Caltech

NOvA

Interdisciplinary Developments in Neutrino Physics

@ KITP, UC Santa Barbara

Neutrino scattering and oscillation measurements with NOvA data

Zoya Vallari

on behalf of NOvA collaboration

28 March 2022

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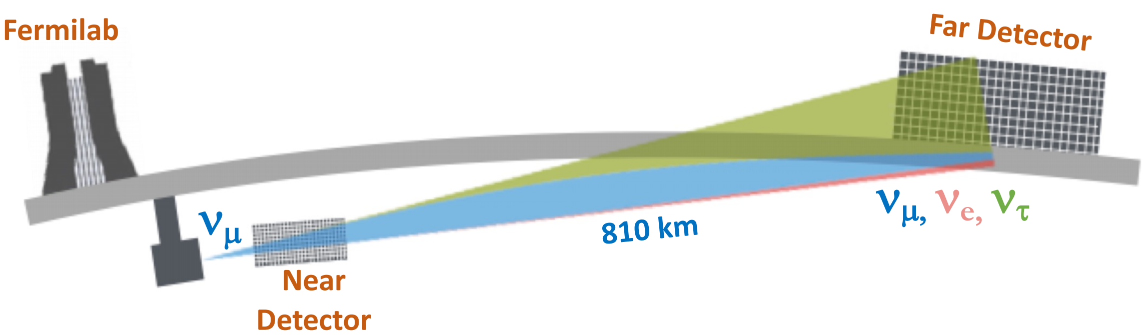
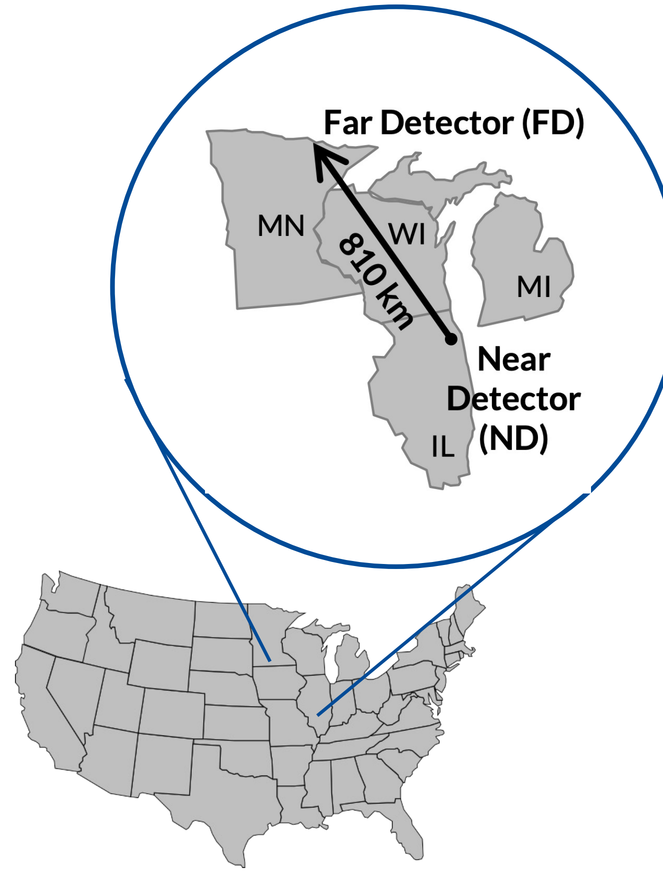
The NOvA Experiment





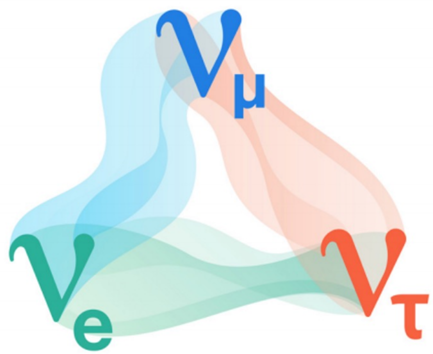
- NOvA is an accelerator based **long-baseline neutrino oscillation** experiment.

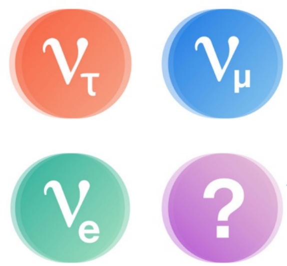
- It receives a beam of **muon (anti)neutrinos** peaked at **2 GeV** energy from the NuMI beam facility at Fermilab.

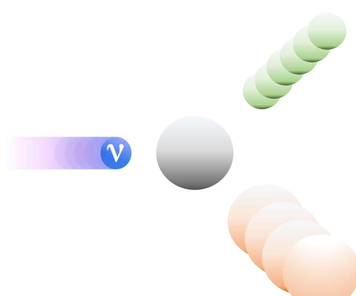
HUMANS OF NOvA

- **200 collaborators**
- **50 institutions**
- **8 countries**

NOvA's Physics Program







3-flavor Neutrino Oscillation

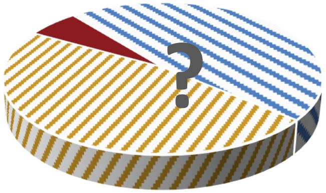
Sterile Neutrino Search

Astrophysical measurements

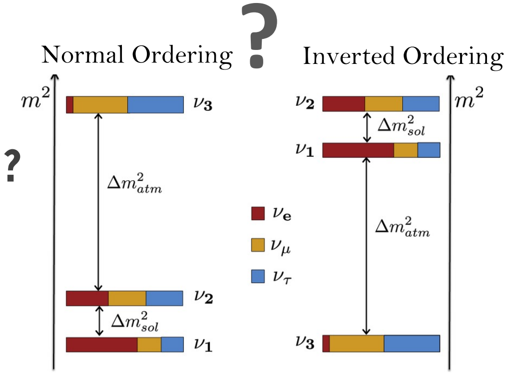
Neutrino-nucleon interaction

NOvA's Physics Goals

1. θ_{23} : Is the mixing maximal?



2. Mass Ordering: Normal or Inverted?



3. δ_{CP}: Do neutrinos violate CP?

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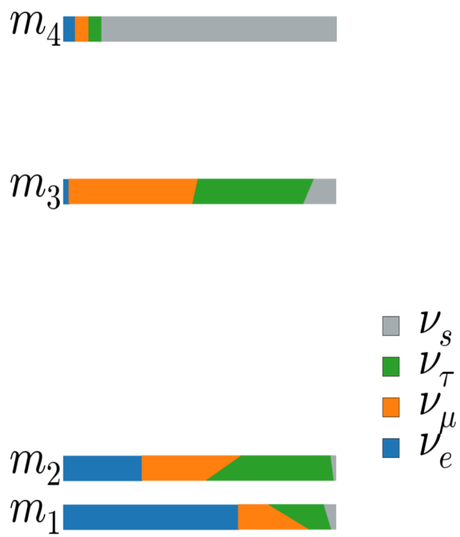
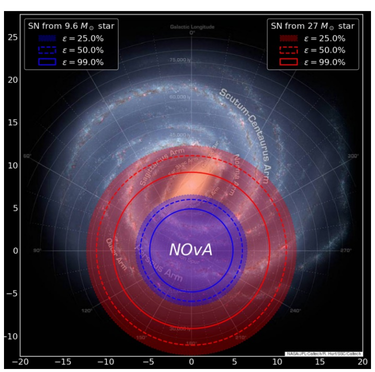
NOvA's Physics Goals



- Search for 3+1 sterile neutrino models in the neutral current disappearance channel.



- Seasonal Cosmic Ray variations.
- Search for a magnetic monopole component of cosmic rays.
- Detection of supernova neutrinos.

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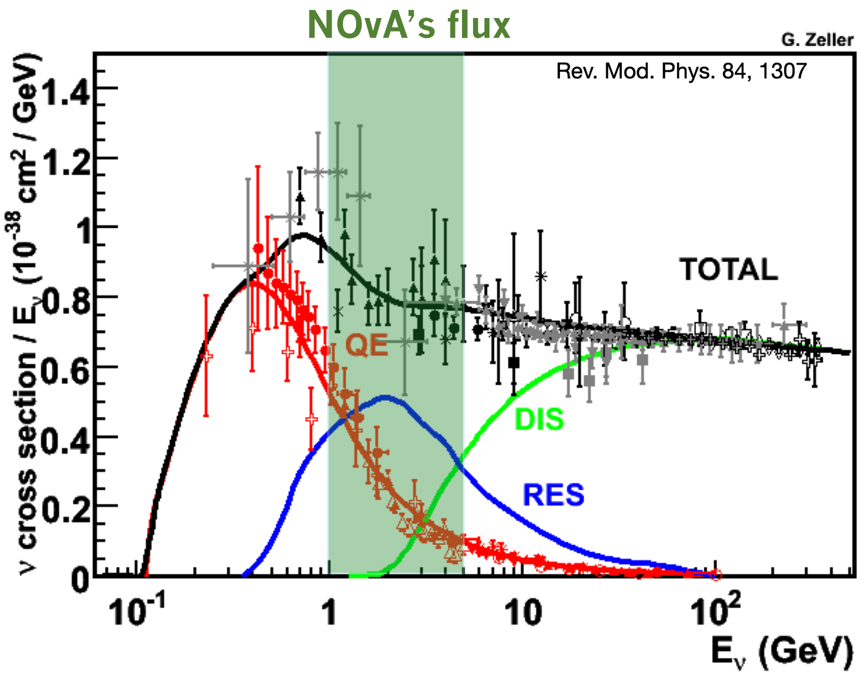
NOvA's Physics Goals



- Very high statistics environment at the NOvA ND.
- Cross section measurements provide constraints on neutrino interaction models.

3-flavor Neutrino Oscillation

Sterile Neutrino Search

Astrophysical measurements

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NOvA's Physics Program

! This talk !

3-flavor Neutrino Oscillation

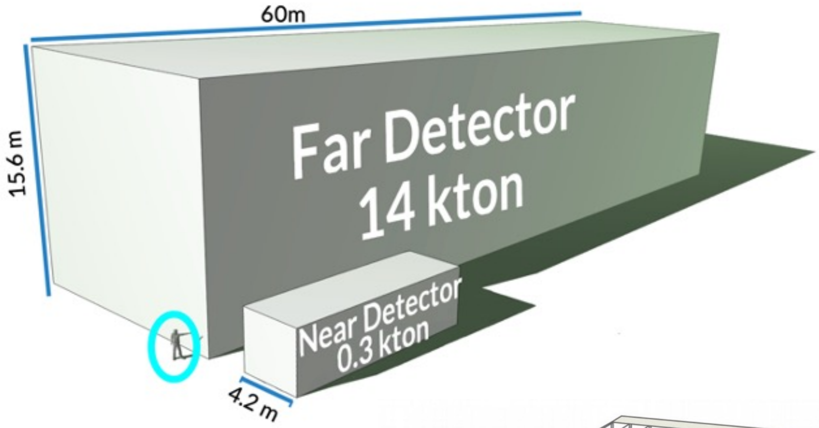
Sterile Neutrino Search

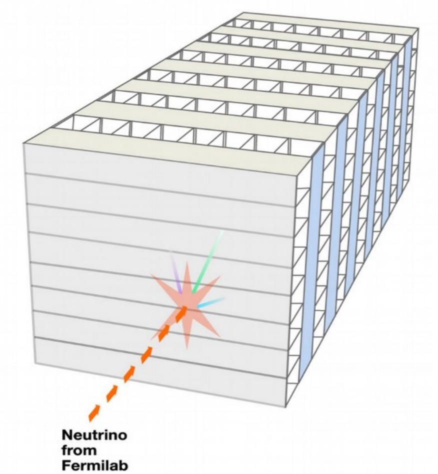
Astrophysical measurements

Neutrino-nucleon interaction

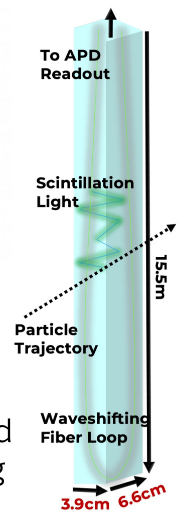
The NOvA detectors

- NOvA's ND and FD are **functionally identical detectors.**
- Segmented liquid scintillator detectors:
  - Particle detection via tracking and calorimetry.
- Optimized for electron showers:
  - **~6 samples per X_0** (40cm) & ~60% active volume
- Nuclear Targets: CH2 (77%), Cl (16%), TiO2(6%)
- Spatial resolution: **~few cm** (good rejection of cosmic events)
- Timing resolution: **few ns** (to distinguish pile-ups)

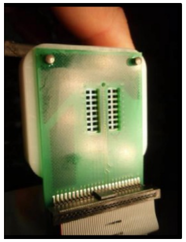




Alternating layers of scintillator planes which provide two 2D views.



Liquid scintillator contained in PVC cells. Scintillation light is carried by the wavelength shifting fibers to APDs.



Avalanche Photodiode (APD)

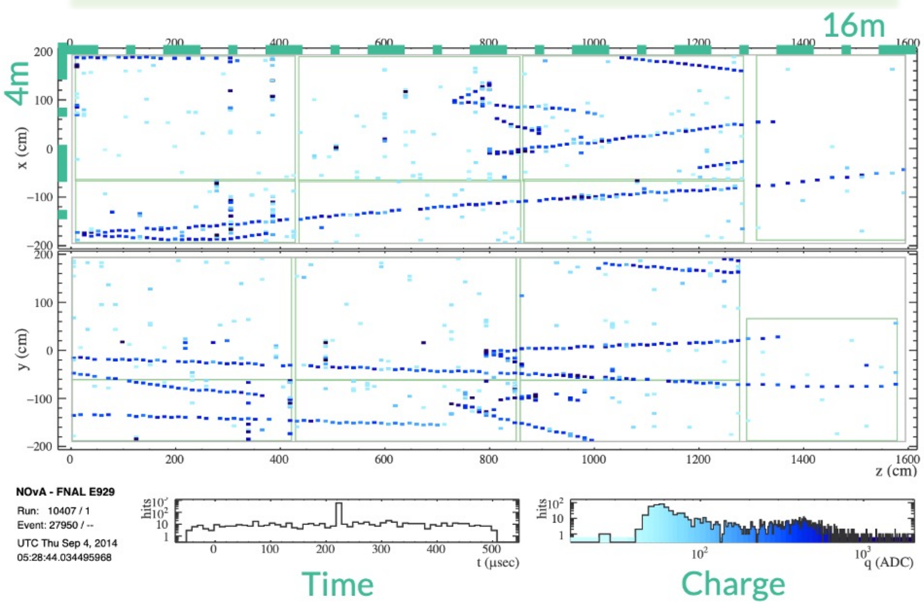
The NOvA detectors

Near Detector (ND)

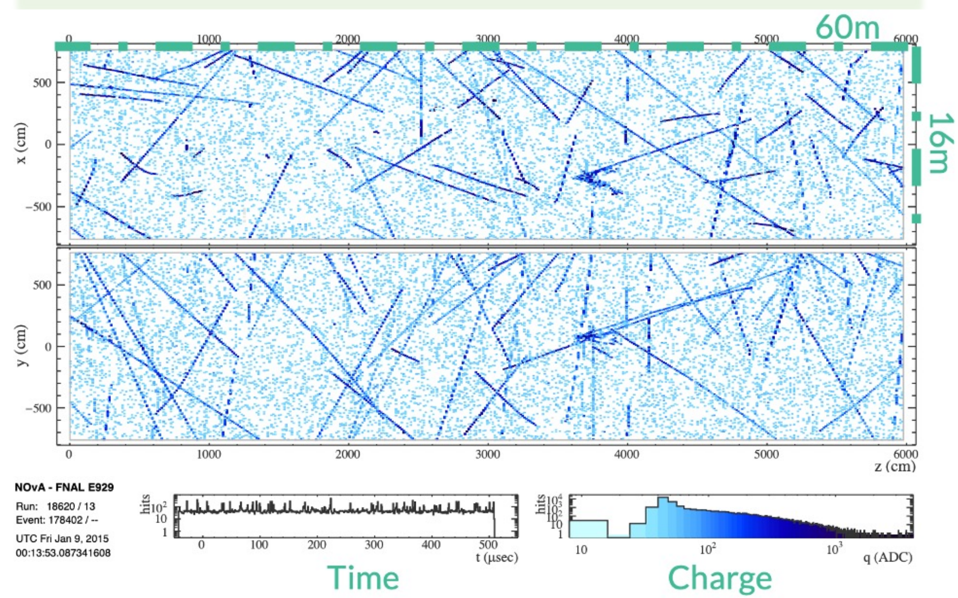
- 290-ton
- ~20k channels
- **1km** from beam target
- 5 contained neutrino events per beam pulse
- **Underground** : negligible cosmic neutrino events

Far Detector (FD)

- 14k-ton
- ~344k channels
- **810 km** from beam target
- < 1 neutrino event per day
- **On the ground** :~150 kHz cosmic neutrino background



ND Event Display : Shows pileup during the 10µs ND beam spill



FD Event Display : full 550µs exposure in FD dominated by cosmics

Simulation

Neutrino Flux

- Geant4 based simulation for NuMI beamline : **G4NuMI**
- Hadron production model constrained with external measurements on thin target.

Neutrino Interaction

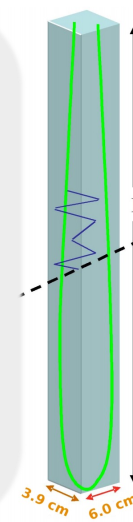
- ν-A interactions are simulated with the GENIE generator.
- The simulation is tuned to both the external and the internal data from the ND.

Today's results:

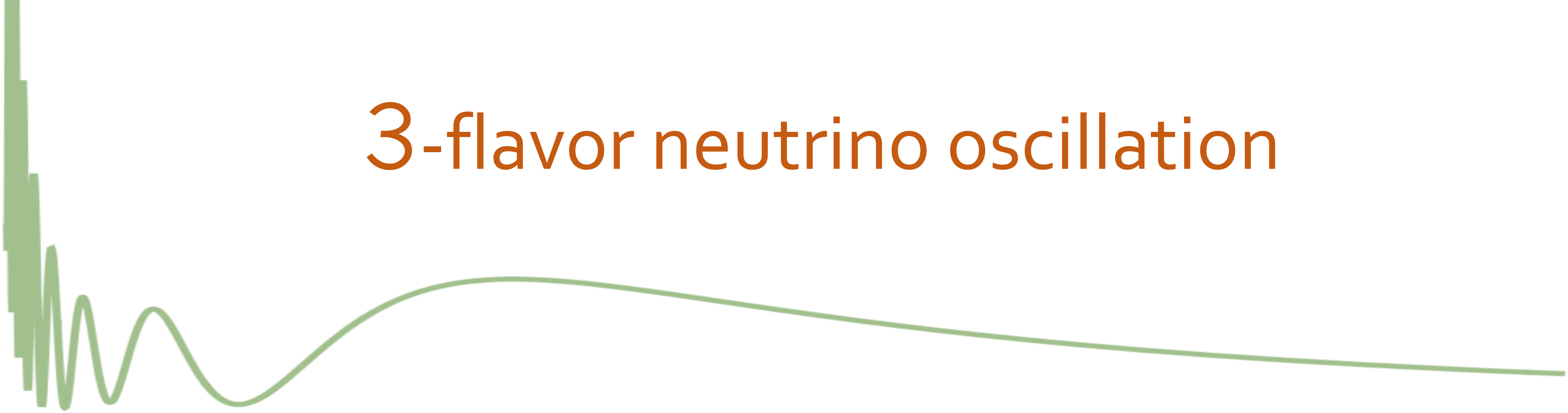
1. Neutrino-oscillation : **GENIE v3.0.6**
2. Cross-section – **GENIE v2.12.2**

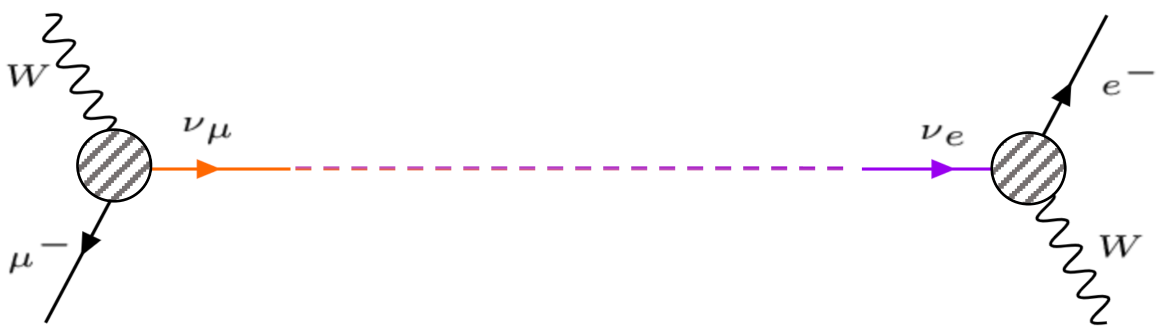
Detector Response

- Geant4 is used to propagate the final state particles inside the detector volume.
- Custom simulation for light readout and front-end electronics.



3-flavor neutrino oscillation

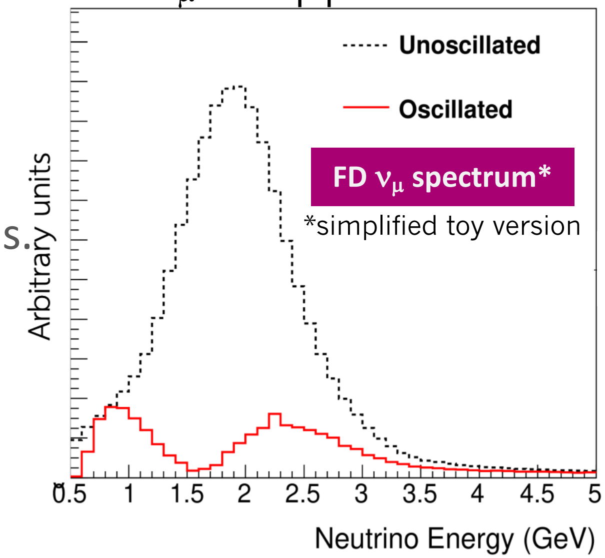




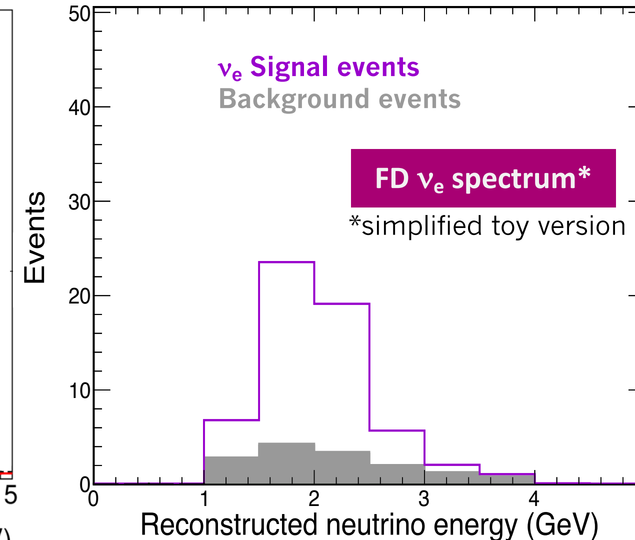
Measuring Oscillations

Two Channels

$\overset{(-)}{\nu}_\mu$ disappearance



$\overset{(-)}{\nu}_e$ appearance



Measurement →

1. **Detect** neutrino interactions.
2. **Identify** the flavor.
3. **Reconstruct** energy.

