Neutrino Oscillation Results from the NOvA Experiment

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for the NOvA collaboration

XIX International Workshop on Neutrino Telescopes

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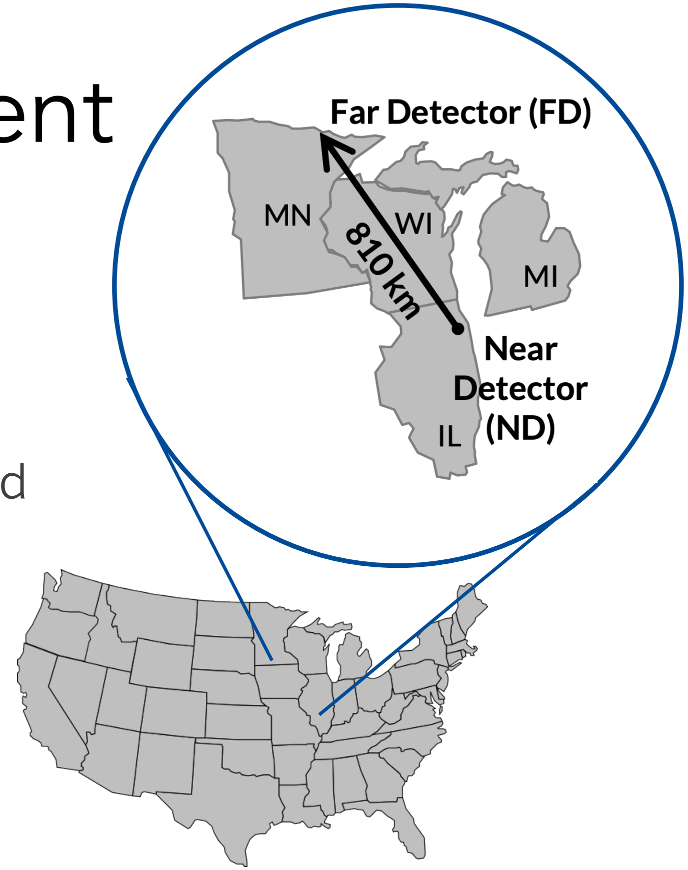
Chair of Galileo, from which, according to tradition, he gave lectures - Credits: Univ. of Padova - M. Pistore

Overview: NOvA Experiment

- NOvA is a long baseline neutrino oscillation experiment located in the United States.
- It receives a beam of **muon (anti)neutrinos** peaked at 2 GeV energy from NuMI beam facility at Fermilab.
- Two functionally identical, liquid scintillator detectors are used to detect and measure the neutrino events from the beam.
- NOvA has a broad physics program, including:
  - **Astrophysics – Plenary Talk by M. Strait**
  - **3-flavor neutrino oscillation – This talk**
  - Search for sterile neutrinos
  - Neutrino cross-section measurements

