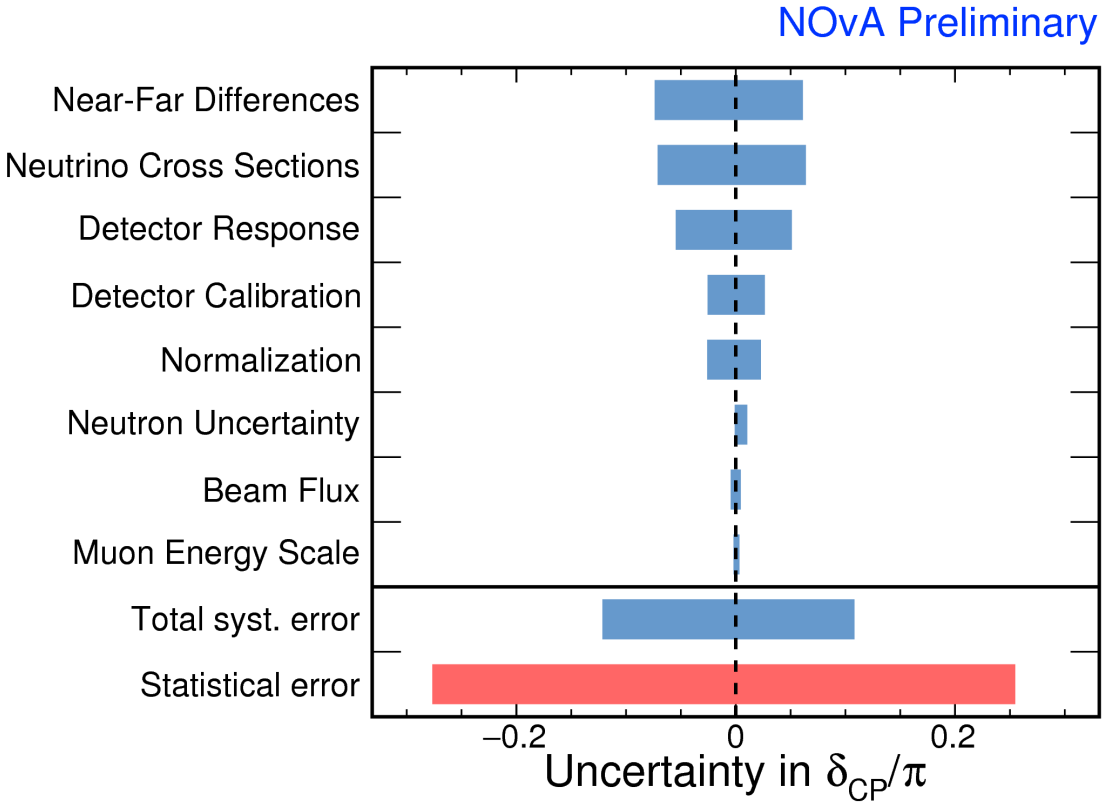




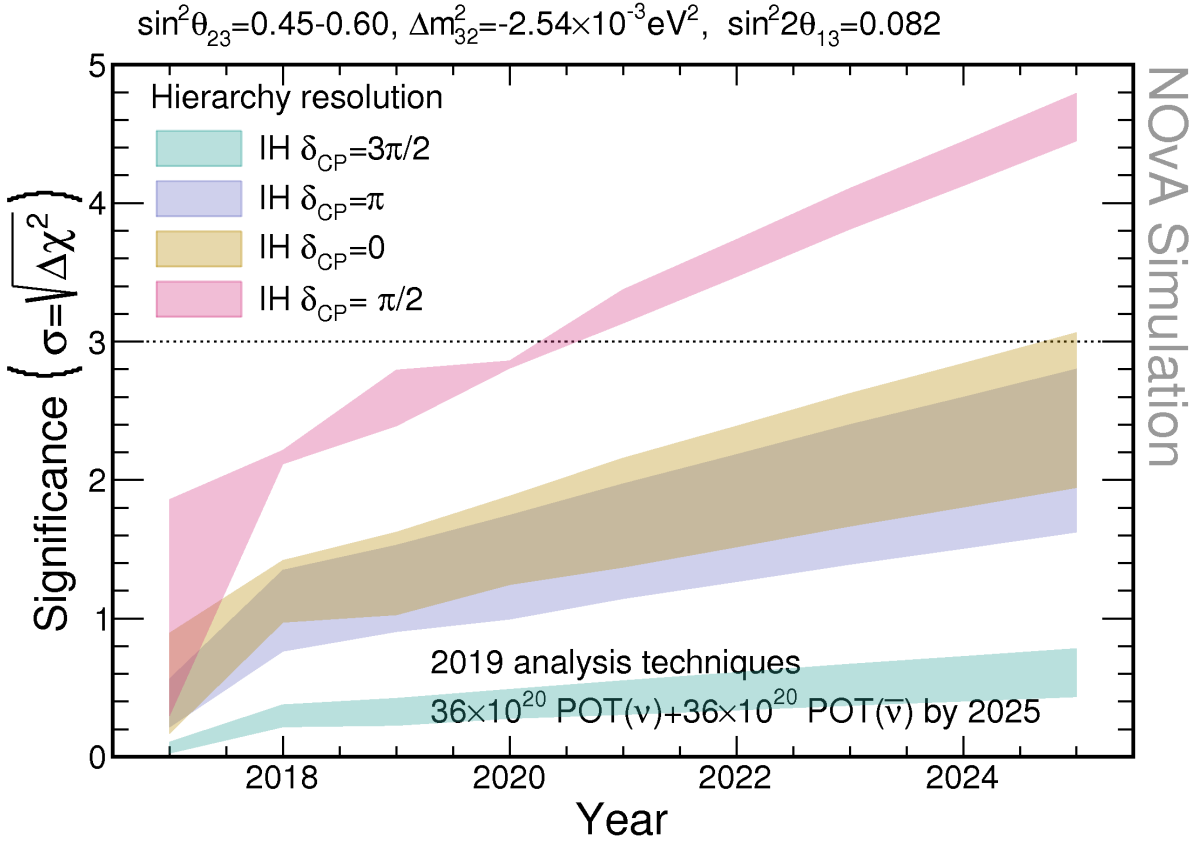
Systematics – $\sin^2\theta_{23}$