Measuring Oscillations

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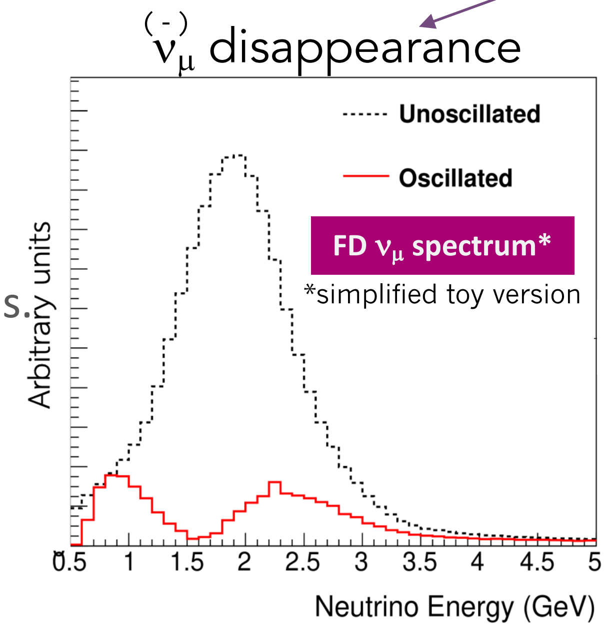
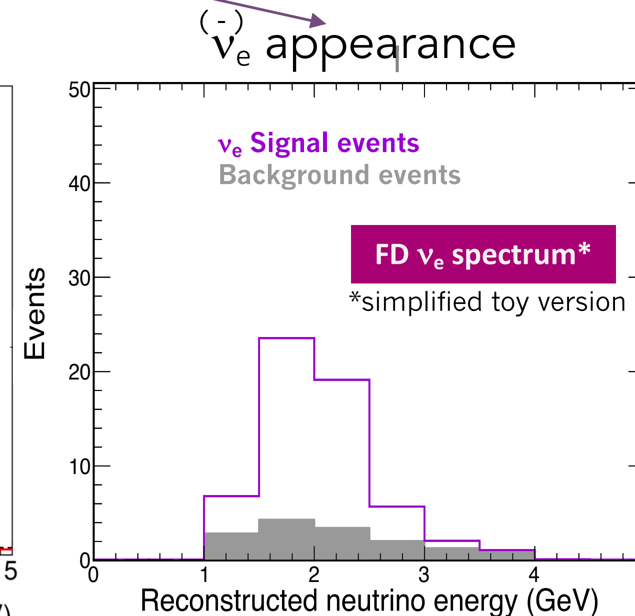
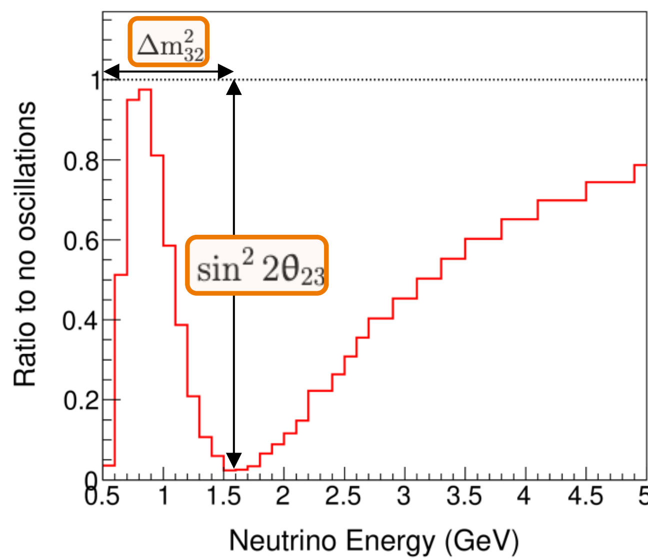
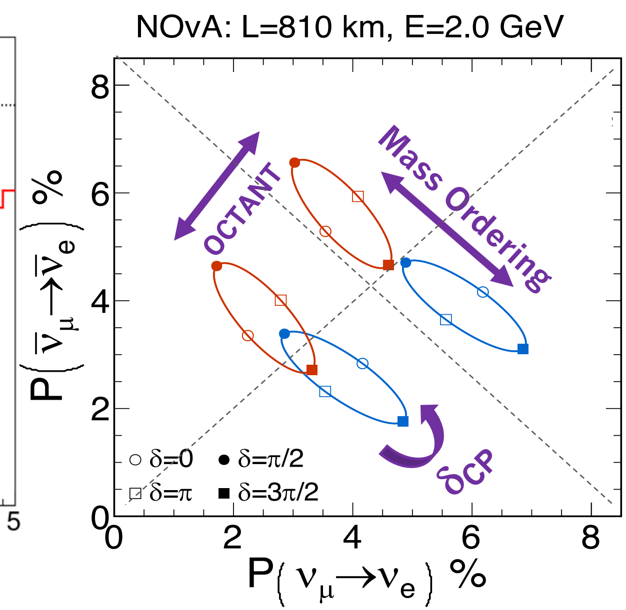




Inference →

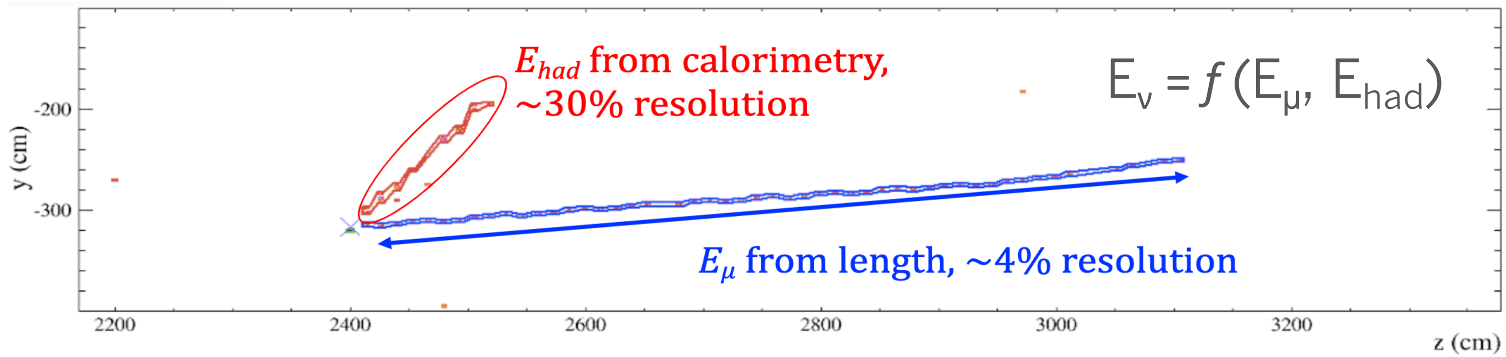
1. Compare with the no oscillation prediction.
2. Compare ν_e and $\overline{\nu}_e$ appearance rate.





Reconstructing Neutrino Energy

ν_μ

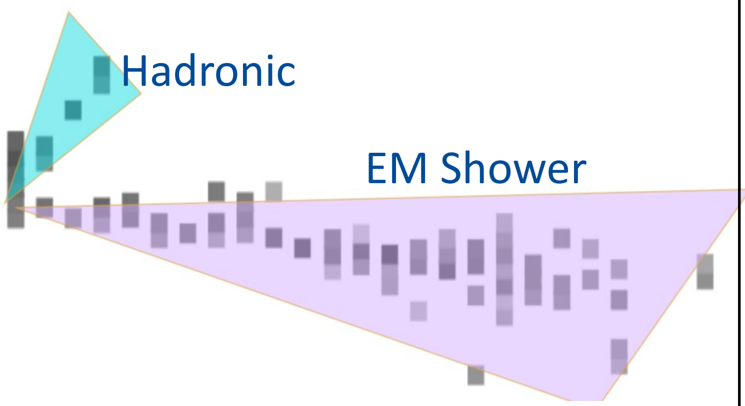


- Muon energy is estimated from the track length and hadronic energy from visible hadronic activity.

ν_e

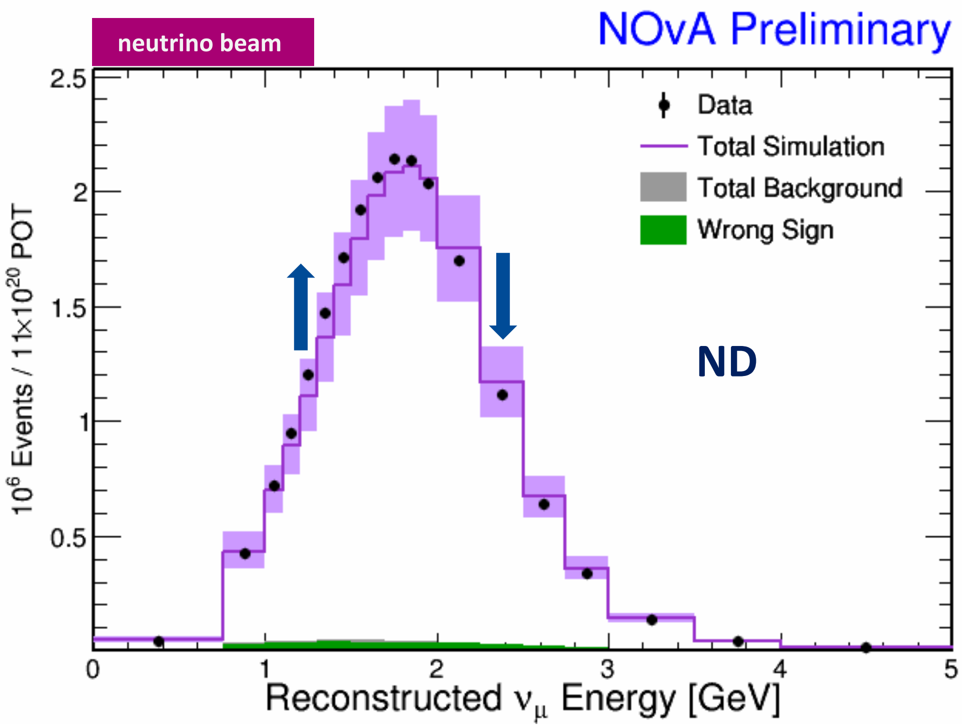
$E_\nu = f(E_{EM}, E_{had})$

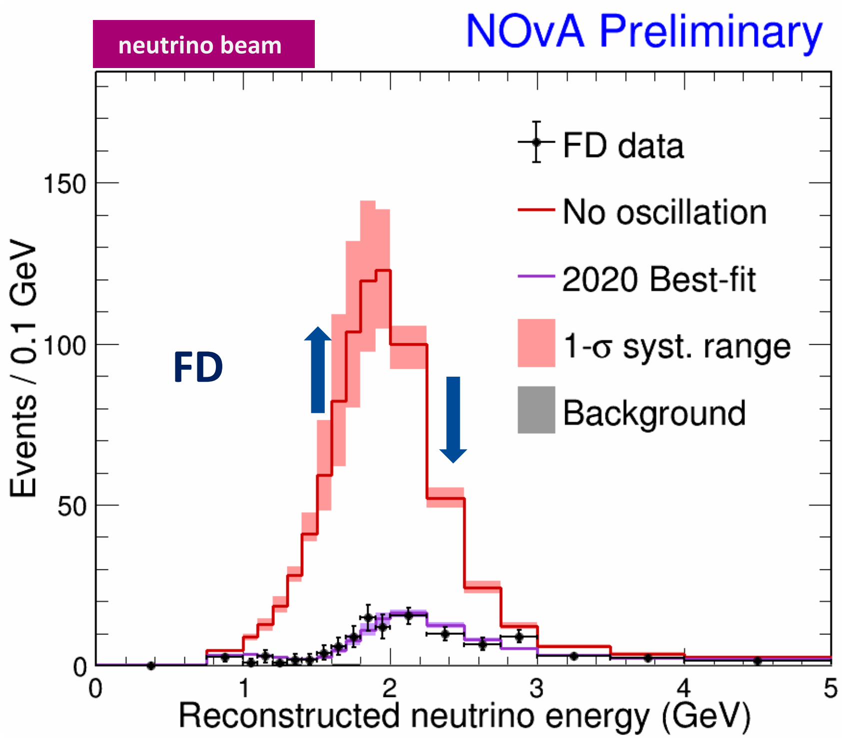
- Calorimetric energy estimation is done for EM and hadronic clusters separately.
- Overall neutrino energy resolution is ~11%.



Extrapolation : ND Data in Oscillation Analysis

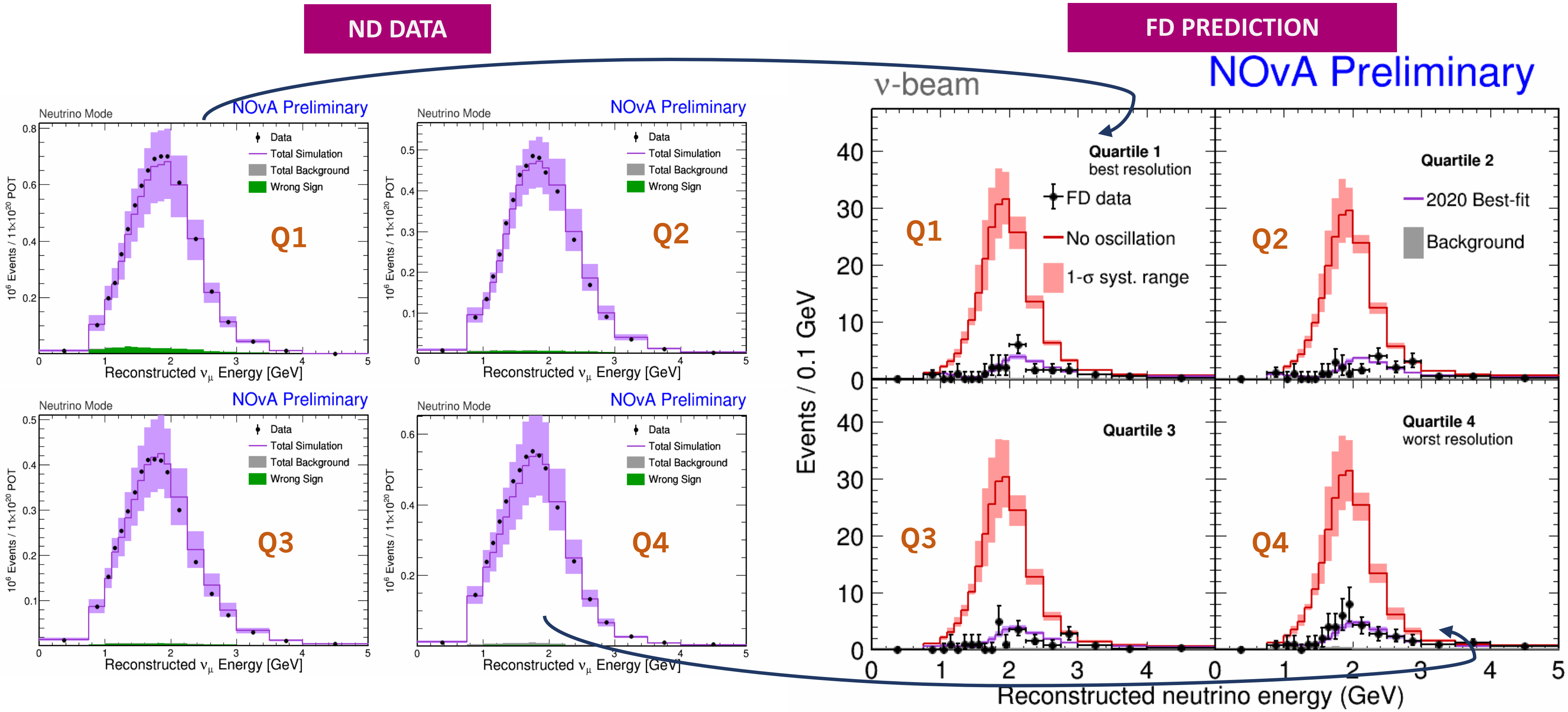
- Data from the functionally identical ND is used to predict both ν_μ and ν_e signal spectra at the FD.
- The differences between the two detectors in flux, acceptance and cross-sections are modeled using simulations and related systematic uncertainties.





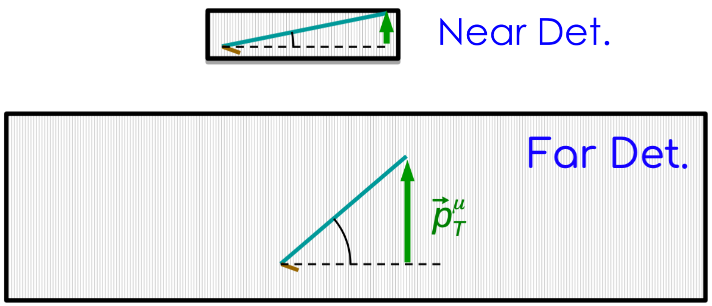
Extrapolation: Energy Resolution

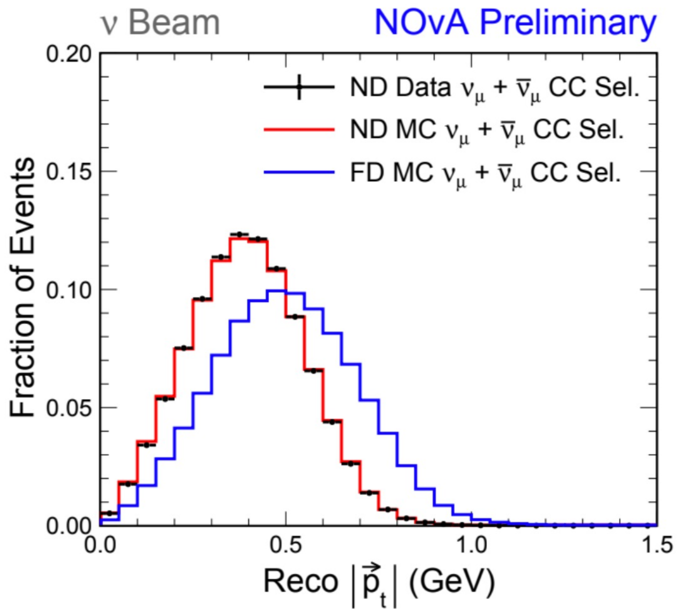
- Oscillation sensitivity for ν_μ disappearance measurement depends on the shape of the spectrum.
- Dividing the ν_μ sample in quartiles (Q1-Q4) of fraction of hadronic energy separates high-resolution events. This increases the sensitivity to the shape of the oscillation dip.

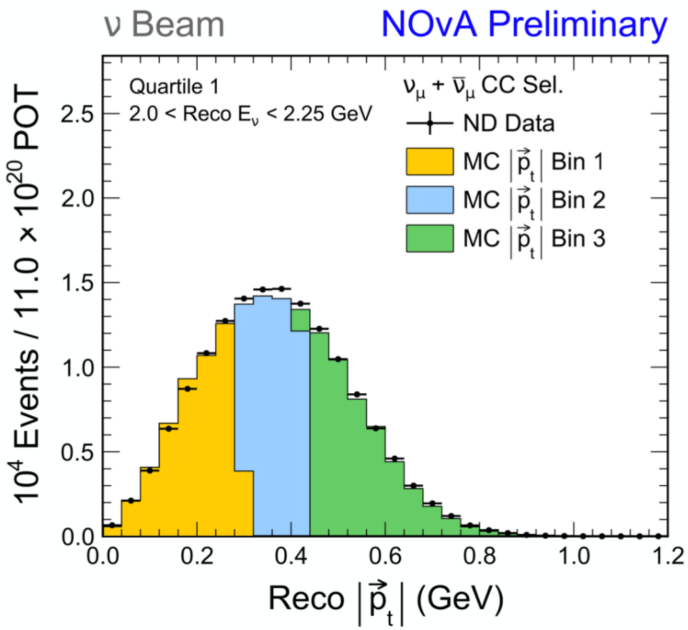


Extrapolation: Detector Acceptance

- Due to a large difference in size of the detector, FD has a larger acceptance of the particles going in the transverse direction than the ND.
- This difference is evident in the lepton $|\vec{p}_t|$ distributions.
- **Sub-divide the sample in 3 bins of lepton $|\vec{p}_t|$** and extrapolate ND data for each bin separately.

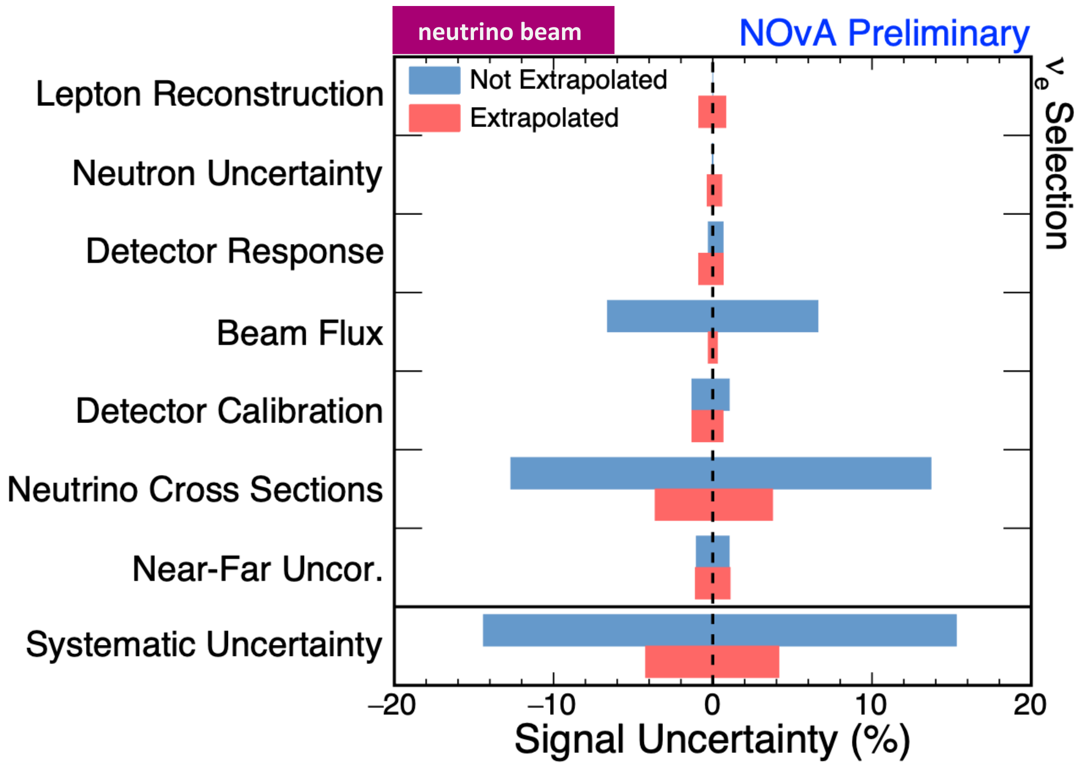




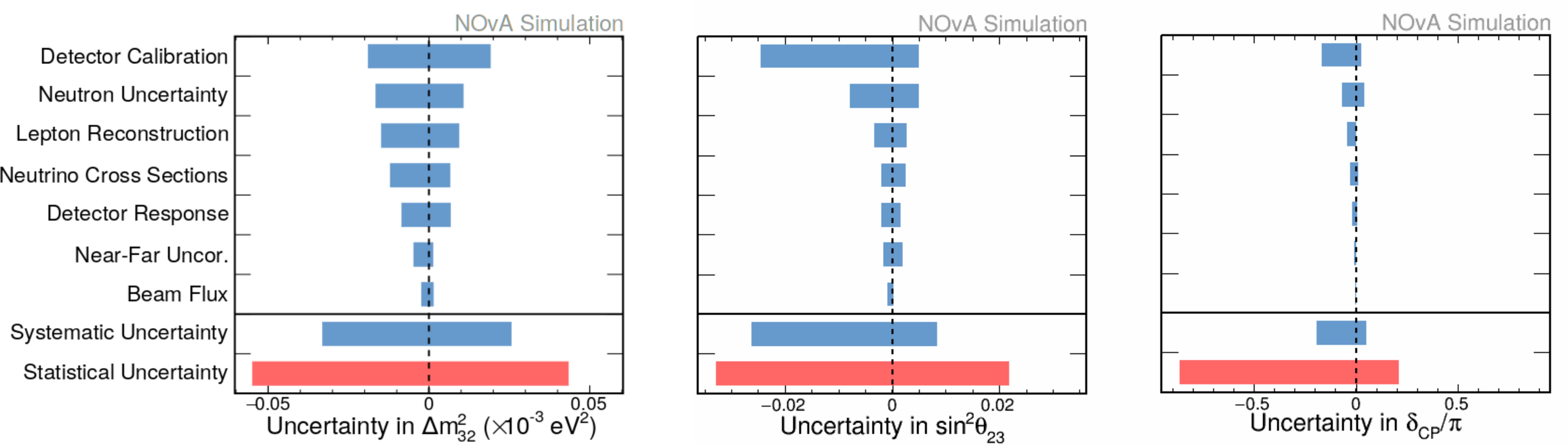


Extrapolation : Constraining Systematics

ND Data constrains the total systematic uncertainties in the FD prediction from >15% to ~5%.