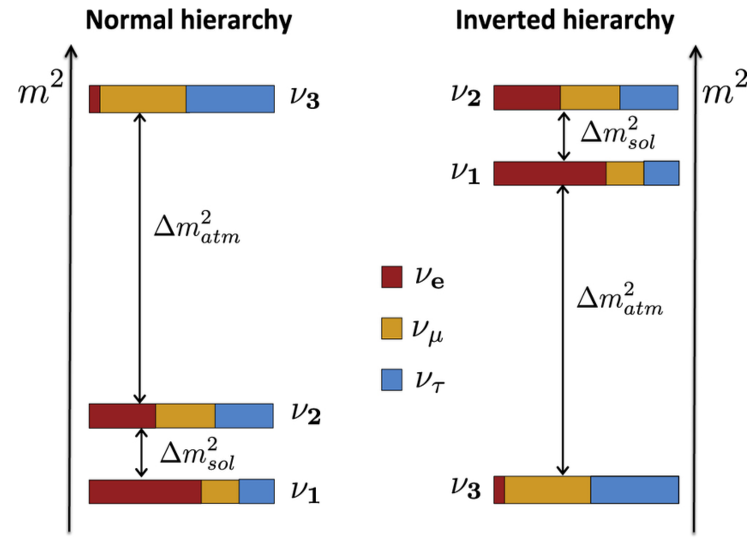


HUMANS OF NOvA

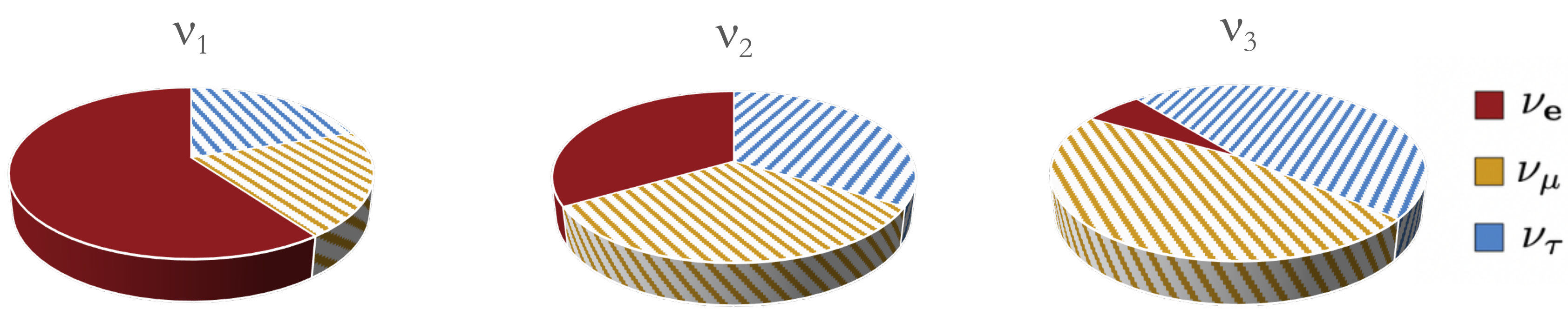
- ◎ 200 collaborators
- ◎ 50 institutions
- ◎ 8 countries

NOvA Physics : Neutrino Masses & Mixing

- **MASS HIERARCHY : Normal or Inverted ?**
  - Does the symmetry that determines the mass of charged leptons influences ν_1 to be the lightest neutrino (Normal Hierarchy) or does the inverse hold (Inverted Hierarchy)?
- **θ_{23} Octant : Is the mixing maximal?**
  - Large uncertainty on θ_{23} mixing angle
  - Is the amount of $\nu_\mu = \nu_\tau$? $\theta_{23} = 45^o$?



Mass eigenstate of neutrinos



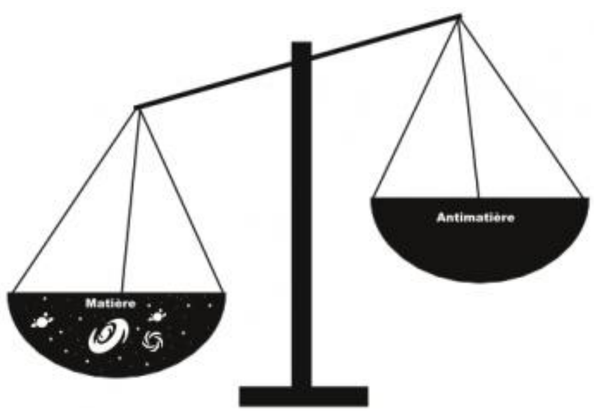
NOvA Physics : CP Violation

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

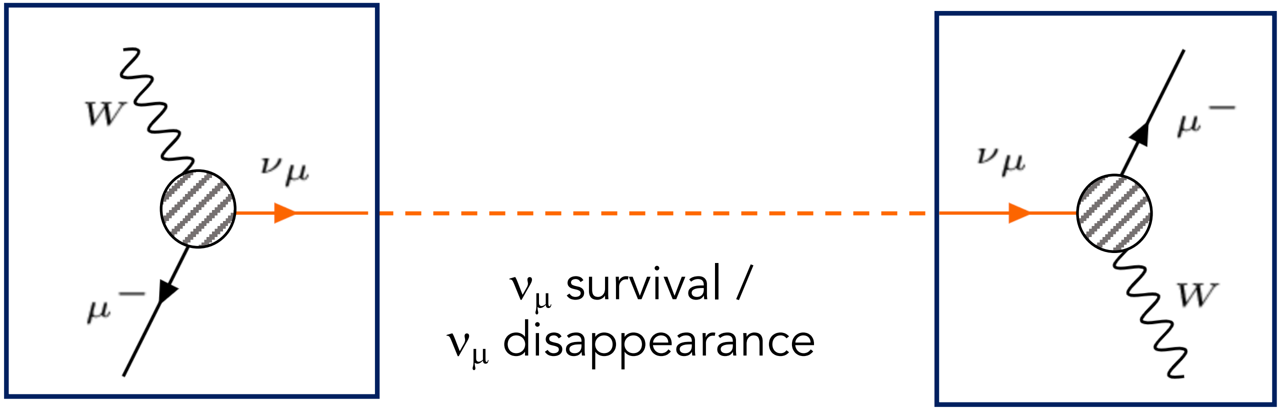
$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