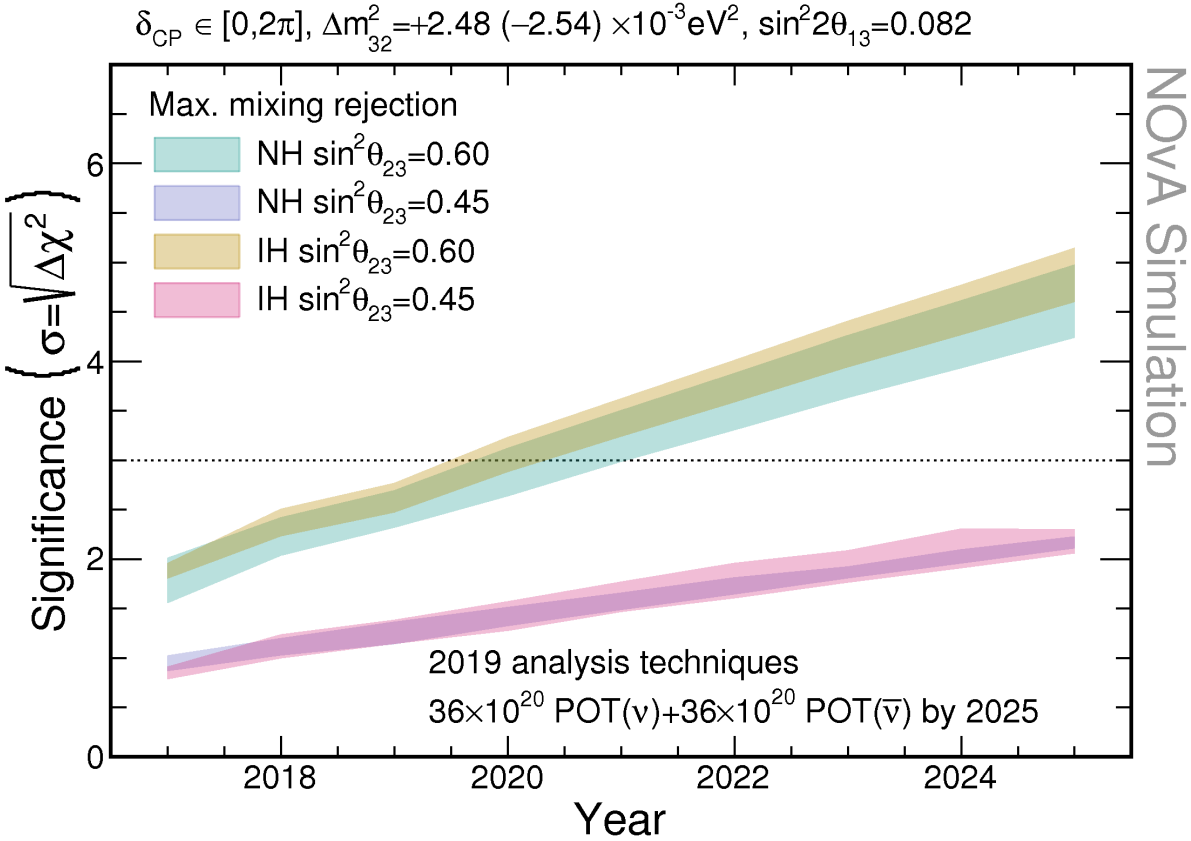
Systematics - δ_{CP}



Reach – Hierarchy Resolution, IH



Reach – Maximal Mixing Rejection



Reach - δ_{CP}