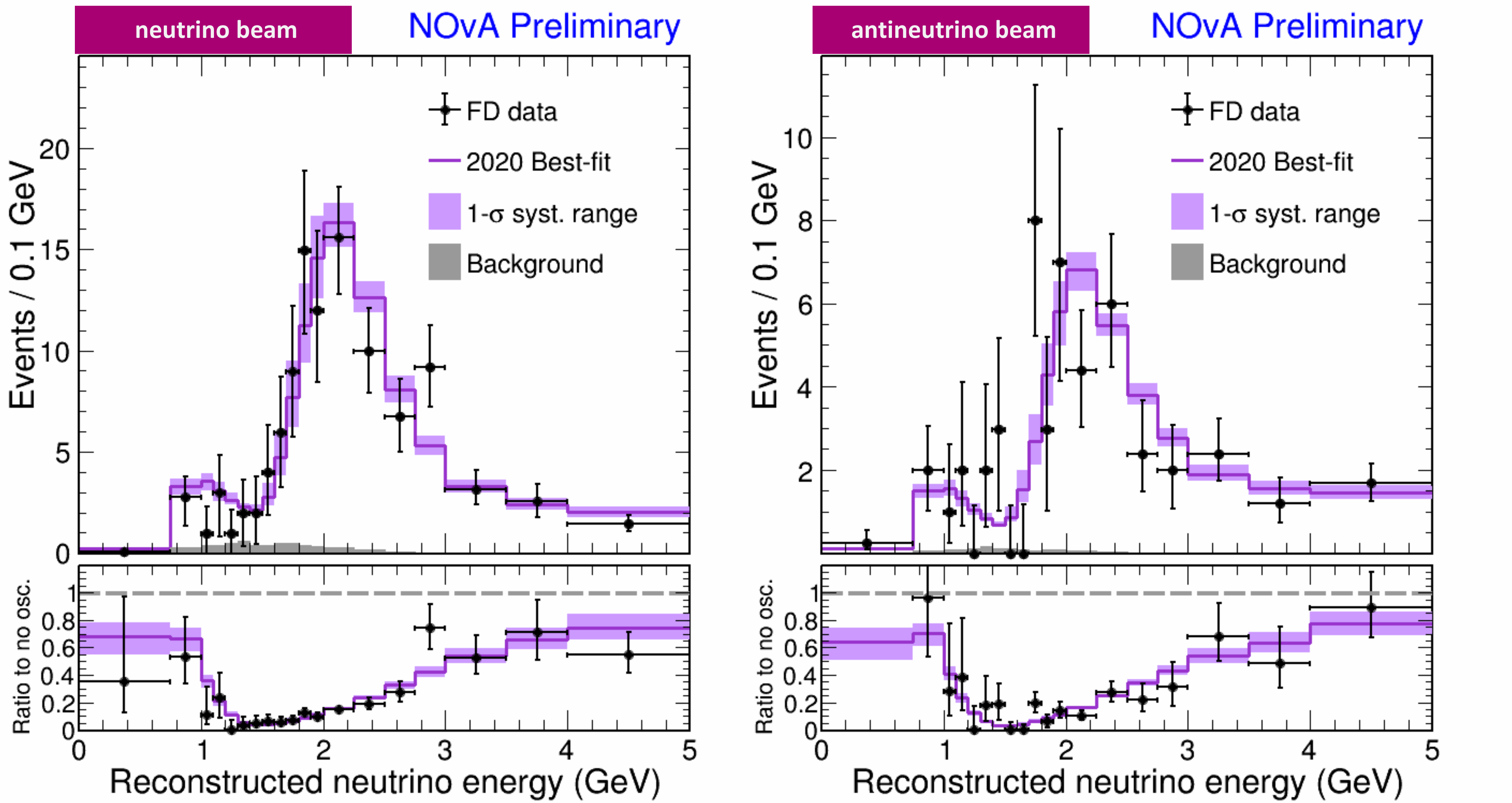


Total uncertainty on oscillation parameters



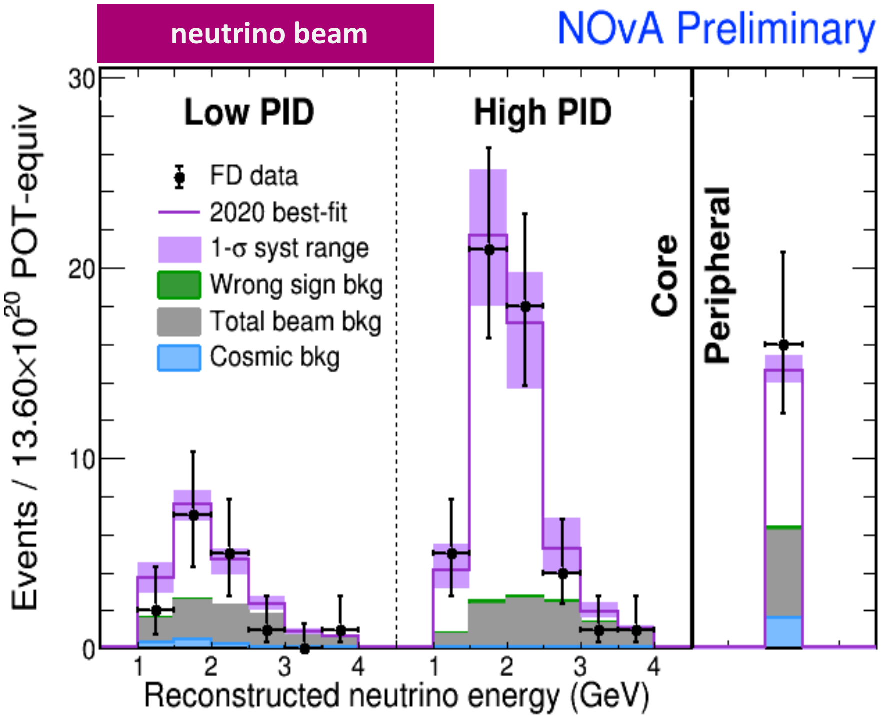
- ➢ Measurement of oscillation parameters at NOvA is significantly statistically limited.
- ➢ Largest source of systematic error comes from detector calibration which directly impacts the energy scale of the events.
- ➢ NOvA Test Beam Program currently underway to improve detector calibration.

FD Data Samples : ν_μ disappearance

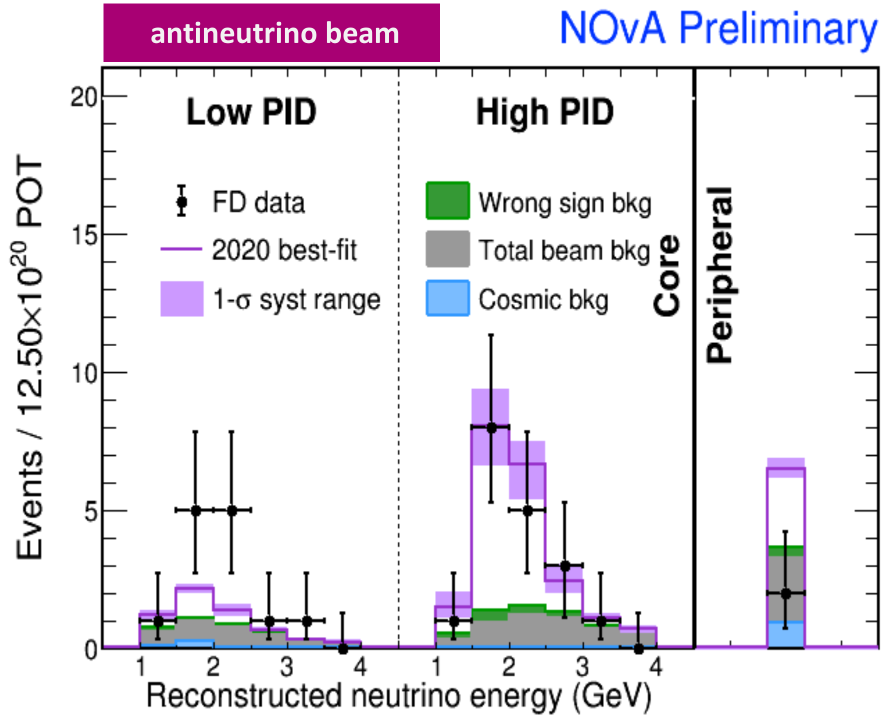


- The predictions (with the systematics band) are varied with the oscillation probabilities until the best-fit values with data are obtained.
- Applying 3-flavor oscillations describes these data well: p=0.705.

FD Data Samples : ν_e appearance



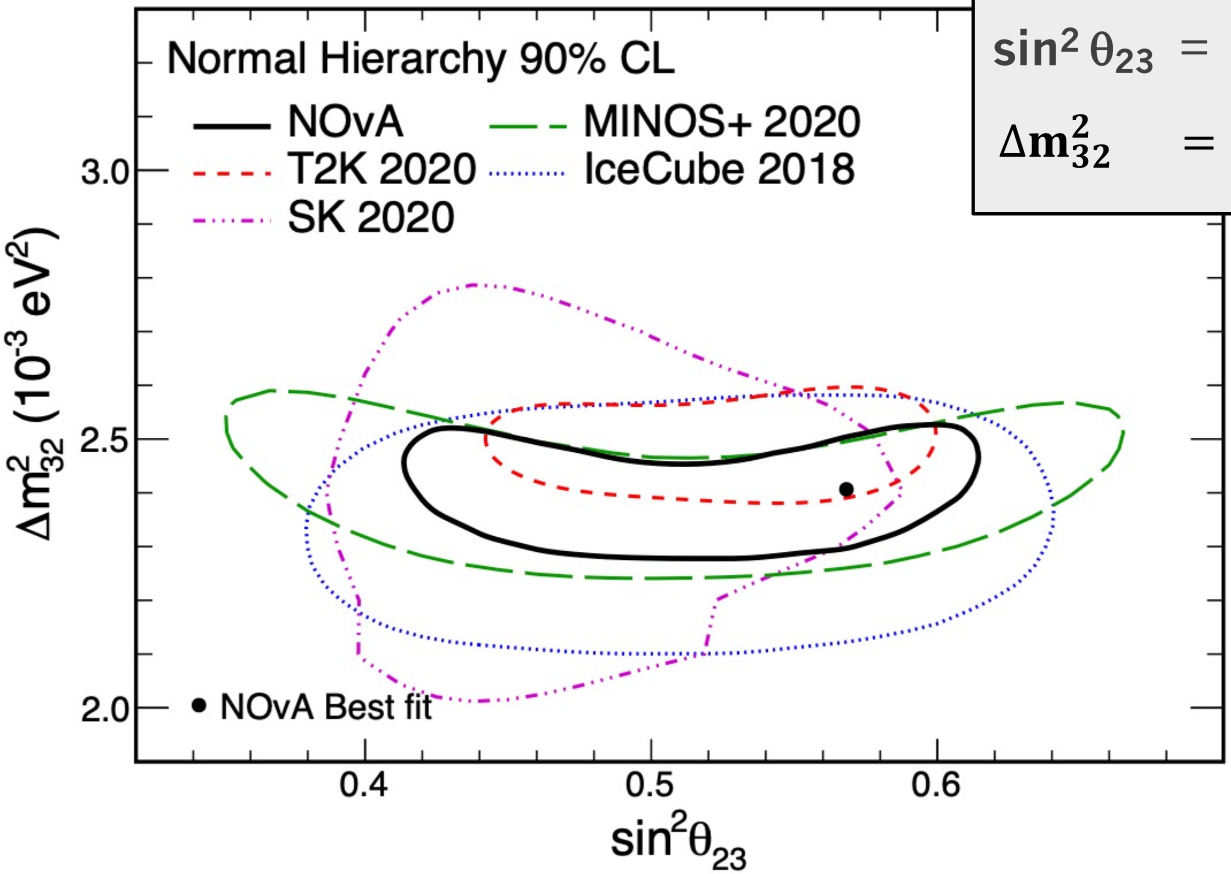
Observed 82 events (27 bkgd)



Observed 33 events (14 bkgd) : > 4σ $\overline{\nu}_e$ appearance

- Separating in bins of Particle ID enhances oscillation sensitivity which is dependent on a better rejection of background events.
- Peripheral sample include high PID events at the edges of the detector which might not be well contained.

Mass splitting and mixing angle



NOvA's Best Fit:

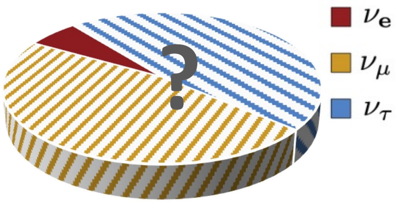
$$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$$

$$\Delta m^2_{32} = (+2.41 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$

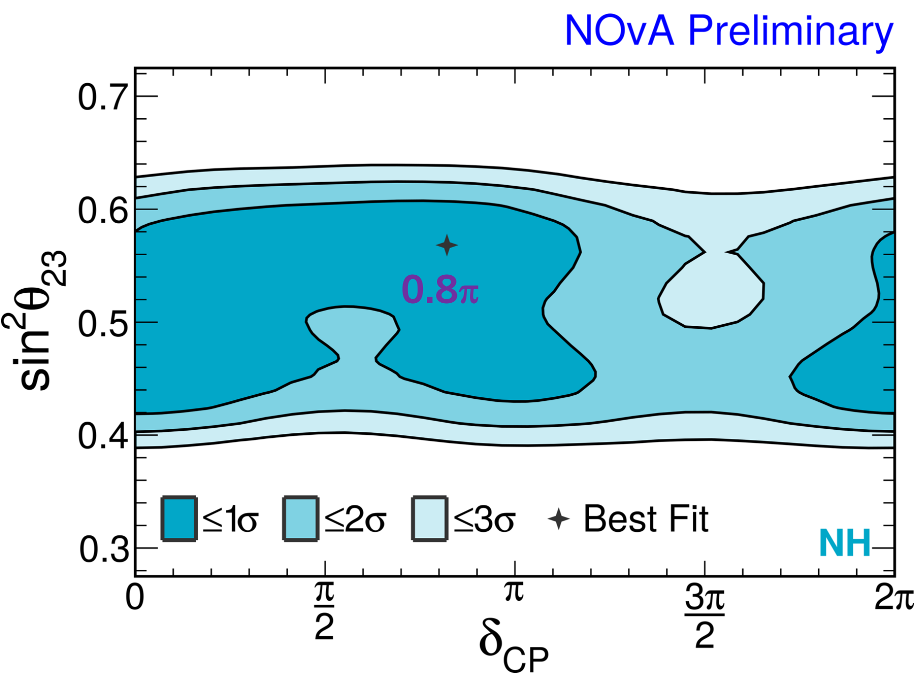
~ 2.9% Precision

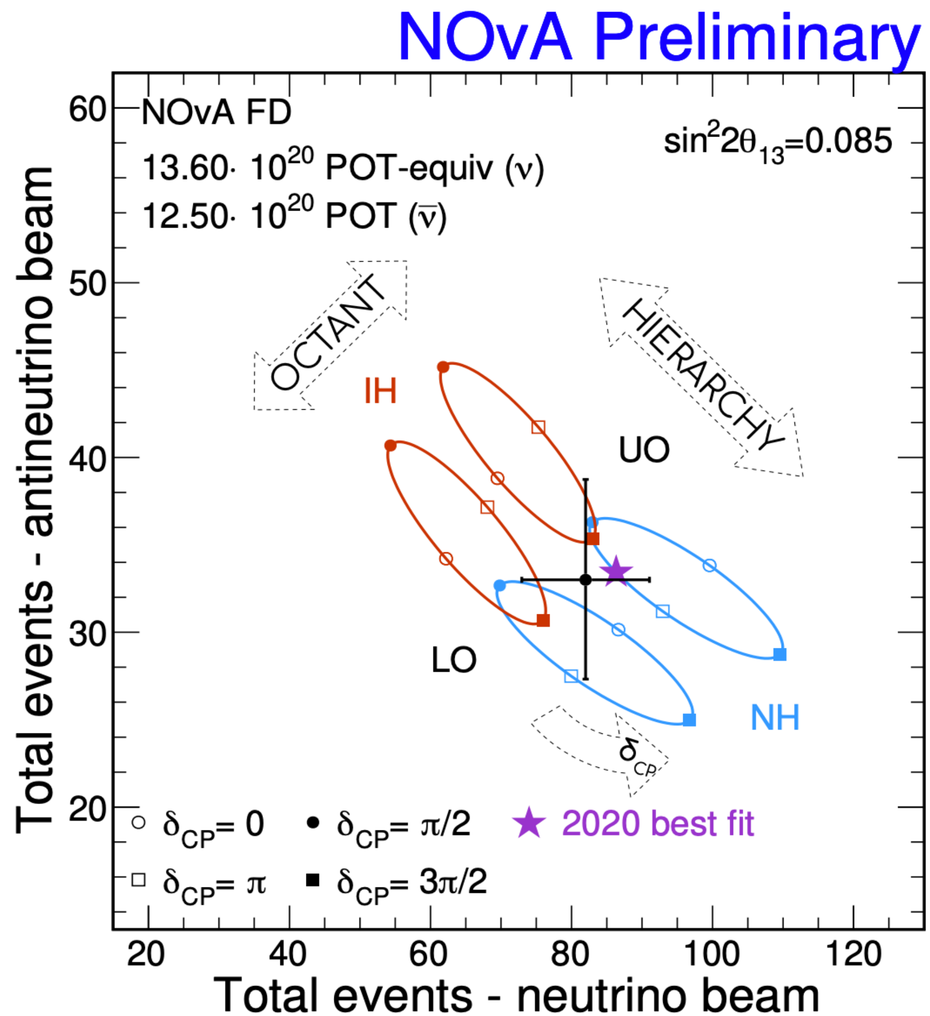
- **Maximal Mixing is disfavored at 1.1σ**
- Upper Octant is preferred at 1.2σ

Is the amount of $\nu_\mu = \nu_\tau$? $\theta_{23} = 45^o$?



δ_{CP} measurement

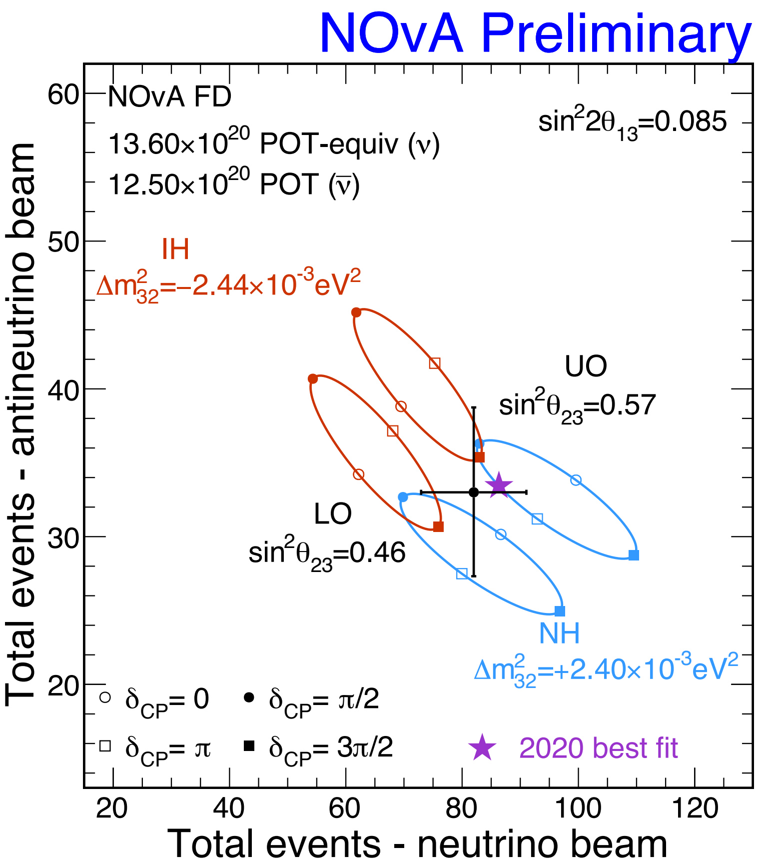


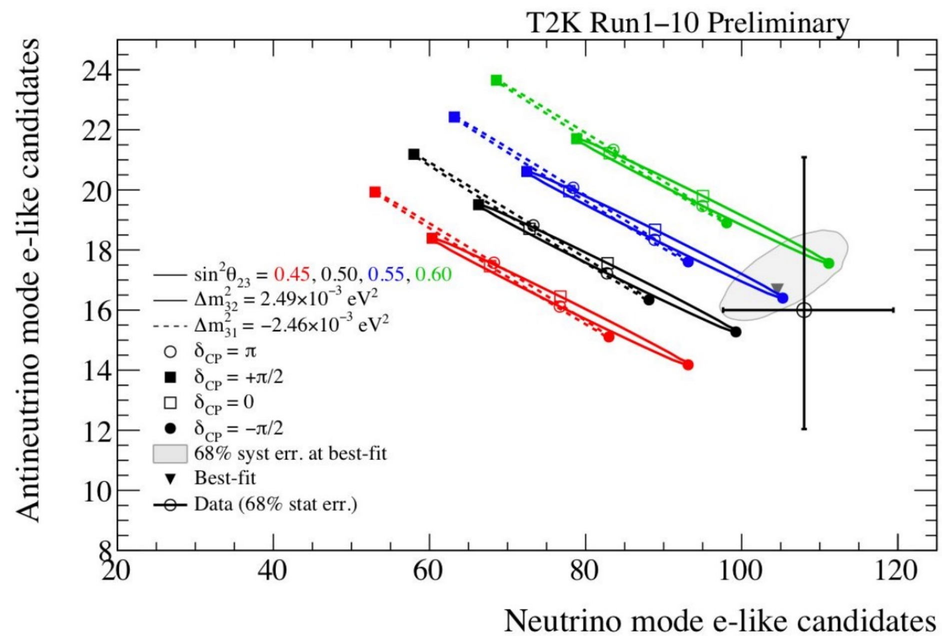


- Excludes {IH, $\delta_{CP} = \pi/2$ at $> 3\sigma$} & {NH, $\delta_{CP} = 3\pi/2$ at $\sim 2\sigma$}

- **Normal Ordering is preferred at 1.0σ**

NOvA and T2K



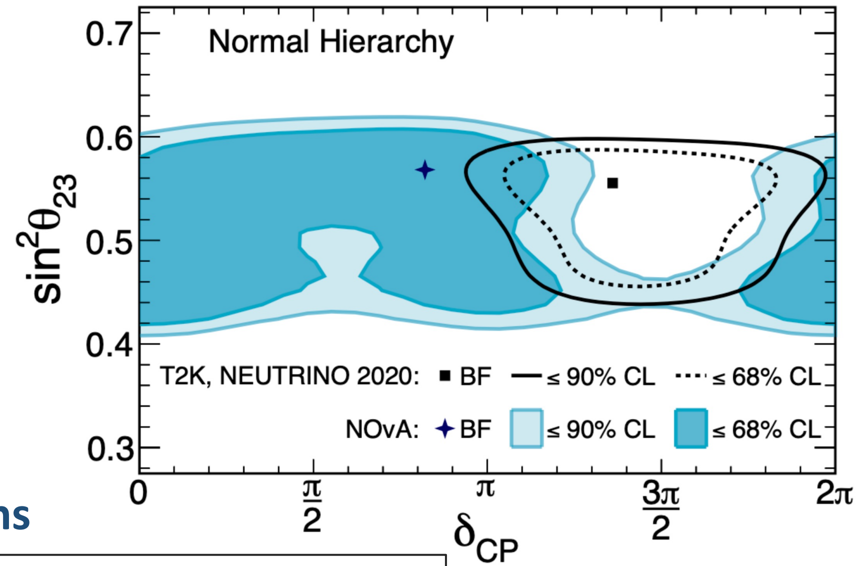


P. Dunne's talk at Neutrino 2020

- T2K sees an asymmetry in their ν_e and $\overline{\nu}_e$ appearance and their best fit is consistent with large CP violation for Normal Hierarchy.