PMNS Neutrino Mixing Matrix

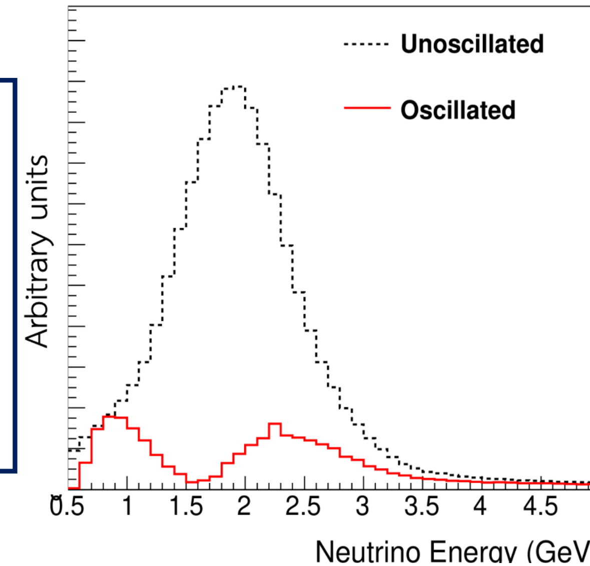
- Do neutrinos and antineutrinos oscillate at the same rate?
- The CP violating phase of the PMNS matrix has not been measured and is only weakly constrained by *current* data.
- CP violation in leptonic sector could provide a path forward towards explaining the baryon asymmetry in the early universe.

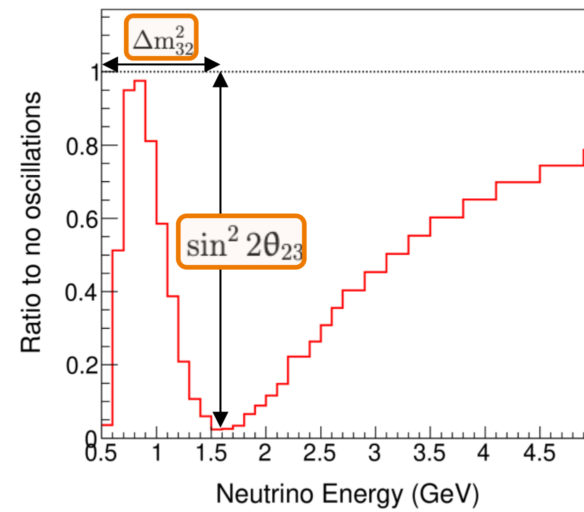


Measuring Oscillations : ν_μ disappearance



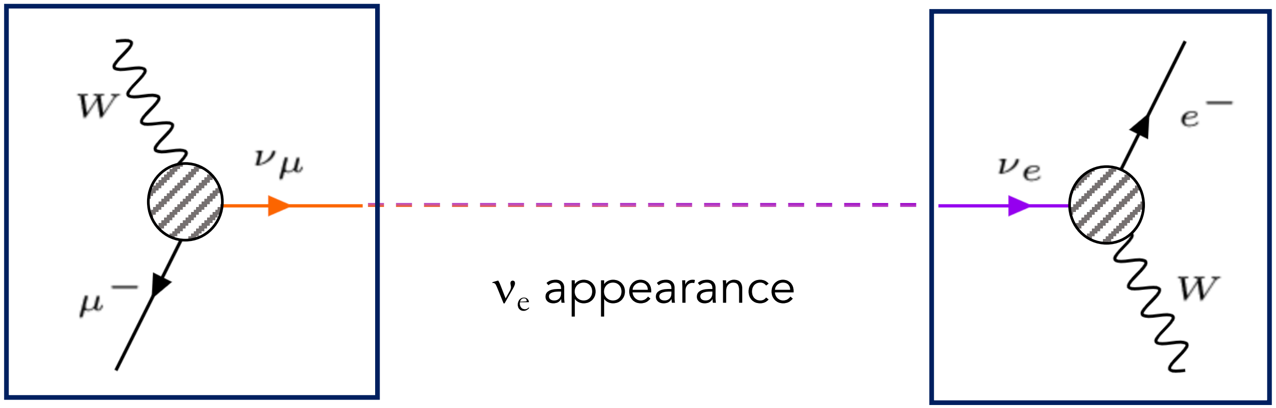
Measurements at FD

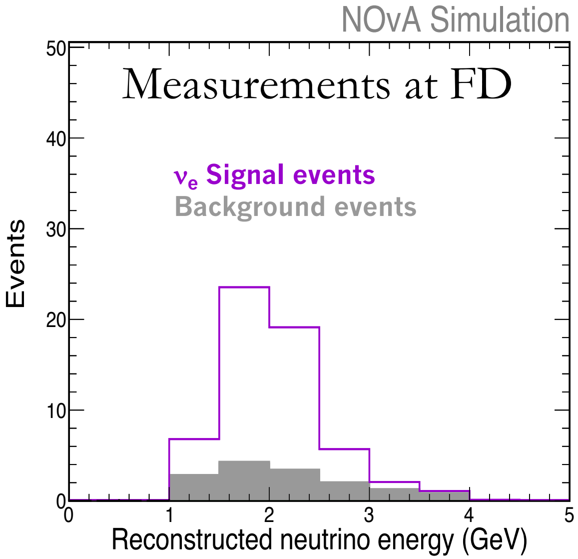




- Leading order dependence on Δm^2_{32} and $\sin^2\theta_{23}$
- Aims to answer the question of maximal mixing in θ_{23}