NOvA and T2K

- **Latest results from the two experiments have generated a lot of excitement in the community.**



- **Non-standard Interactions**

CP-Violating Neutrino Non-Standard Interactions in Long-Baseline-Accelerator Data

Peter B. Denton,[1,*] Julia Gehrlein,[1,†] and Rebekah Pestes[1,2,‡]

Non-standard neutrino interactions as a solution to the NOνA and T2K discrepancy

Sabya Sachi Chatterjee[1,*] and Antonio Palazzo[2,3,†]

- **Global preference for Inverted Hierarchy**

Back to (Mass-)Square(d) One: The Neutrino Mass Ordering in Light of Recent Data

Kevin J. Kelly,[1,*] Pedro A. N. Machado,[1,†] Stephen J. Parke,[1,‡] Yuber F. Perez-Gonzalez,[1,2,3,§] and Renata Zukanovich Funchal[4,¶]

The fate of hints: updated global analysis of three-flavor neutrino oscillations [NuFit 5.0]

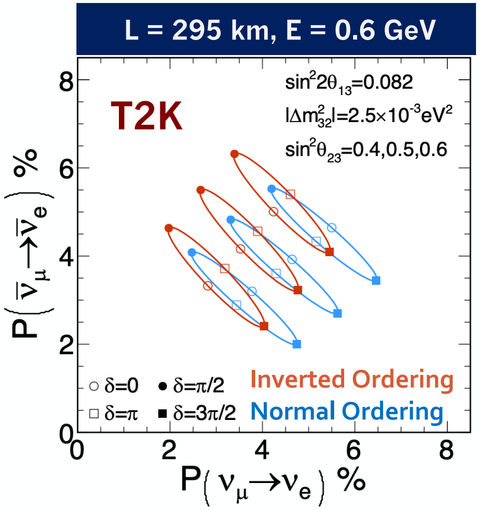
Ivan Esteban,[a] M. C. Gonzalez-Garcia,[a,b,c] Michele Maltoni,[d] Thomas Schwetz,[e] Albert Zhou[e]

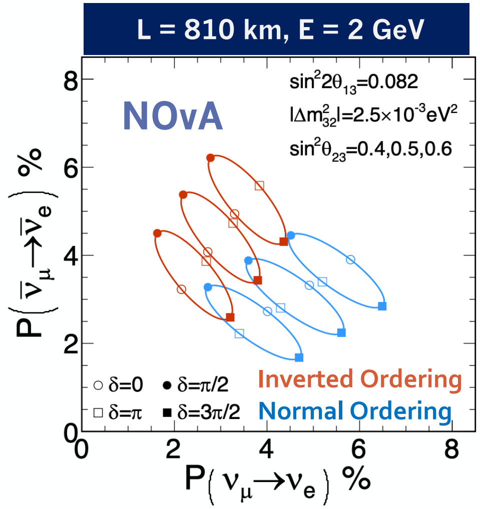
- **Energy-dependent parameters**

Energy-Dependent Neutrino Mixing Parameters at Oscillation Experiments

K. S. Babu,[1] Vedran Brdar,[2,3] André de Gouvêa,[2] and Pedro A. N. Machado[3]

NOvA - T2K Joint Fit





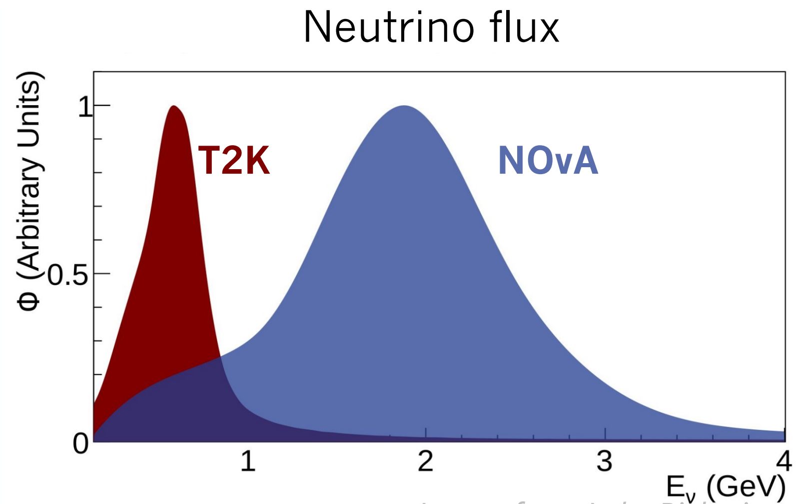
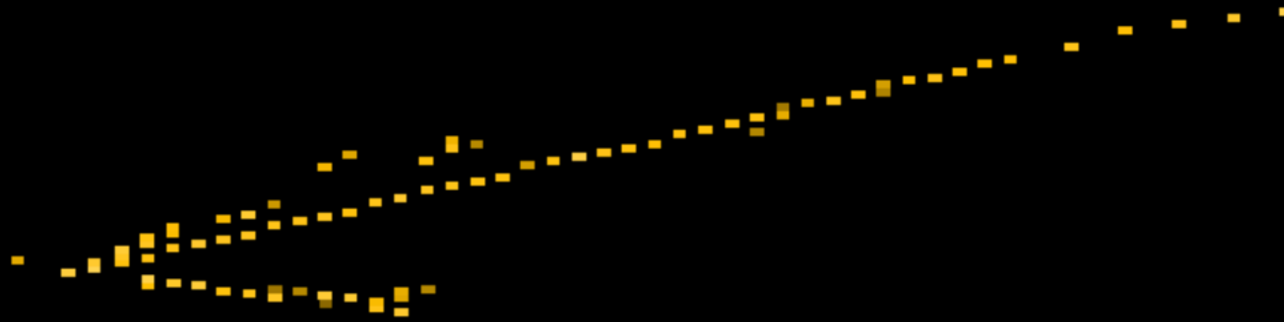


Image from Luke Pickering

- The NOvA and T2K collaborations are working on a combined joint-fit of their data.
- The joint-fit will provide a significantly **tighter statistical constraint.**
- **Complementary features** in NOvA and T2K experiments will be important for **breaking degeneracies** in the individual measurements.
  - Longer baseline sees larger matter effects and has greater sensitivity to mass hierarchy.
  - T2K is mostly dominated by CCQE (and MEC) events while NOvA has a larger component of RES and DIS events.
  - NOvA and T2K use distinct methods to estimate neutrino energy and different approaches to incorporate Near Detector data to constrain systematics.

First Result in * 2022 *

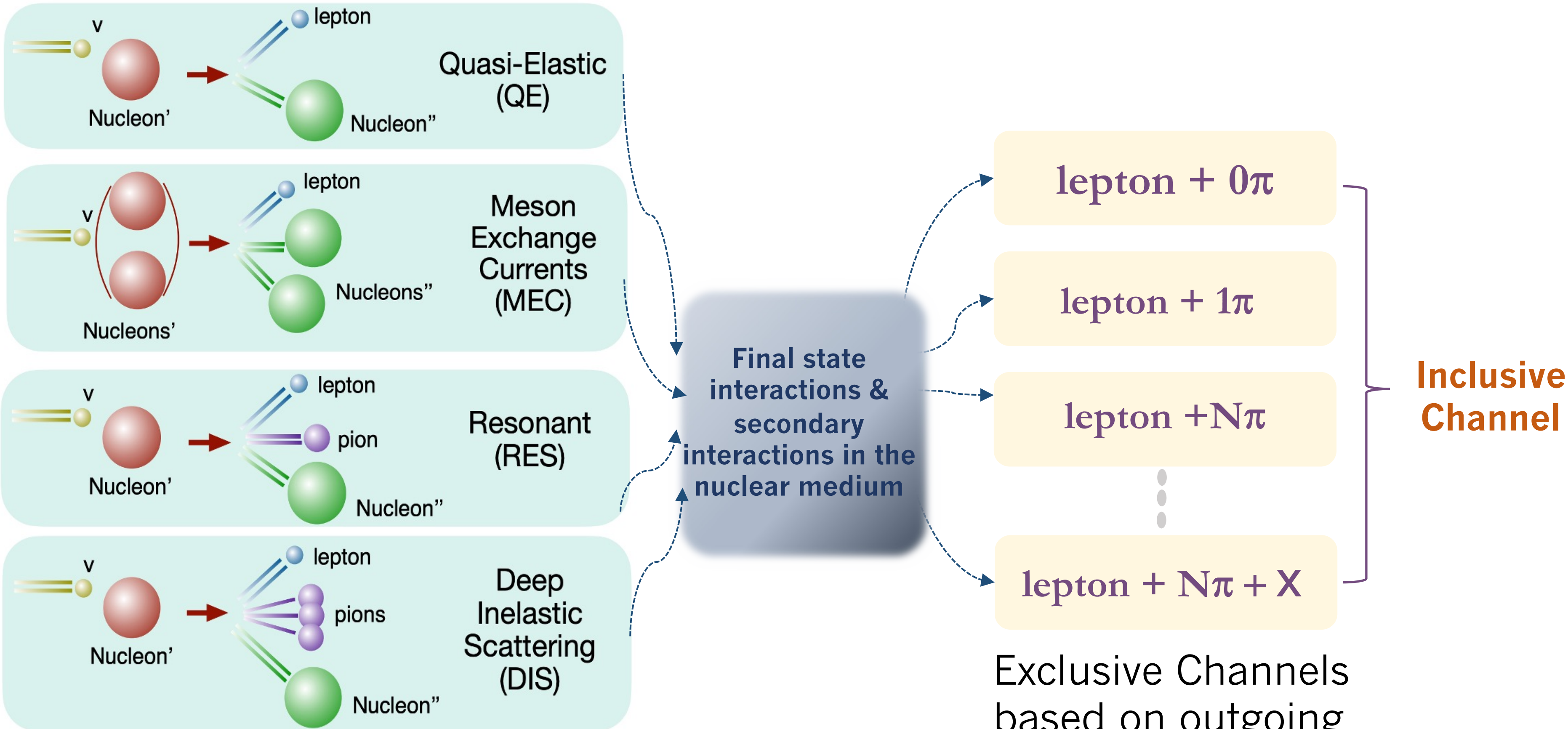


ν_μ CC

Neutrino-nucleon cross-section measurements

ν_e CC

Cross-section measurements



Interaction channels based on true interaction type

Exclusive Channels based on outgoing particles

Cross-section measurements at NOvA

Previous results

- ✓ NC Coherent π^0 — flux averaged cross-section — Phys. Rev. D 102, 012004 (2020)
- ✓ ν_μ CC π^0 — single differential cross-section — seminar *[publication in progress]*

Recent results [discussed today]

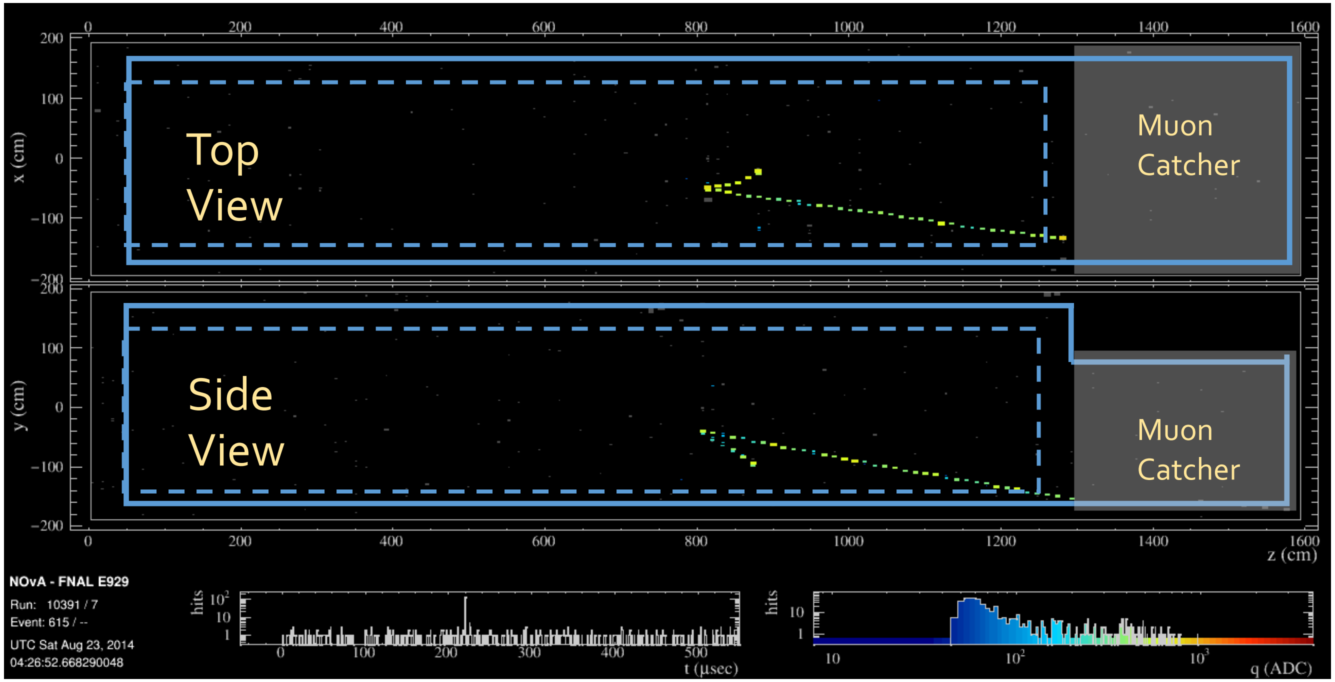
- ✓ ν_μ CC inclusive — double differential cross-section — seminar *[publication in progress]*
- ✓ ν_e CC inclusive — double differential cross-section — seminar *[publication in progress]*

Coming soon

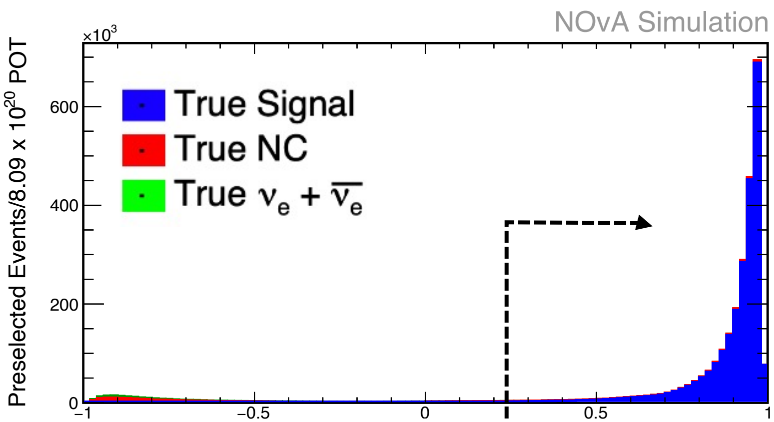
- $\bar{\nu}_\mu$ CC π^0
- $\bar{\nu}_\mu$ CC inclusive
- $\bar{\nu}_e$ CC inclusive
- ν on e
- Low hadronic energy

… and many more exclusive state topologies!

ν_μ CC Inclusive : Selection



dashed line : Fiducial Volume
solid line : Containment Volume



Muon ID

- MuonID derived using a Boosted Decision Tree with muon dE/dx and scattering input observables.
- MuonID cut optimized on total cross section fractional uncertainty, provides a neat separation of signal from background.

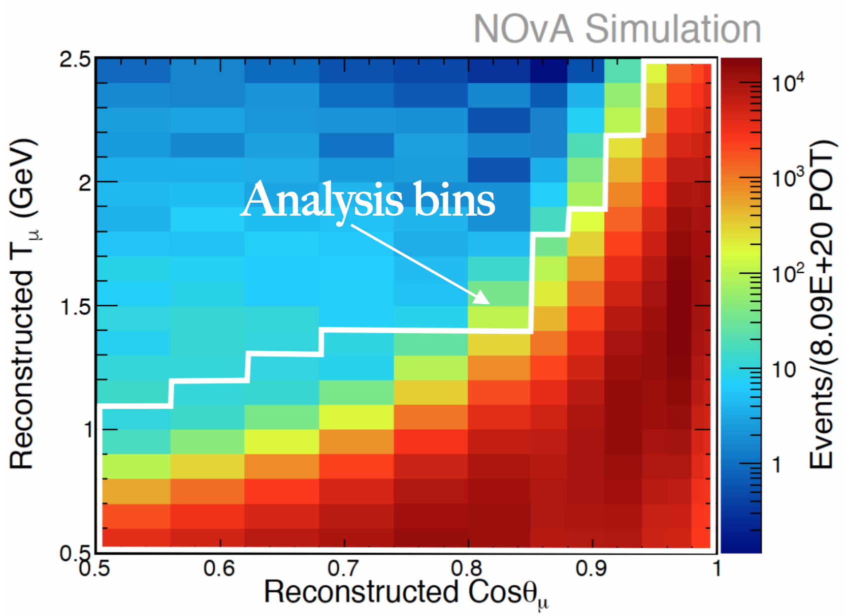
ν_μ CC Inclusive : Selection

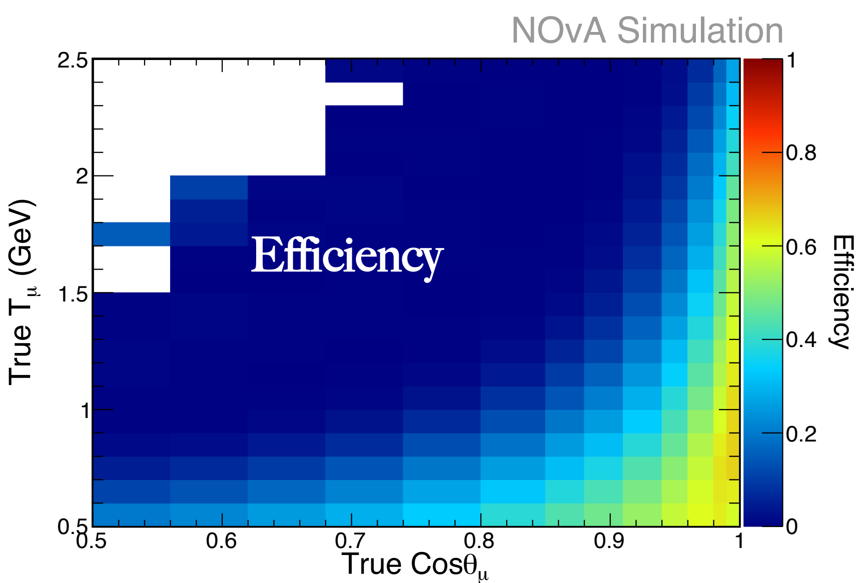
More than **1M** ν_μ CC events are selected in **172 analysis bins**.

Resulting sample has **86% purity** and **~90% efficiency** with respect to the preselection cut.

Efficiency drops with the increase in muon energy due to longitudinal containment.

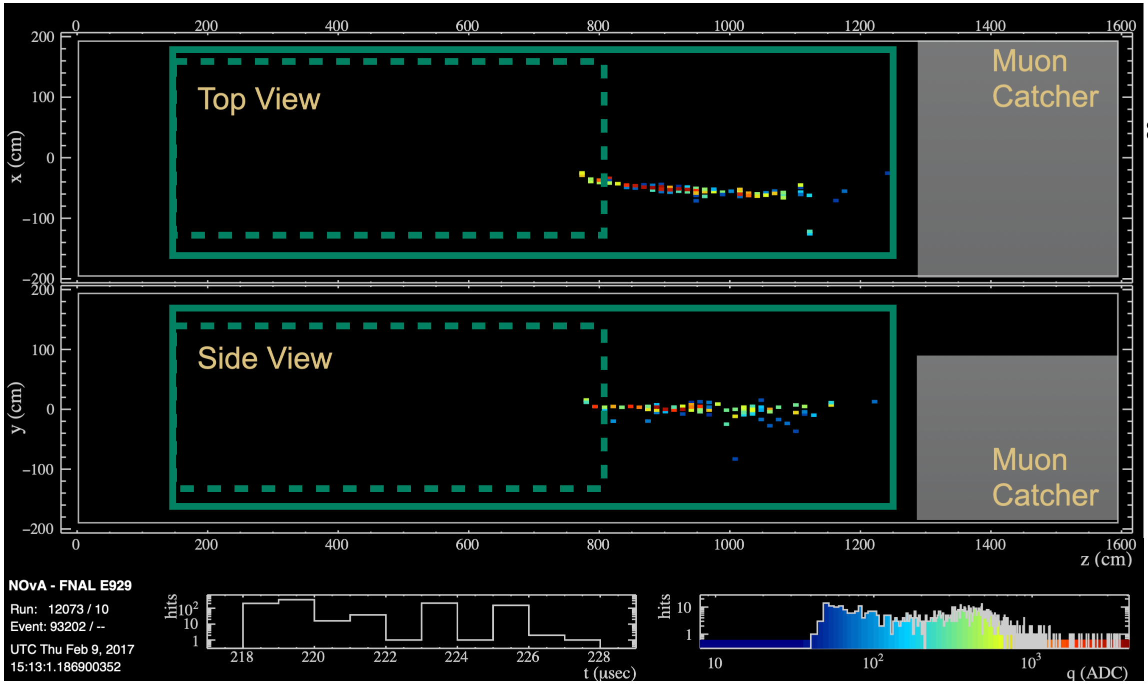
Efficiency drops as the muon angle increases due to transverse containment.

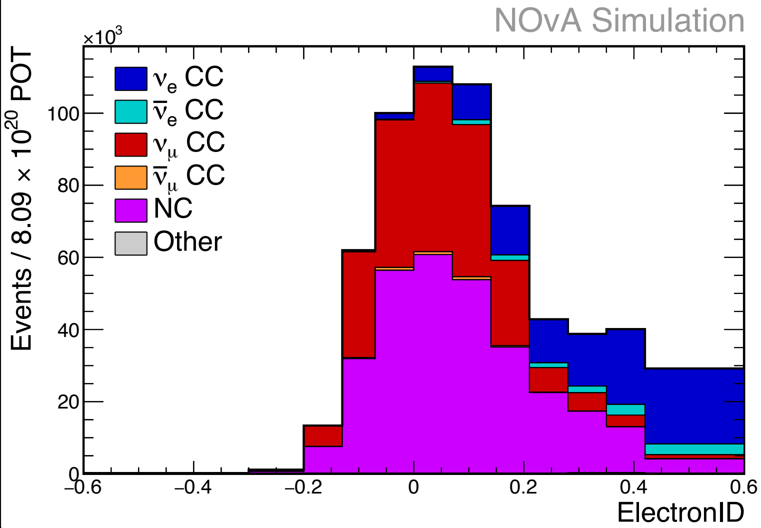




ν_e CC Inclusive : Selection

dashed line : Fiducial Volume
solid line : Containment Volume



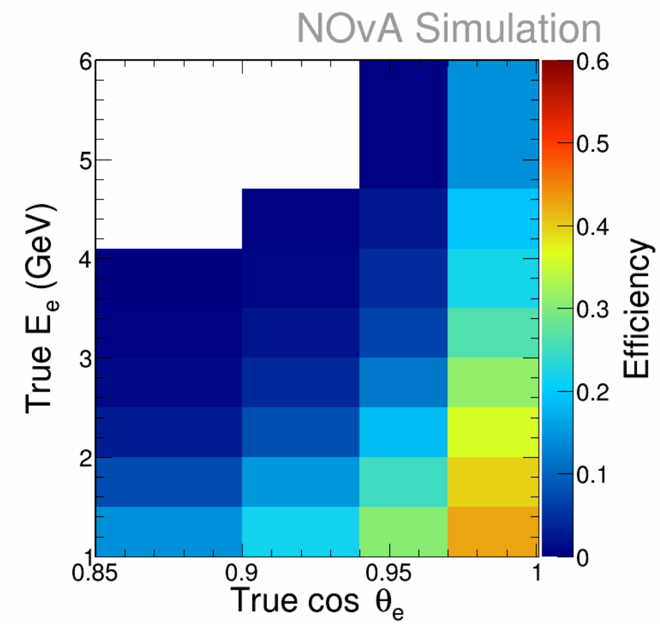


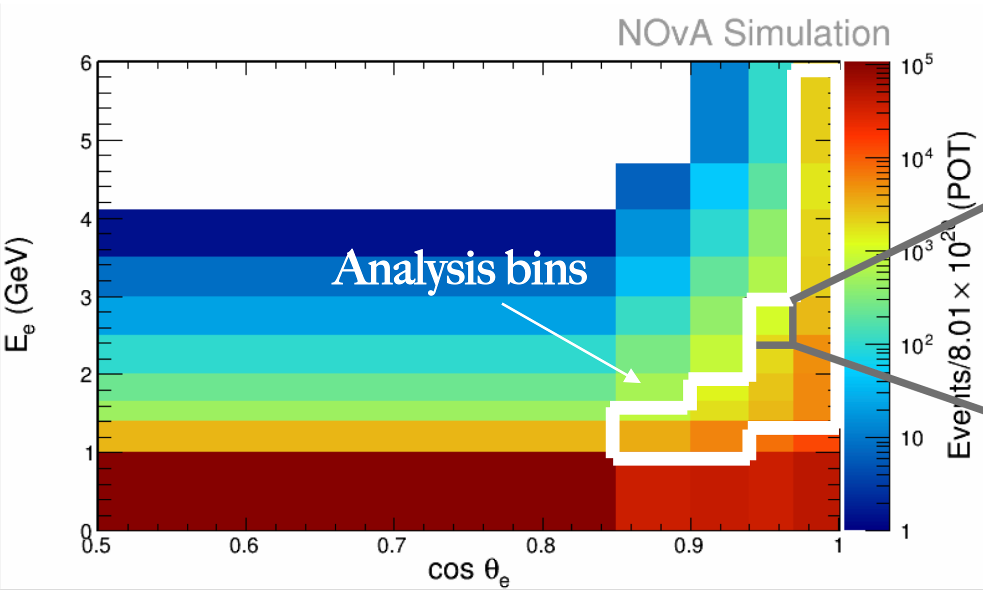
ElectronID is not as strongly discriminating as MuonID.

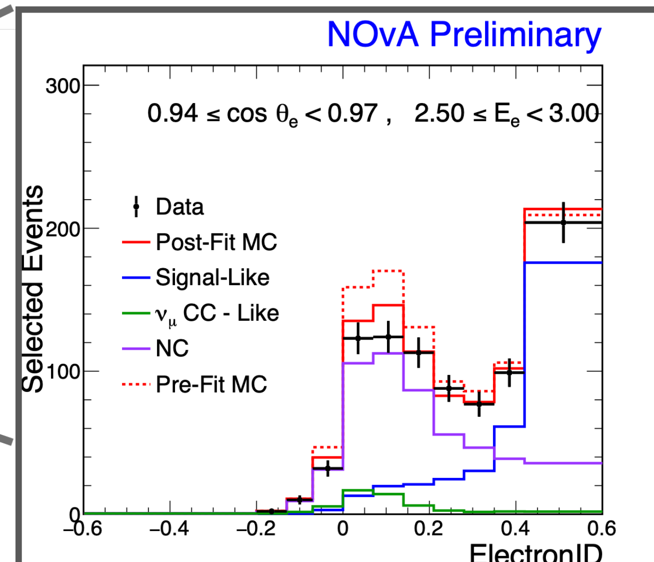
- Analysis uses a Boosted Decision Tree to distinguish electrons from other particles using output of a particle id from a deep convolutional network and EM shower properties.
- ElectronID is used to generate templates in which the fit is done.

ν_e CC Inclusive : Selection

- Around **10k events** in the final selection.
- Background estimation in each electron kinematic bin is done via a template fit of the ElectronID distribution.
- Uncertainties in templates shape are accounted for using a covariance matrix.





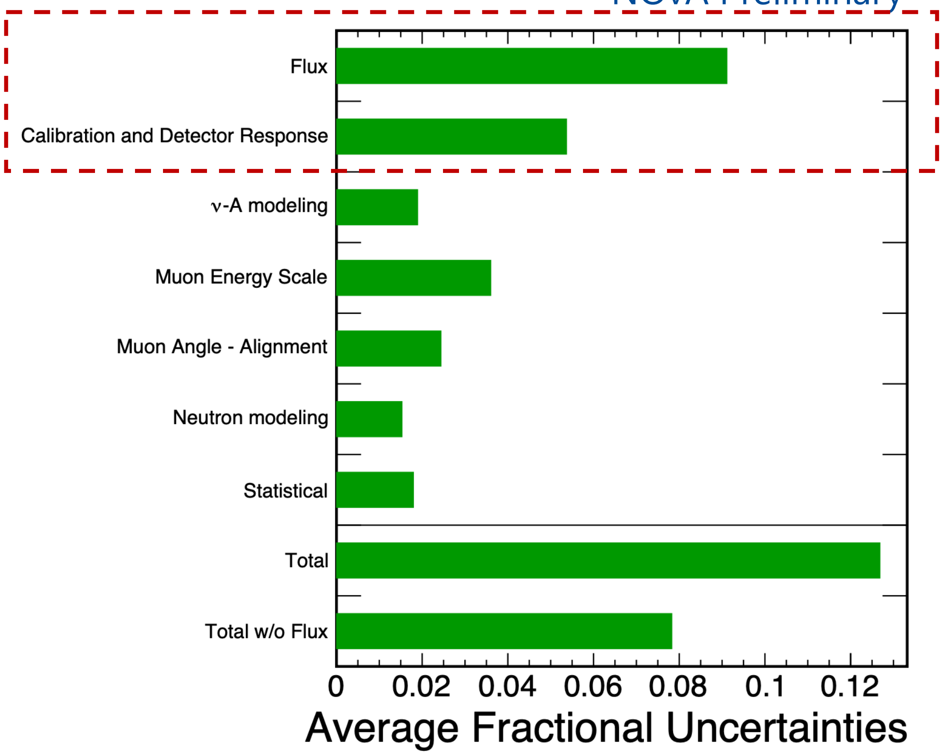


Systematics

ν_μ CC Inclusive

- Flux contributes a normalization uncertainty of ~9%.
- Interaction modeling uncertainties are sub-dominant.
- Measurements have typical total uncertainties around **12%** in each bin.

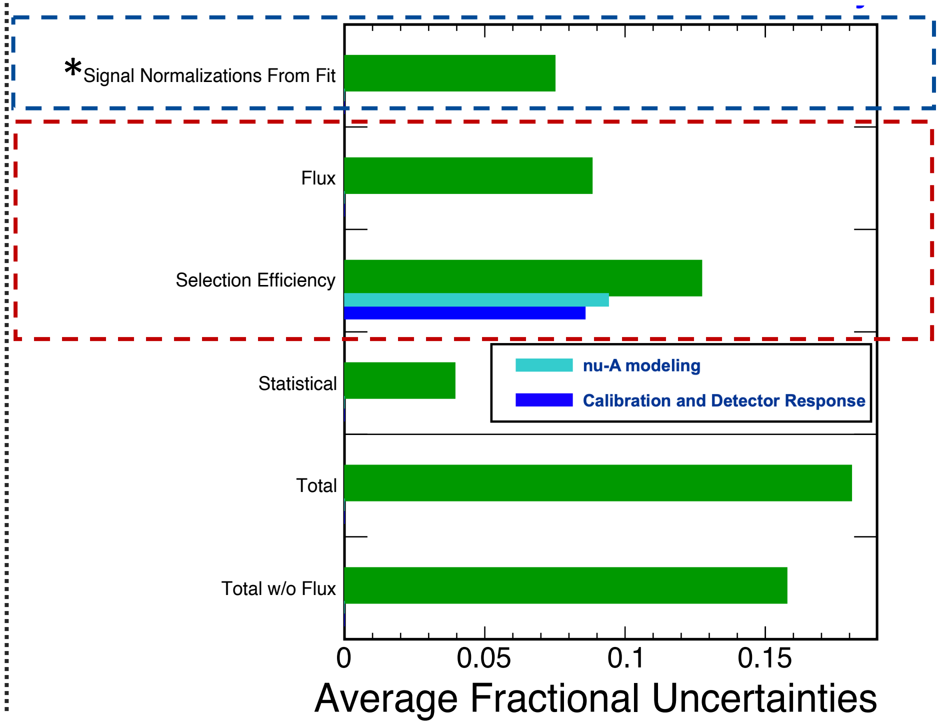
NOvA Preliminary



ν_e CC Inclusive

- *Uncertainty from the template fit.
- Interaction modeling uncertainties play a substantial role due to significant background events.
- Measurements have typical total uncertainties **~15% to 20%** in each bin

NOvA Preliminary

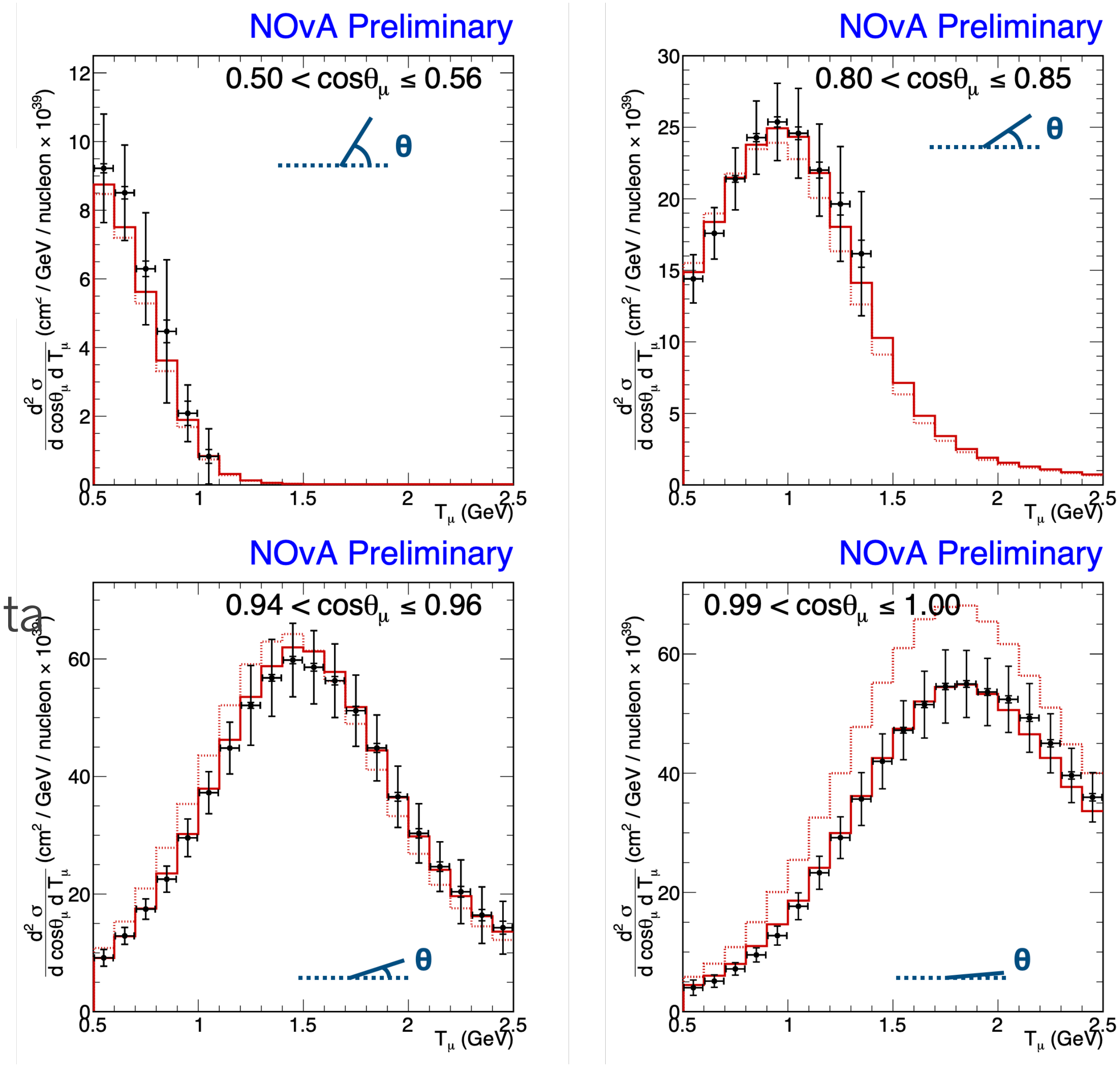


ν_μ CC Inclusive : Results

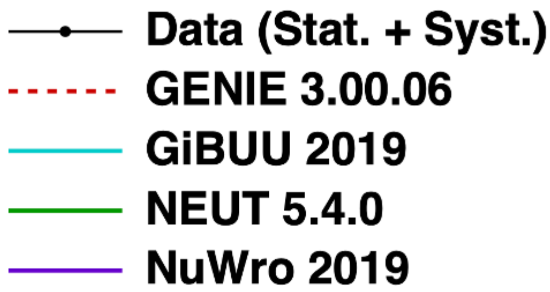
- Data (Stat. + Syst.)
- GENIE 2.12.2 - NOvA Tune
- GENIE 2.12.2 - Untuned

- At very forward angles (low Q^2) the untuned GENIE 2 overshoots data significantly.

Generator	Total p-value
GENIE 2.12.2 - Tuned	0.93
GENIE 2.12.2 - Untuned	0.24

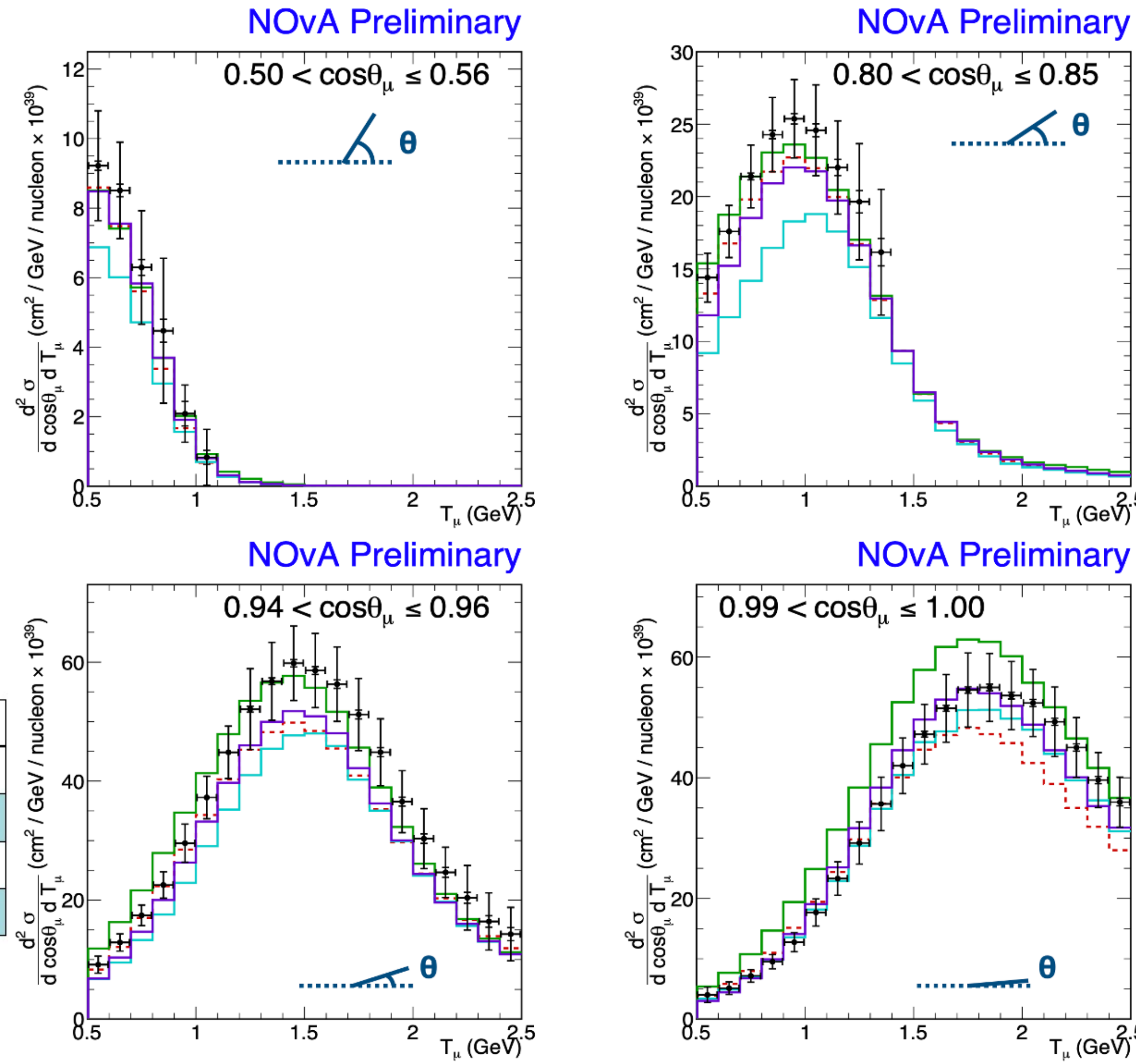


ν_μ CC Inclusive : Results

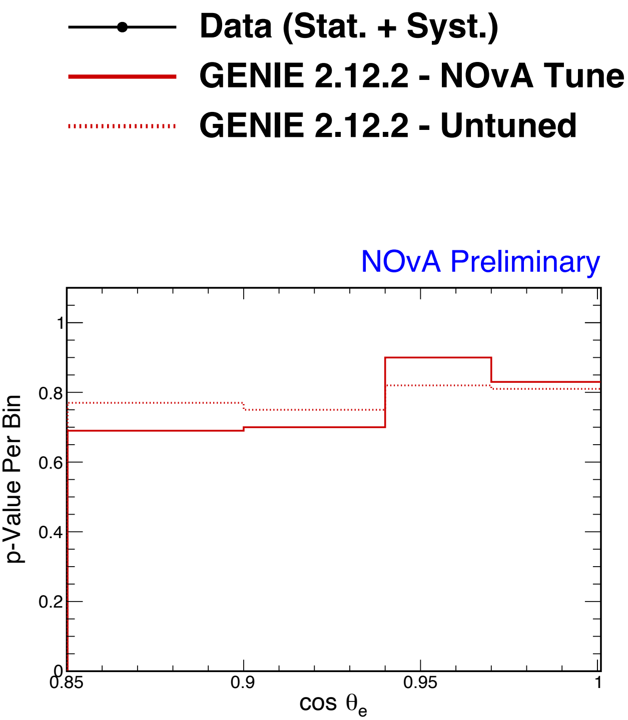


- Out of the box generator comparisons reproduces the shape of our data.

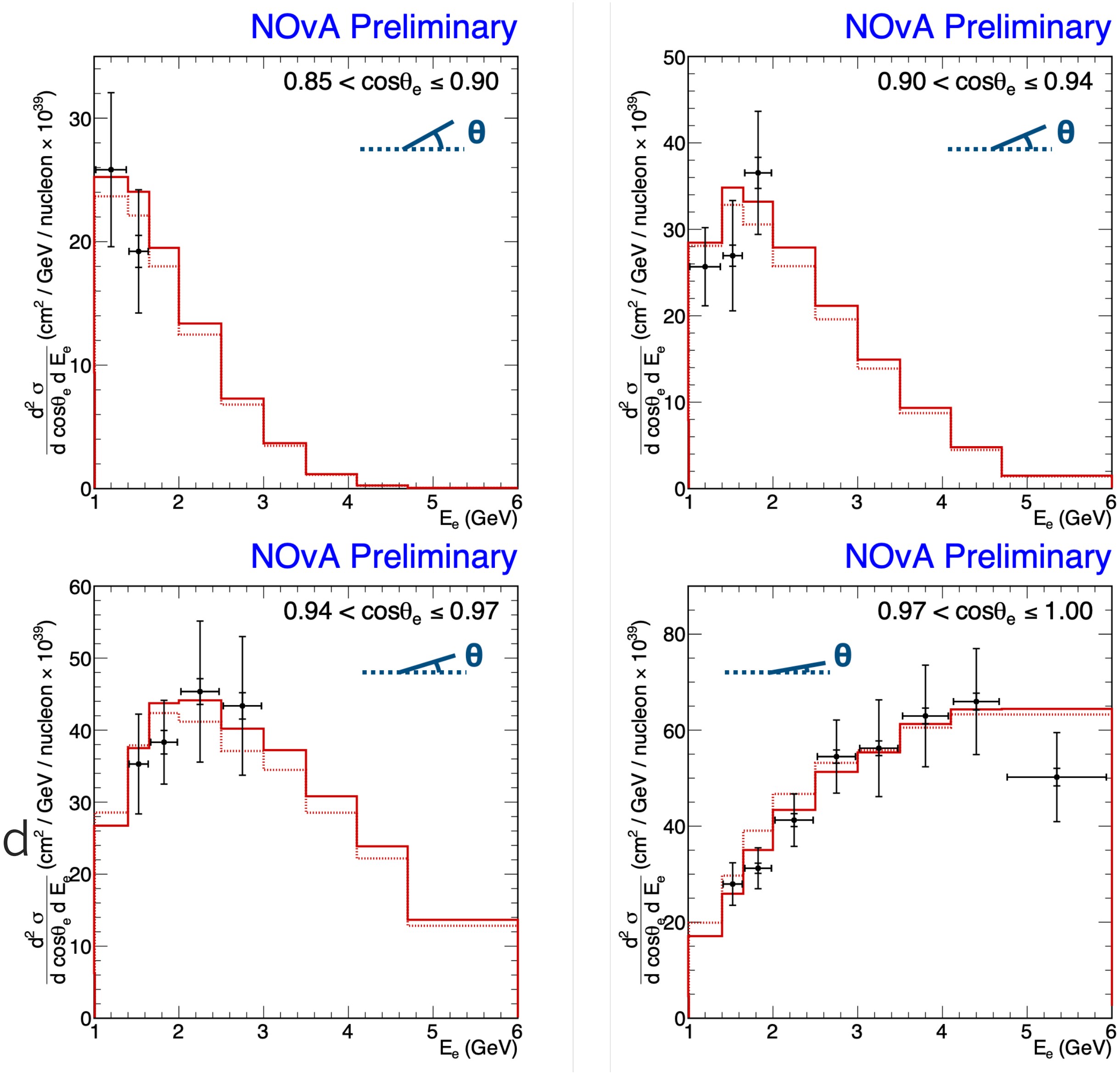
Generator	Total p-value
GENIE 3.00.06*	0.26
GiBUU 2019	0.03
NEUT 5.4.0	0.52
NuWro 2019	0.22