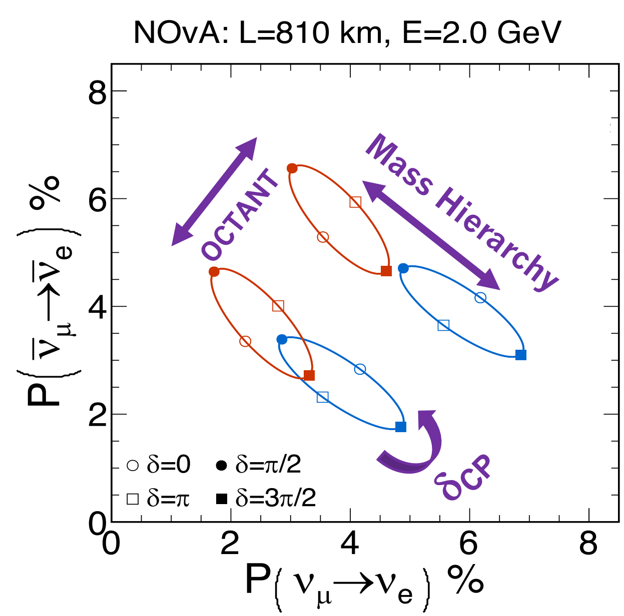
Measuring Oscillations : ν_e appearance





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

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



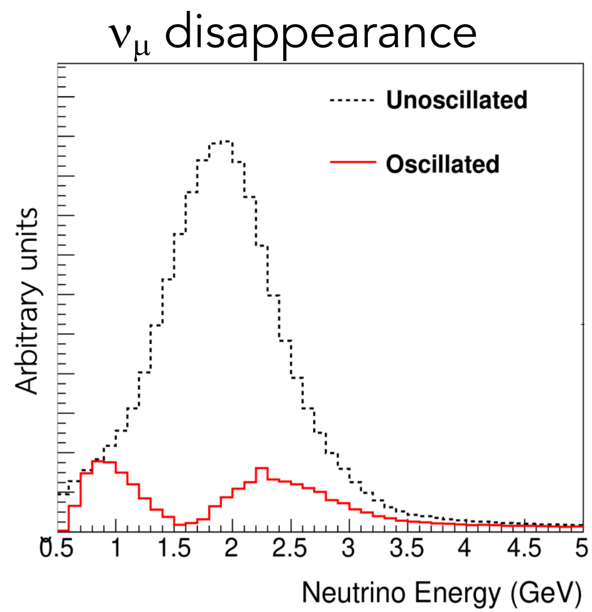
Measuring Oscillations

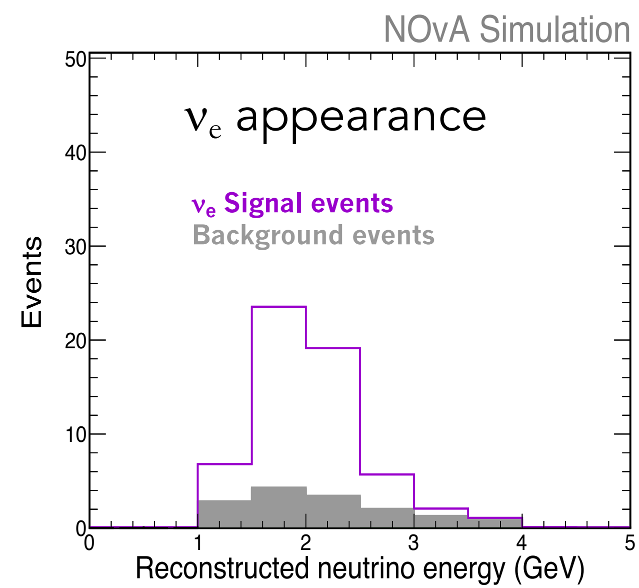
A. Measurement:

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

B. Inference :

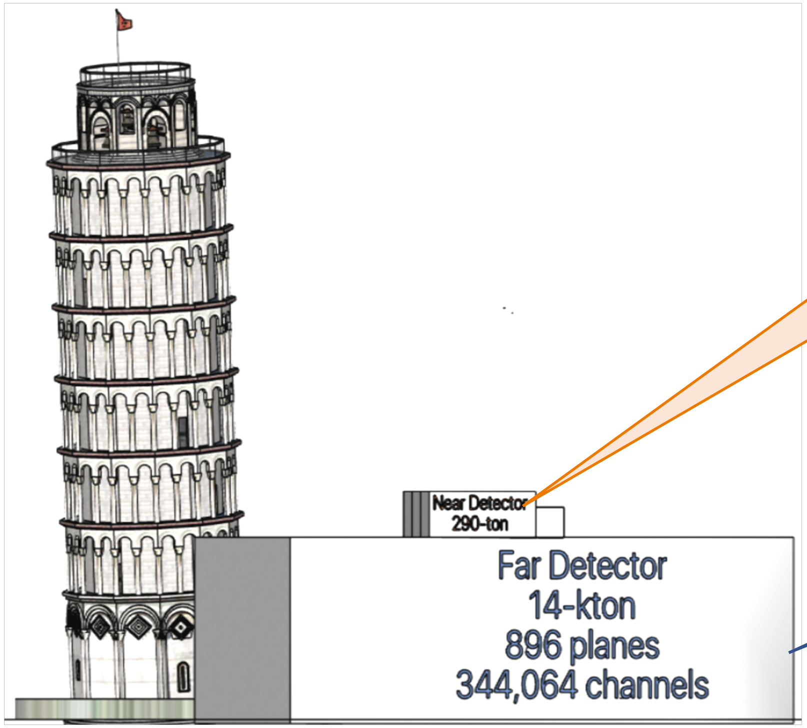
1. Compare ν_μ spectrum with the no oscillation prediction.
2. Compare ν_e and $\overline{\nu}_e$ appearance rate.





Detecting Particles : NOvA Detectors

- Segmented liquid scintillator detectors provide particle detection via tracking and calorimetry.
- **Good time and spatial resolutions** to distinguish pile-ups and reject cosmic events.