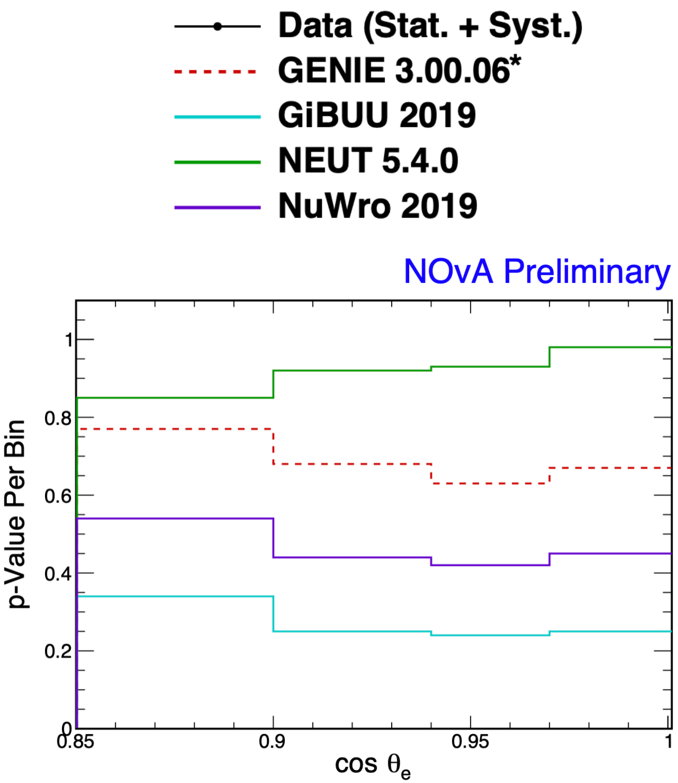
ν_e CC Inclusive : Results

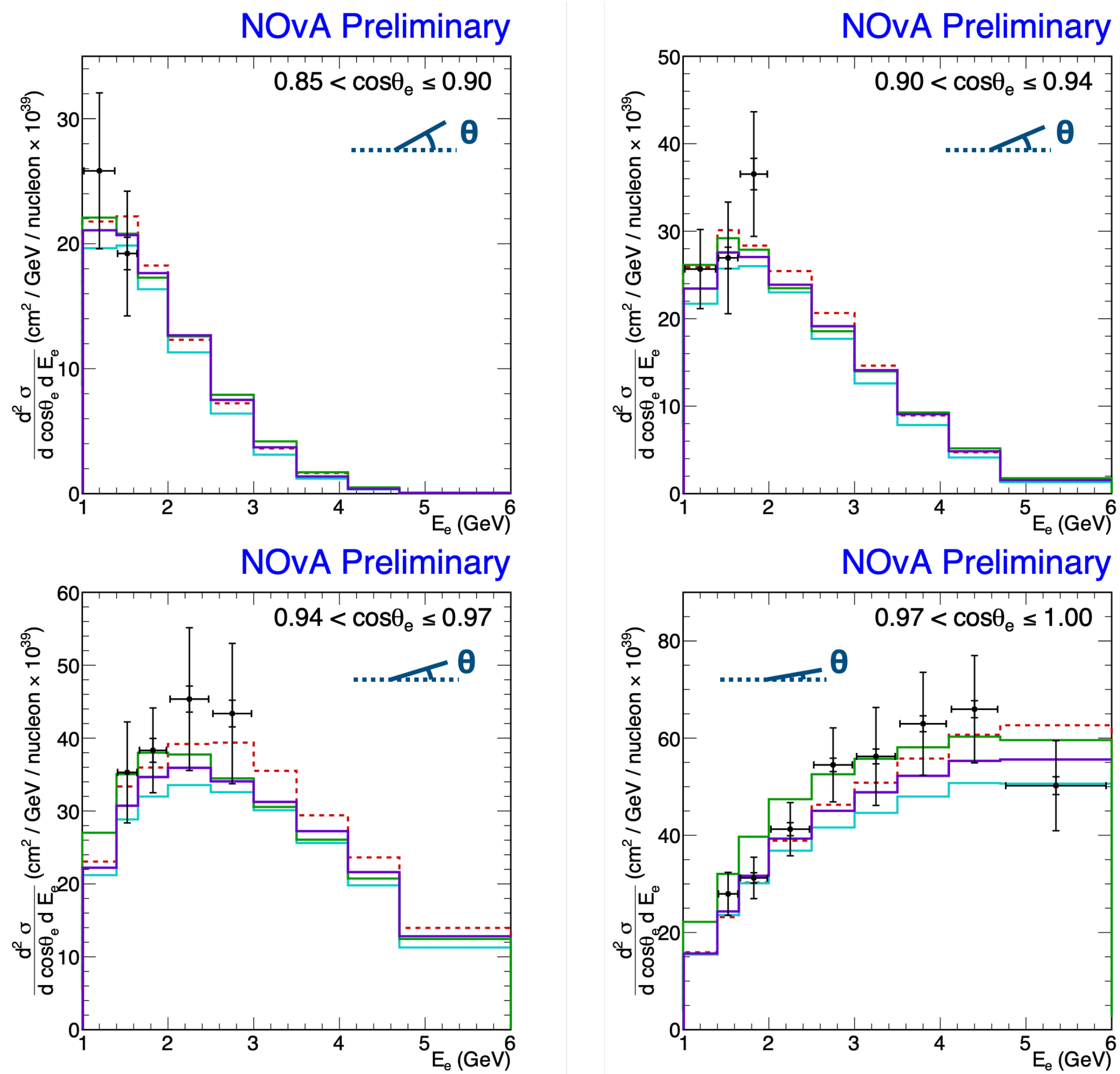


- Both tuned and untuned genie provide a good description of the observed data.



ν_e CC Inclusive : Results

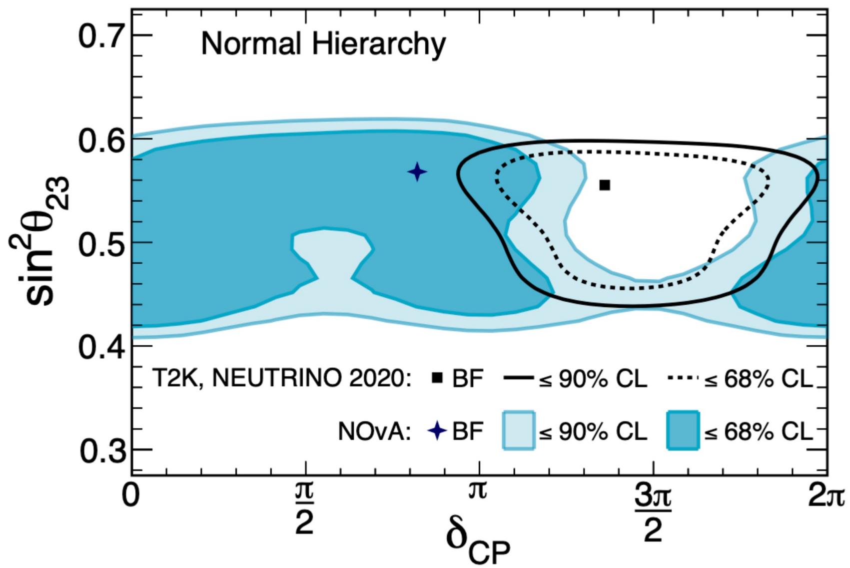




- GiBUU and NuWro provide a better description of data when their normalization is enhanced by ~15 – 20%.
- Cross-section modeling systematics are large for this measurement.

Summary & Outlook

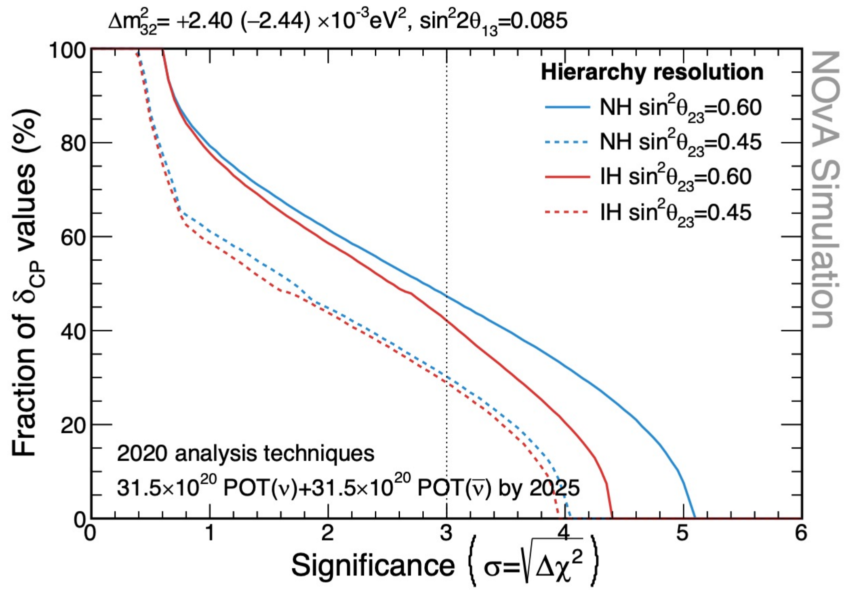
Summary



- NOvA data **disfavors asymmetry** between ν_e and $\overline{\nu}_e$ appearance while T2K sees a large asymmetry and their best fit is consistent with maximal CP violation.
- Precision measurements of $\Delta \mathbf{m}^2_{32}$**(3%)** and $\mathbf{sin^2}\,\theta_{23}$ **(6%).**
- Presented the **first** measurement of the double-differential ν_e CC inclusive cross section (15-20% uncertainties) and the double-differential ν_μ CC inclusive cross section with ~1M events (12% uncertainty).
- **Detector energy scale and response systematics** dominate systematic uncertainty budget for most measurements.

Outlook

- NOvA is expected to run until 2026 and at least double its dataset for a total of 60-70 x 10^{20} POT.
  - A 3 σ determination of mass ordering is possible for 30-50% values of dCP.



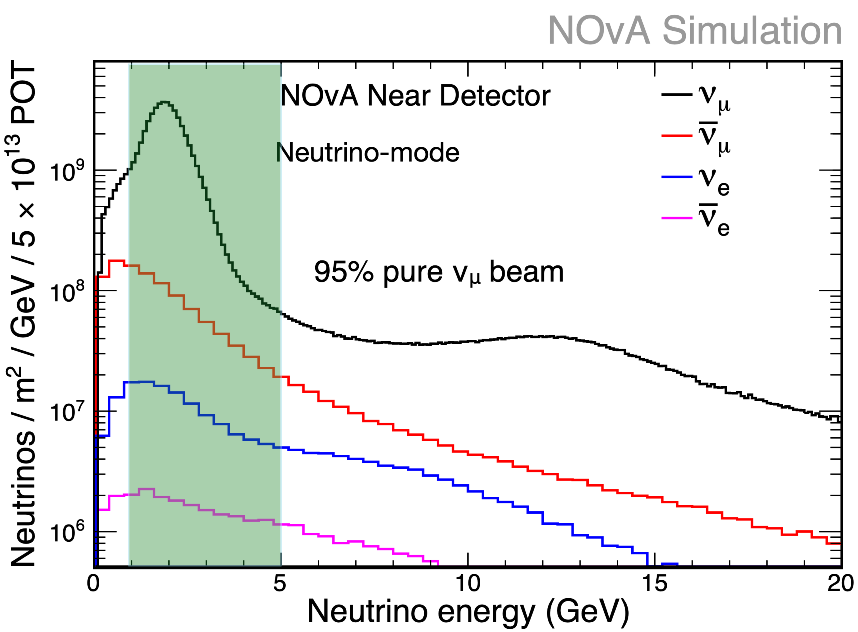
- **NOvA-T2K joint analysis** is converging rapidly and is on-track to report first measurements **this year!**

- Many more cross-section analyses with ND data that use the antineutrino mode beam and measure exclusive final state are coming out soon!

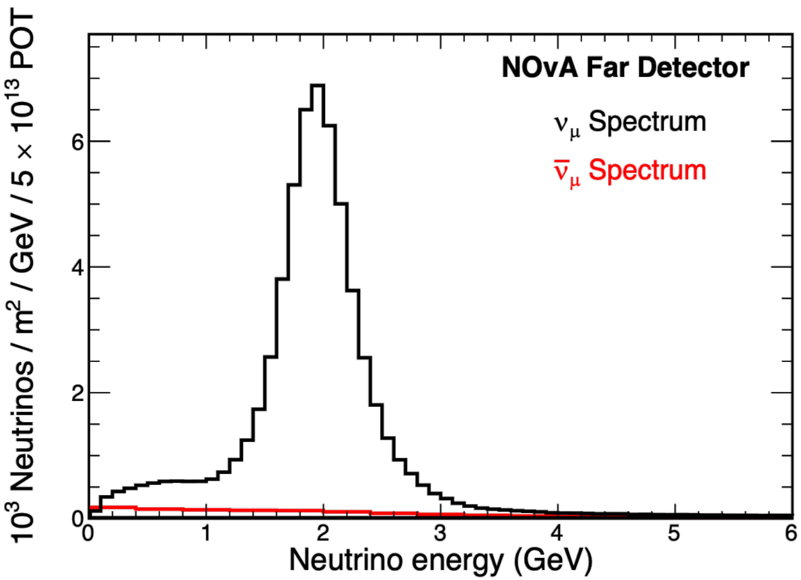
- **NOvA Test Beam** is a miniature NOvA detector placed at Fermilab Test Beam Facility to study hadronic response and better understand the detector energy scale and response systematics.

backup

NOvA Flux

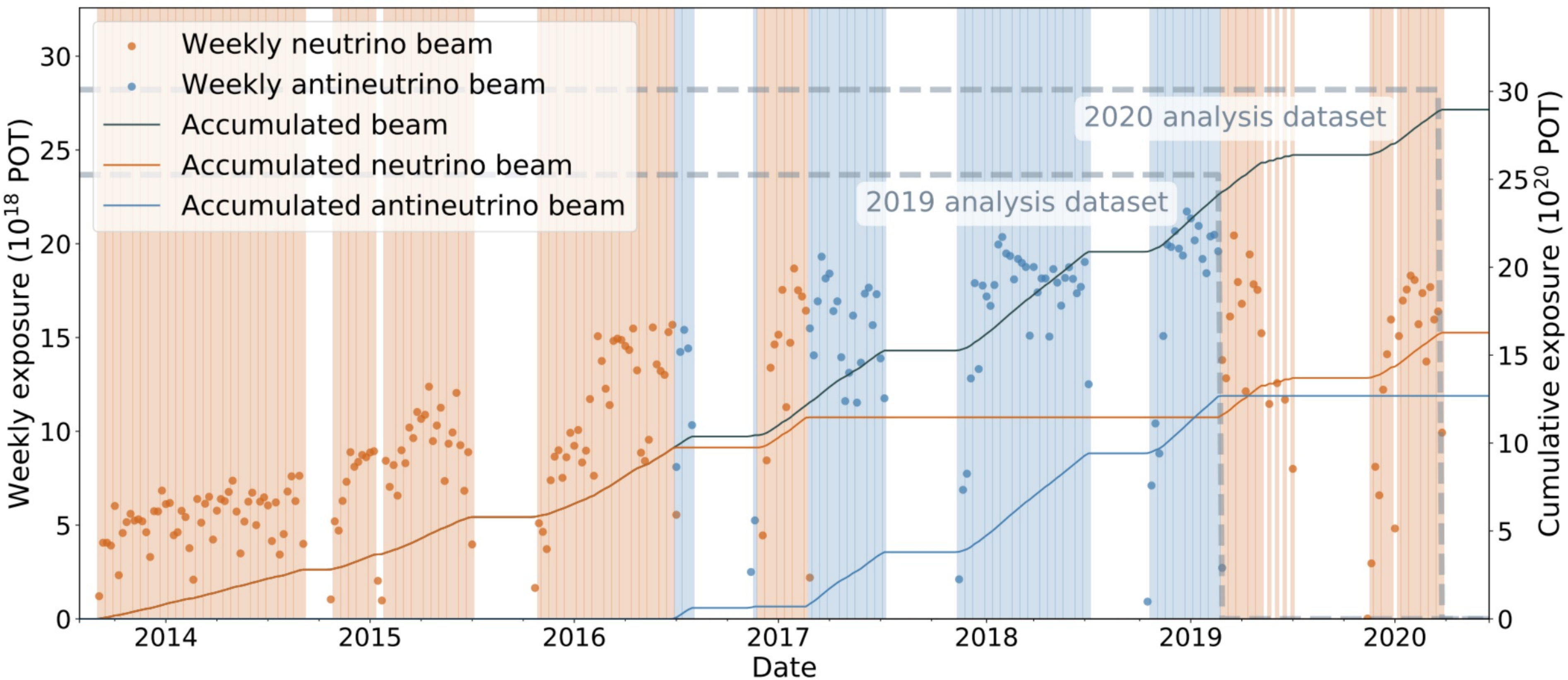


NOvA Simulation
NOvA Near Detector
Neutrino-mode
95% pure ν_μ beam
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
Neutrinos / m^2 / GeV / 5 × 10^{13} POT
Neutrino energy (GeV)



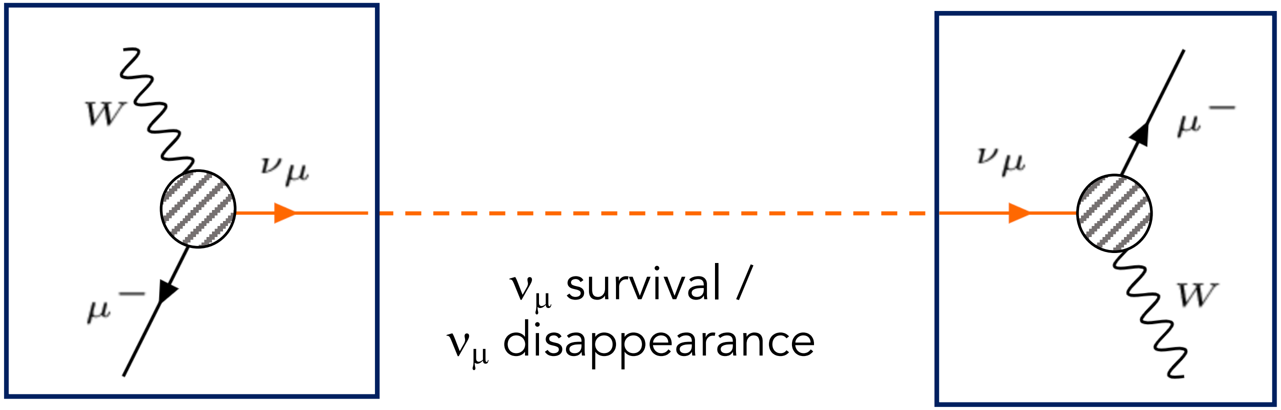
NOvA Far Detector
ν_μ Spectrum
$\bar{\nu}_\mu$ Spectrum
10^3 Neutrinos / m^2 / GeV / 5 × 10^{13} POT
Neutrino energy (GeV)

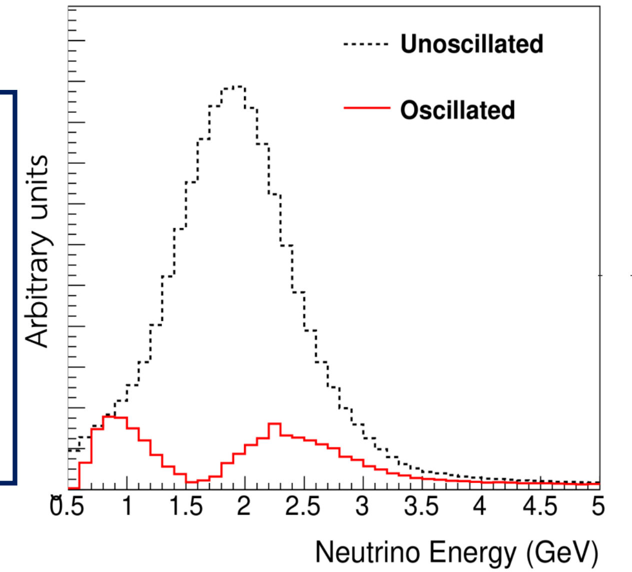
NuMI Beamline



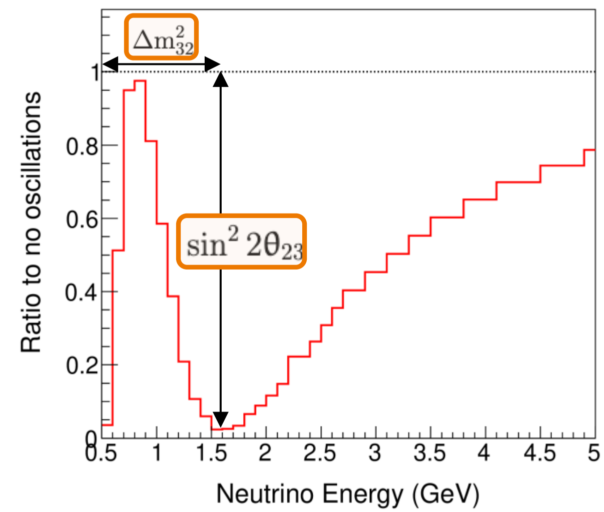
- The data analyzed for this analysis:
  - 13.6×10^{20} POT neutrino beam
  - 12.5×10^{20} POT anti-neutrino beam

ν_μ disappearance



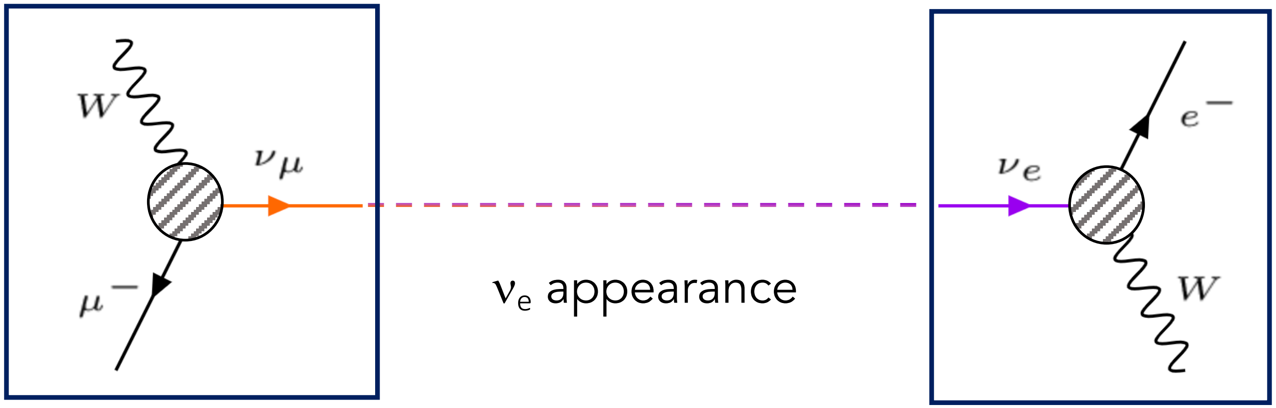


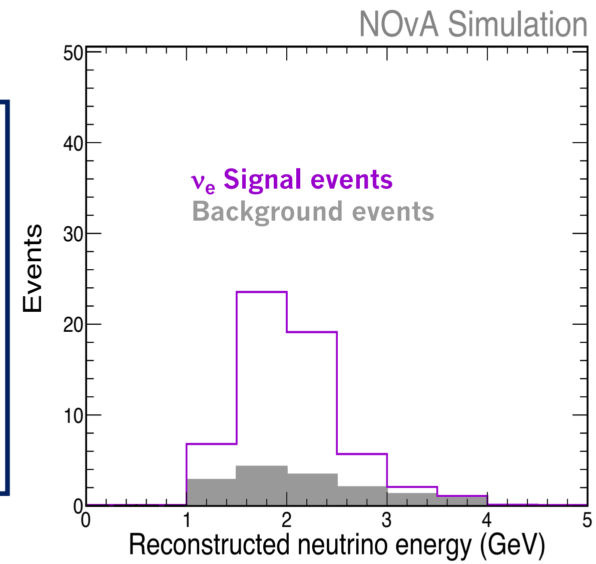
$$P\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu\right) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32}\frac{L}{4E}\right)$$



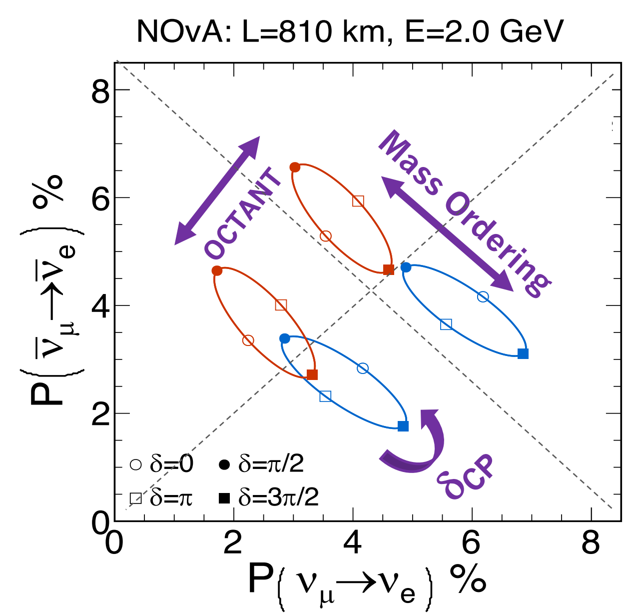
- Leading order dependence on Δm^2_{32} and $\sin^2\theta_{23}$
- Aims to answer the question of **maximal mixing in θ_{23}**

LBL Oscillations : ν_e appearance





- Comparing the rate of ν_e appearance with $\overline{\nu}_e$ appearance provides a measurement of δ_{CP} and mass ordering.



- **δ_{CP} and mass ordering have inverse dependence on probability of ν_e and $\overline{\nu}_e$ appearance** while changing the octant is symmetric for the two beam modes.

differential cross-section

$$\frac{d\sigma}{dx_i} = \frac{\sum_j U_{ij}^{-1}(N_j^{\mathrm{sel}} \times P_j)}{\epsilon_i N_{\mathrm{T}} \langle \Phi \rangle \Delta x_i}$$

Smearing | Selected events | Purity | Efficiency | # of targets | Integrated flux

ν_μ CC Inclusive

$$\left(\frac{d^2\sigma}{d\cos\theta_\mu dT_\mu}\right)_i = \sum_k \left(\frac{\sum_j U_{ijk}^{-1}(N^{\mathrm{sel}}(\cos\theta_\mu, T_\mu, E_{\mathrm{avail}})_j P(\cos\theta_\mu, T_\mu, E_{\mathrm{avail}})_j)}{N_{\mathrm{t}}\Phi\epsilon(\cos\theta_\mu, T_\mu, E_{\mathrm{avail}})_{ik}\Delta\cos\theta_{\mu_i}\Delta T_{\mu_i}}\right)$$

- Purity and efficiency corrections are applied in 3D space that consists of muon energy, direction and Eavail.
- Including Eavail in these corrections reduces potential model dependence on the final-state hadronic predictions.

differential cross-section

$$\frac{d\sigma}{dx_i} = \frac{\sum_j U_{ij}^{-1}(N_j^{\text{sel}} \times P_j)}{\epsilon_i N_{\text{T}} \langle \Phi \rangle \Delta x_i}$$

Smearing | Selected events | Purity | Efficiency | # of targets | Integrated flux

ν_e CC Inclusive

$$\left(\frac{d^2\sigma}{d\cos\theta_e dE_e}\right)_i = \sum_j \left(\frac{U_{ij}^{-1}(N^{\text{sel}}(\cos\theta_e, E_e)_j - N^{\text{bkg}}(\cos\theta_e, E_e)_j)}{N_{\text{t}}\Phi\epsilon(\cos\theta_e, E_e)_{ik}\Delta\cos\theta_{e_i}\Delta E_{e_i}}\right)$$

- Analysis is performed in a 3D template space $\Longrightarrow$ ($\cos\theta_e$, E_e, ElectronID)

Neutrino Interactions : GENIE

GENIE

- Using the latest GENIE v3.0.6
- Built a Custom-Model-Configuration (CMC) from the available collections of model
- ‘Theory-driven’ models with tune to external free-nucleon data were chosen as NOvA’s nominal interaction model

GENIE N1810j_0211a *

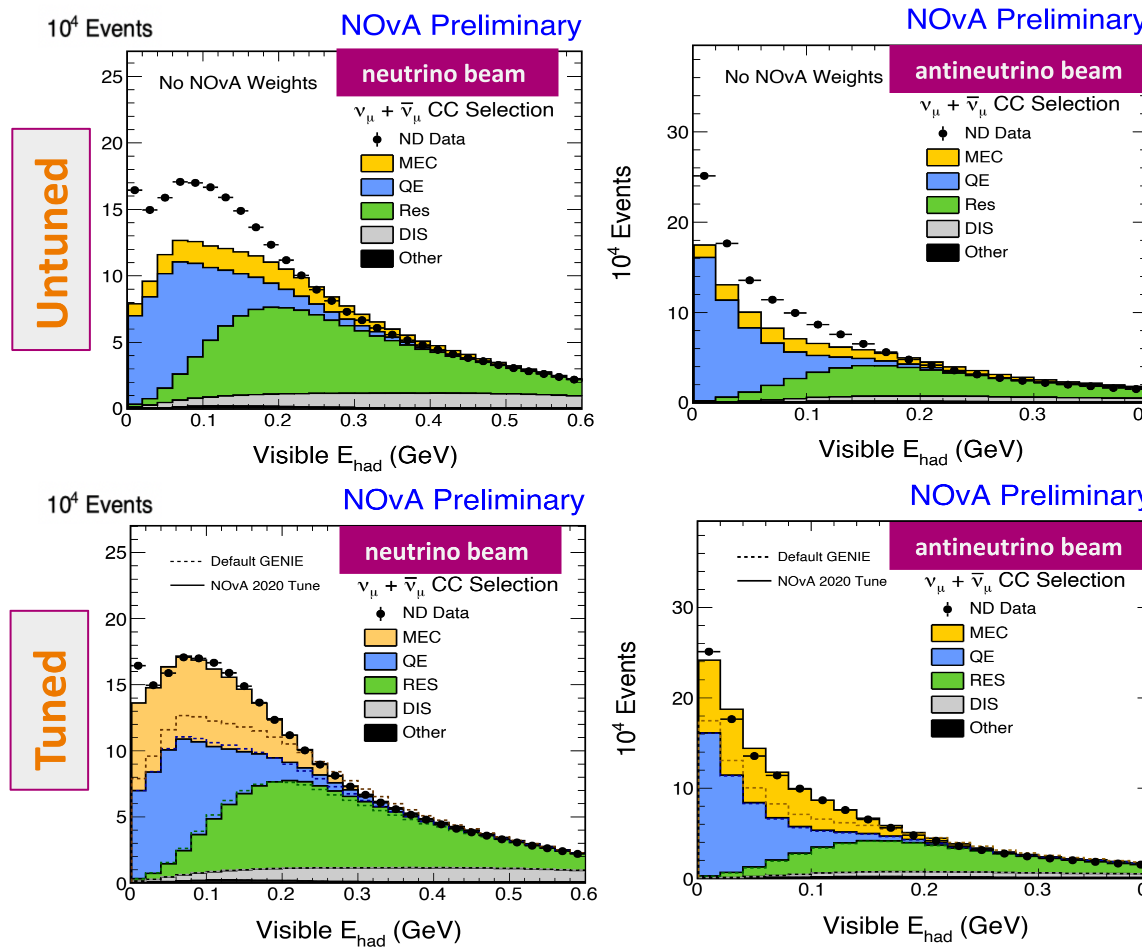
QE	MEC/2p2h	RES	DIS	FSI
• Valencia 1p1h • Z-expansion axial form factor	• Valencia MEC	• Berger-Sehgal	• Bodek-Yang	• hN Semi Classical Cascade

NINJA GENIE

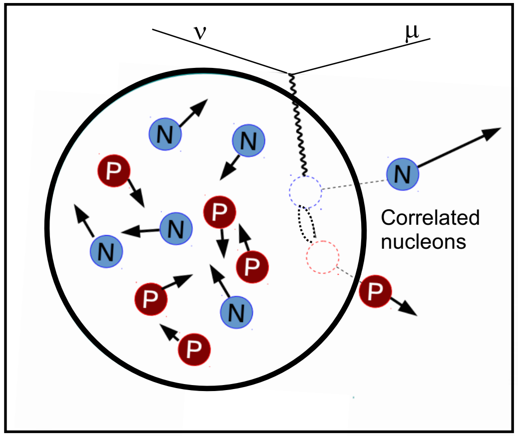
*We call our “tune” N1810j_0211a. It is built by starting with G1810b_0211a and substituting the Z-expansion QE axial form factor for the dipole one. This combination was not available in the 3.0.6 release, but it may be available in future versions

NOvA ND Tune

- We use **GENIE**(v3.0.6) for neutrino interaction generation.
- Nuclear effects are still not well-modeled. Out-of-the-box GENIE does not describe ND data well.
  - Tuned GENIE by varying the MEC and FSI components.
  - Any remaining differences between data and MC are covered by systematic uncertainty band and are extrapolated to FD Simulation as ND Data Constraints.

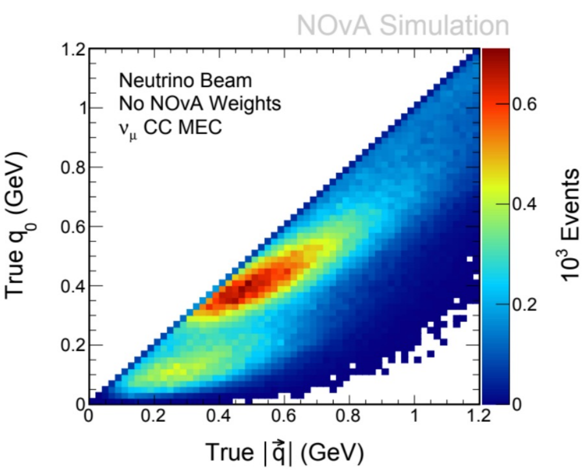


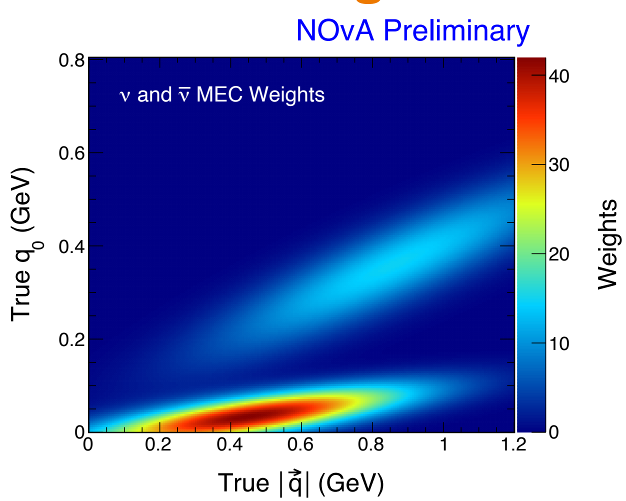
2p2h Tune

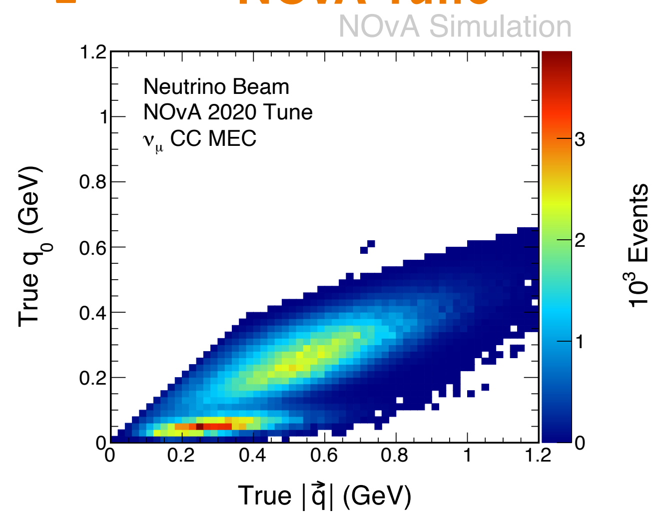


- “2p2h” or MEC (meson exchange current) interaction occurs when a neutrino interacts with a correlated pair of nucleons.
- NOvA tunes the MEC component of interaction simulation by doing a double gaussian fit to its data.

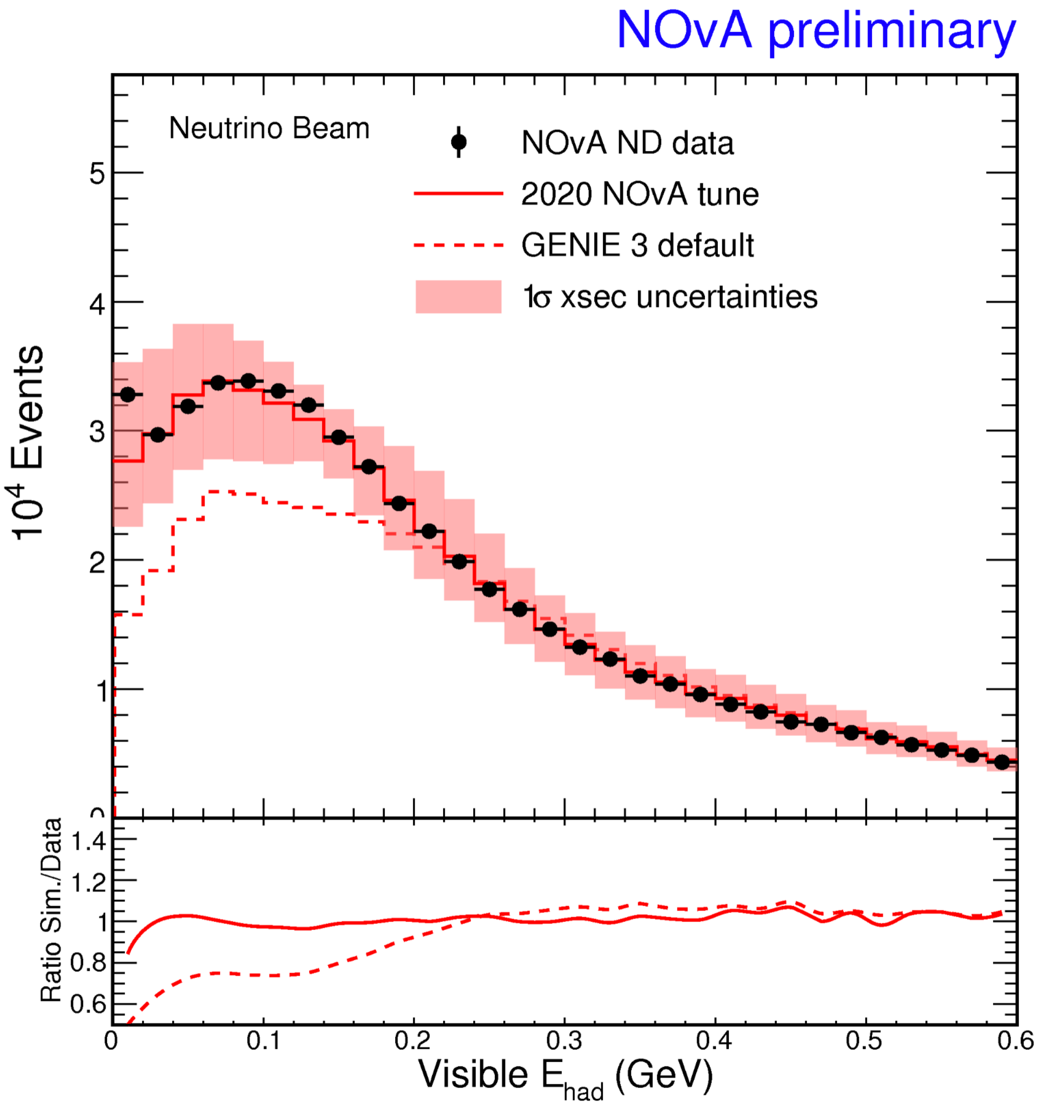
Valencia 2p2h **x** **MEC Weights** **=** **NOvA Tune**





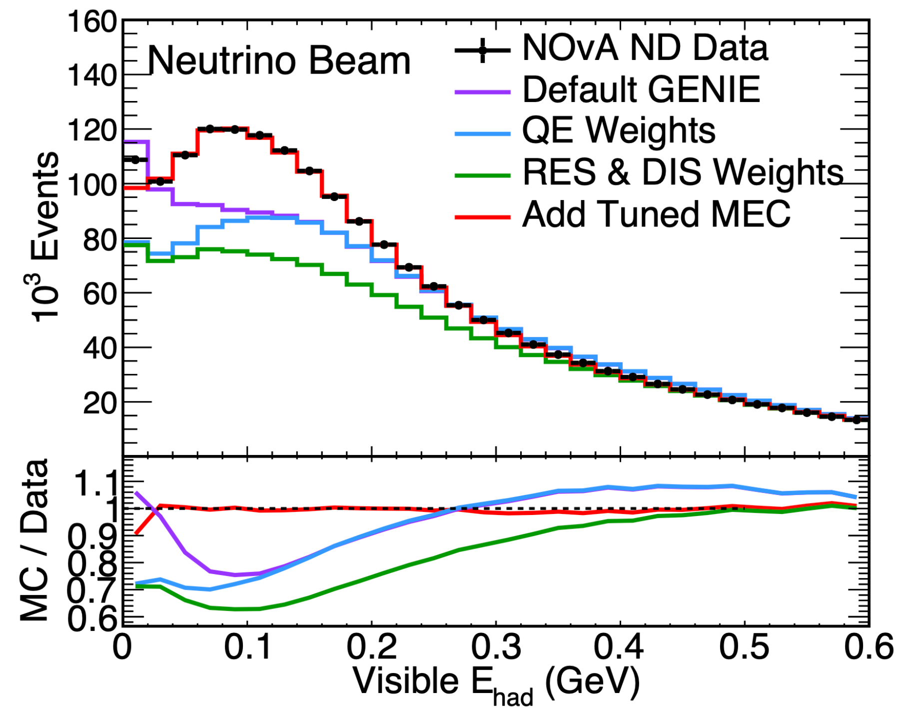


NOvA 2020 Tune & Systematics



NOvA 2019 Tune

- This analysis uses the same tune as the NOvA 2019 oscillation results
- **From external theory:**
  - Valencia RPA model of nuclear charge screening applied to QE.
  - Same model is applied to RES interactions
- **From NOvA ND Data:**
  - 10% increase in non-resonant inelastic scattering at high W (> 1.7 GeV²/c²)
  - Add in MEC interactions
    - Start from Empirical MEC and tune to NOvA data in bins of momentum transfer



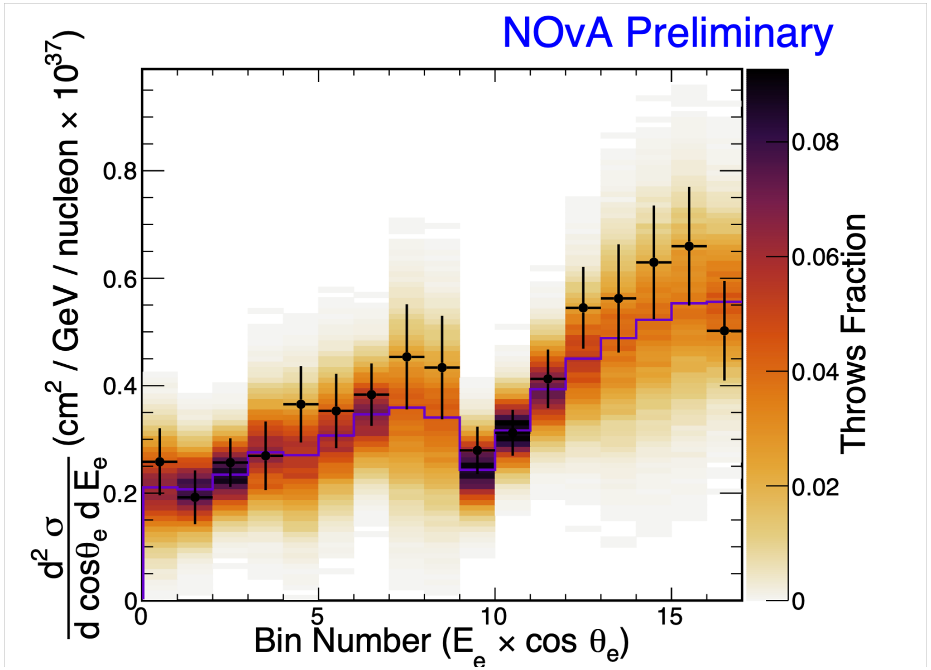
- Details of tune procedure are in arXiv:2006.08727.