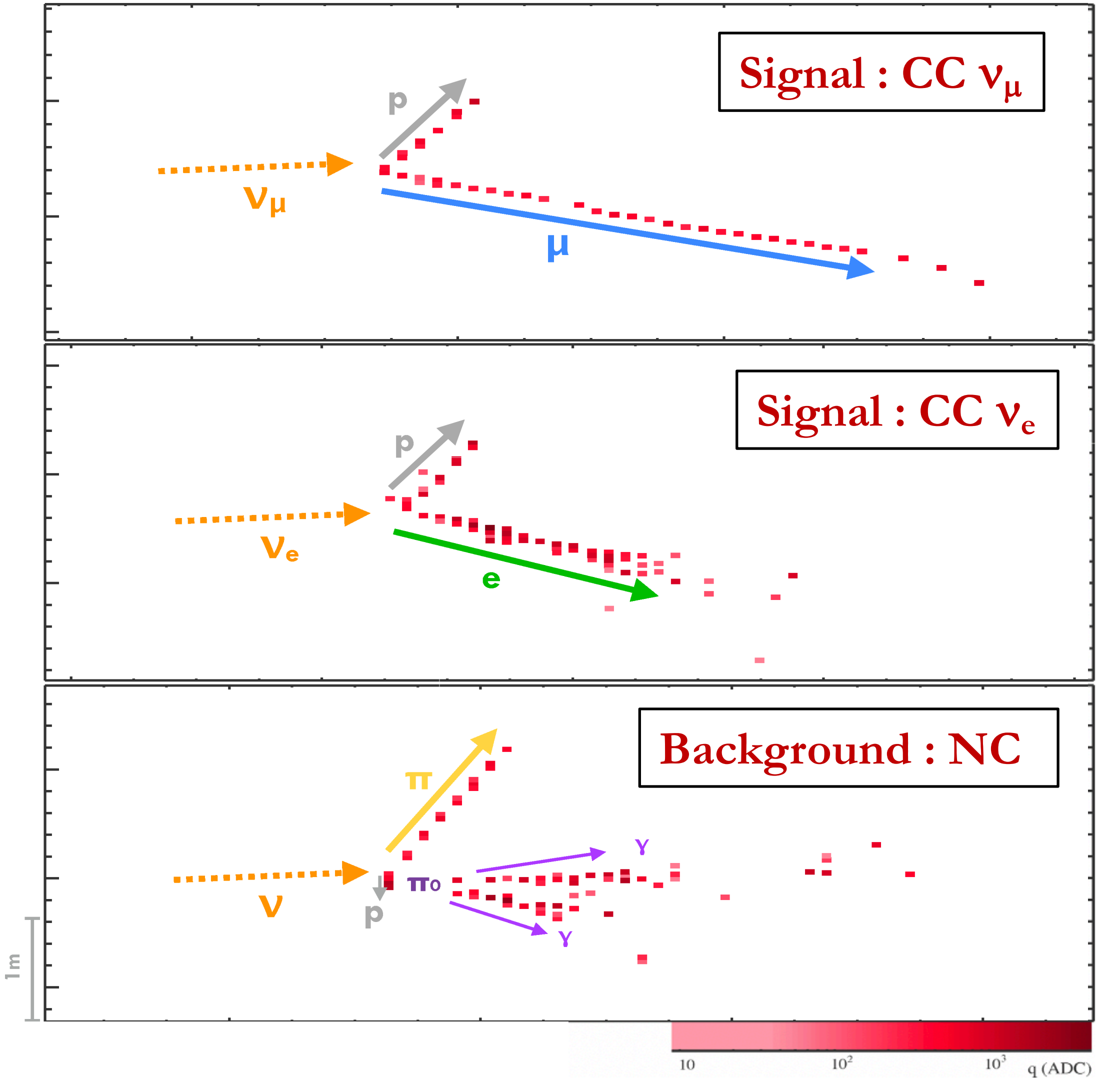
Near Detector (ND)

- 290-ton
- 100 m underground
- 1km from beam target

Far Detector (FD)