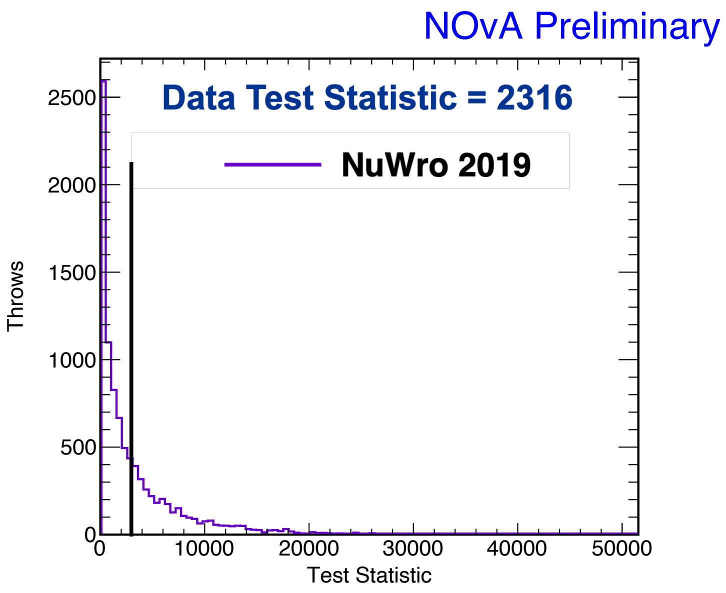
Generator comparisons

	QE/MEC Initial State	QE	MEC	Res	DIS	FSI
GENIE v2.12.2	RFG	L-S	Empirical (NOvA tune)	R-S	PYTHIA 6	hA
GENIE v3.00.06	LFG	Valencia (Nieves, et al)	Valencia (Nieves, et al)	B-S	PYTHIA 6	hN
NEUT 5.4.0	LFG	Valencia (Nieves, et al)	Valencia (Nieves, et al)	B-S	PYTHIA 5	Oset (low mom. pions) + ext. data
NuWro 2019	LFG	L-S + RPA	Valencia (Nieves, et al)	NuWro	PYTHIA 6	Oset (pions) + NuWro (nucleons)
GiBUU 2019	LFG	GiBUU Model				BUU equations

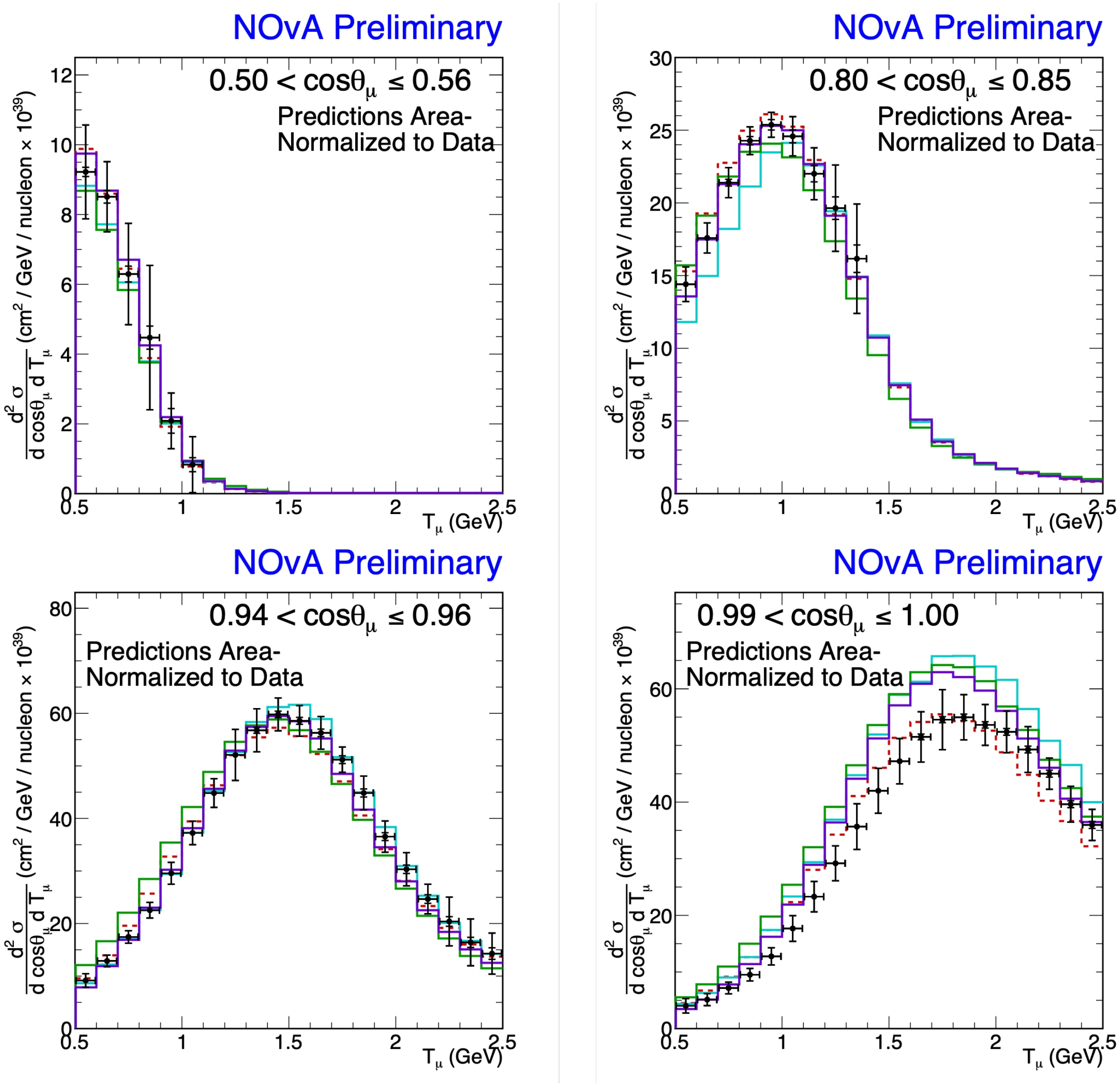
Generator comparisons

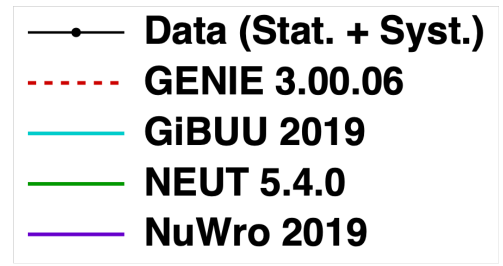
- Use the covariance matrix to calculate 50,000 throws from each generator prediction (RooFit).
- Compare test statistics of throws to data to find p-values.





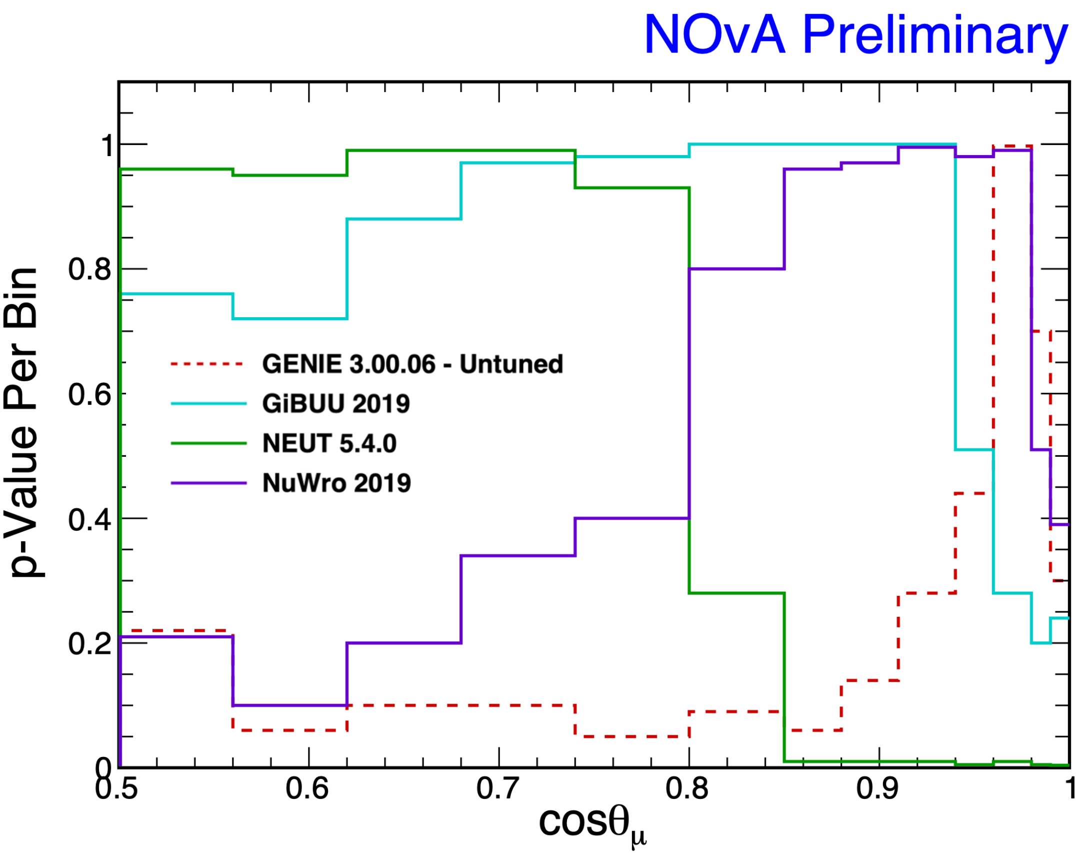
Shape only comparisons : ν_μ CC





Generator	Total p-value	Norm.
GENIE 3.00.06*	0.31	1.15
GiBUU 2019	0.38	1.28
NEUT 5.4.0	0.004	1.02
NuWro 2019	0.54	1.15

Shape only p-values : ν_μ CC

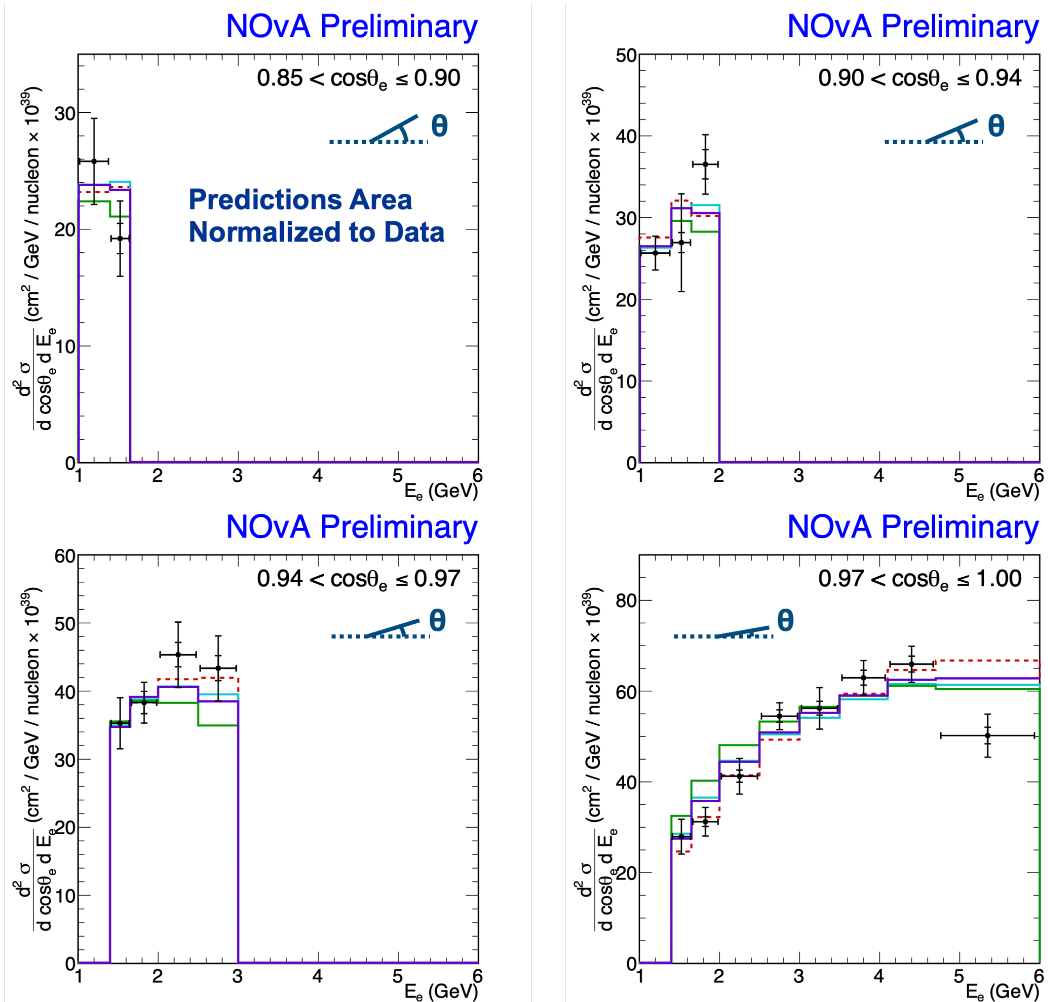


- Shapes from GiBUU agree much better with a normalization increase of ~28%.
- Generally the shapes predicted by the generators still need improvement in the most forward angles.

Generator	Total p-value	Norm.
GENIE 3.00.06*	0.31	1.15
GiBUU 2019	0.38	1.28
NEUT 5.4.0	0.004	1.02
NuWro 2019	0.54	1.15

Shape only comparisons : ν_e CC

Data (Stat. + Syst.)
GENIE 3.00.06 - Untuned
GiBUU 2019
NEUT 5.4.0
NuWro 2019

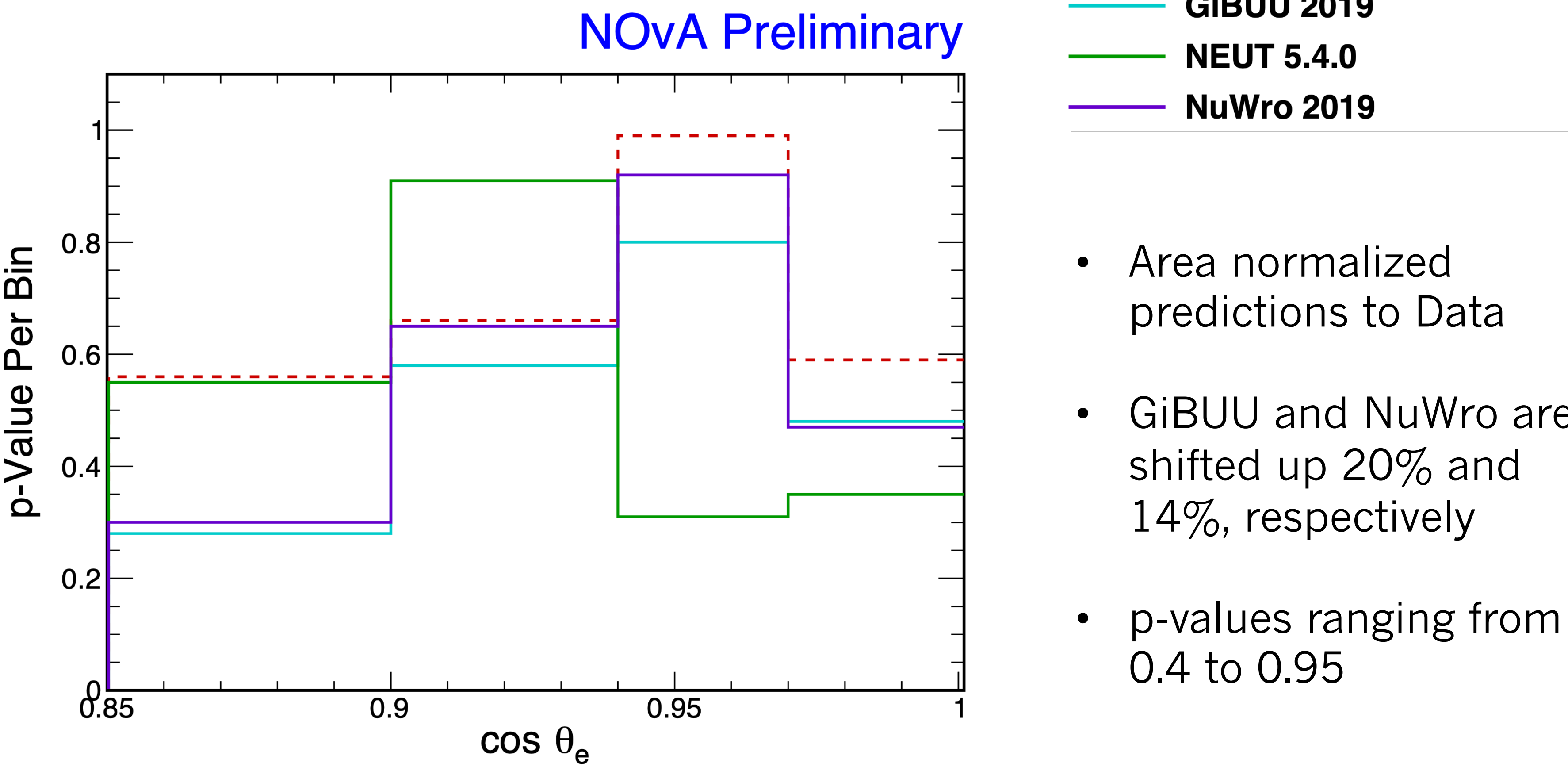


Area normalized predictions to Data

GiBUU and NuWro are shifted up 20% and 14%, respectively

p-values ranging from 0.4 to 0.95

Shape only p-values : ν_e CC

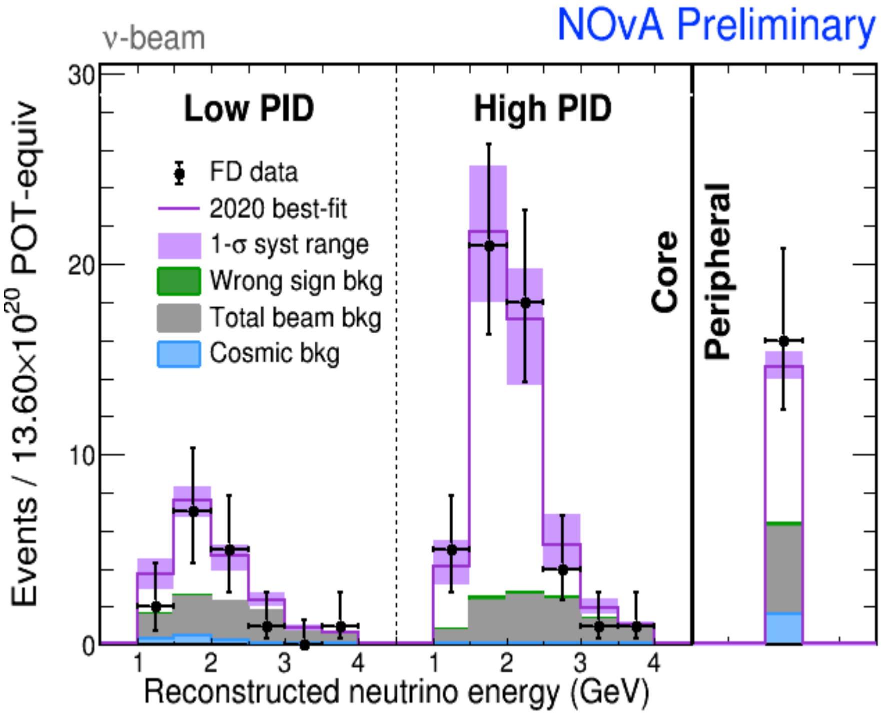


- Area normalized predictions to Data
- GiBUU and NuWro are shifted up 20% and 14%, respectively
- p-values ranging from 0.4 to 0.95

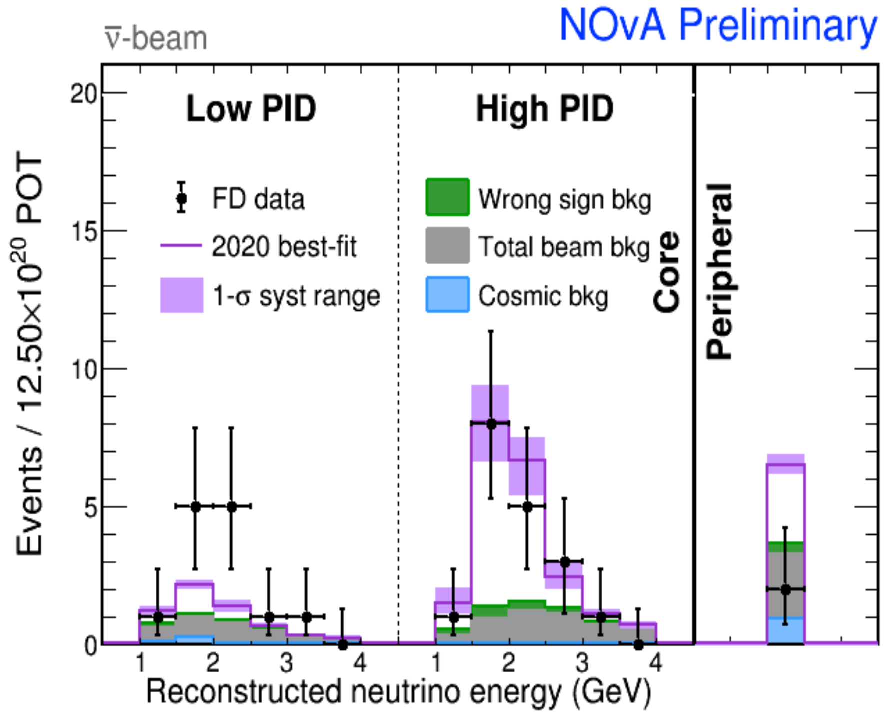
Test Beam

- Our systematics are dominated by detector energy scale and response. Data-MC disagree at 5% level for proton candidates.
- Feature : NOvA Test Beam at Fermilab Test Beam Facility to study hadronic response.
- A tertiary beam is created from 64 GeV secondary beam particles to study charged particles in 0.2 – 2 GeV range relevant to NOvA.
- **Currently taking data!**

FD Data Samples : ν_e appearance



Observed	: 82
Total Predicted	: 85.8
Total Background	: 26.8
Wrong-Sign	: 1.0
Beam Bkg	: 22.7
Cosmics	: 3.1



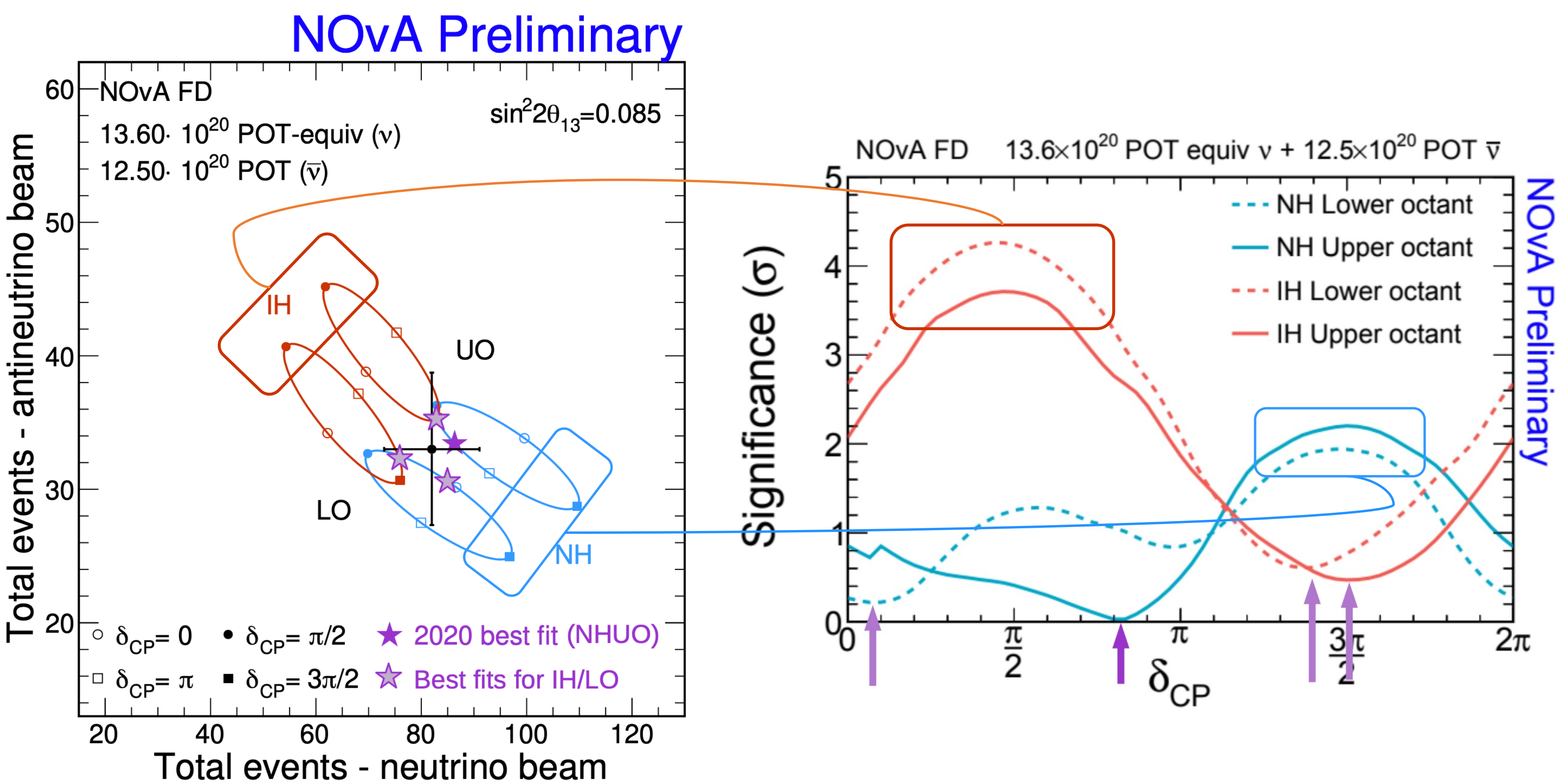
Observed	: 33
Total Predicted	: 33.2
Total Background	: 14.0
Wrong-Sign	: 2.3
Beam Bkg	: 1.6
Cosmics	: 3.1

FD Data Samples : ν_μ disappearance

Muon Neutrino Disappearance

	Neutrino	Antineutrino
Observed	211	105
No Disappearance	1156	488
Best Fit Expectation	222	105
Background	8.2	2.1

Extracting Oscillation Parameters



- **NOvA data disfavors strong asymmetry in rates of ν_e and $\overline{\nu}_e$ appearance.**