- 14-kton
- On the surface
- 810km from beam target

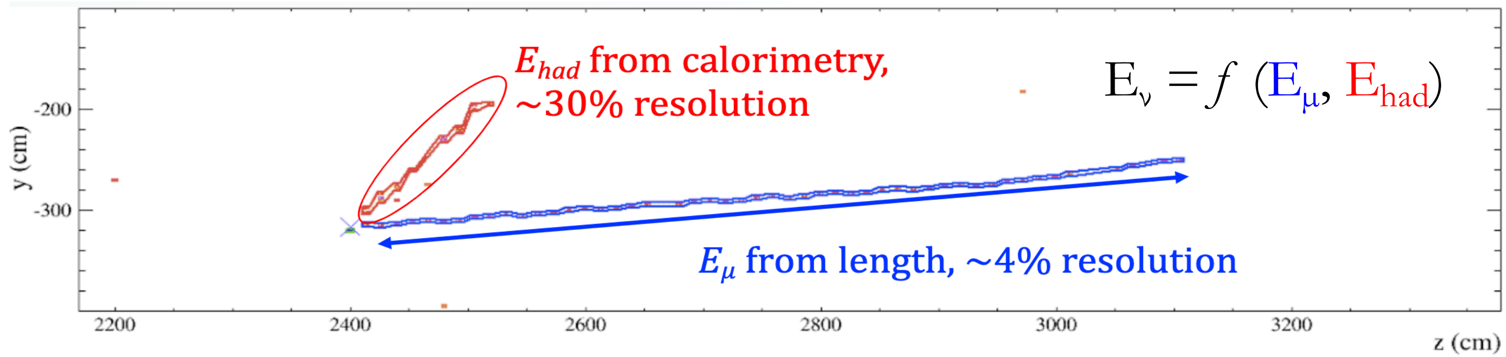
Identifying particles



- A Convolution Neural Network called **Convolution Visual Network (CVN)** is used to ID particles.
- Calibrated Hits in various events topologies are provided to network as input pixel maps.
- The network classifies these events in various signal and background output categories.
- Neutrino and antineutrino modes are trained separately.

Measuring Neutrino Energy

ν_μ

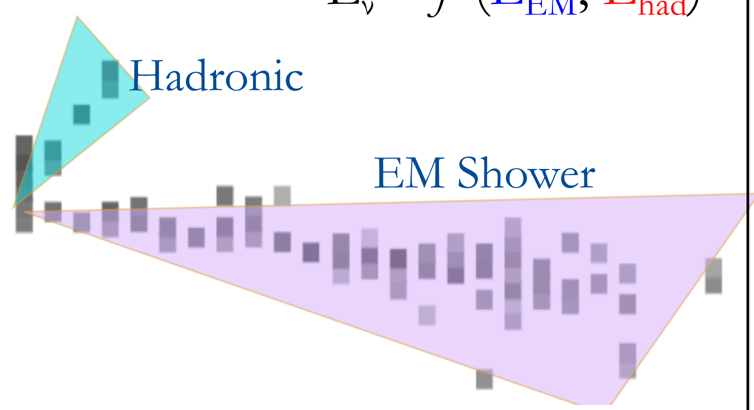


- Muon energy is estimated from the track length and hadronic energy from visible hadronic activity.

ν_e

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

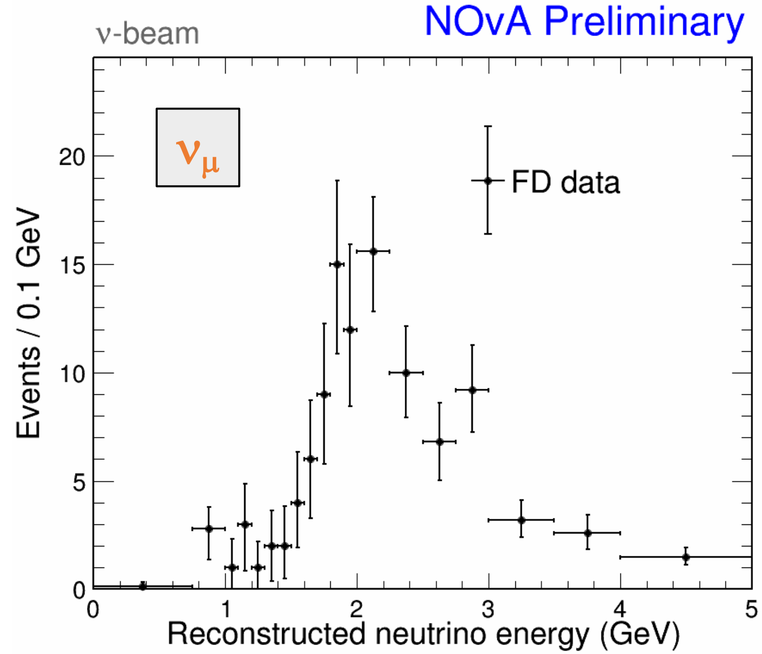
- Calorimetric energy estimation is done for EM and hadronic clusters separately.
- Overall neutrino energy resolution is ~11%.

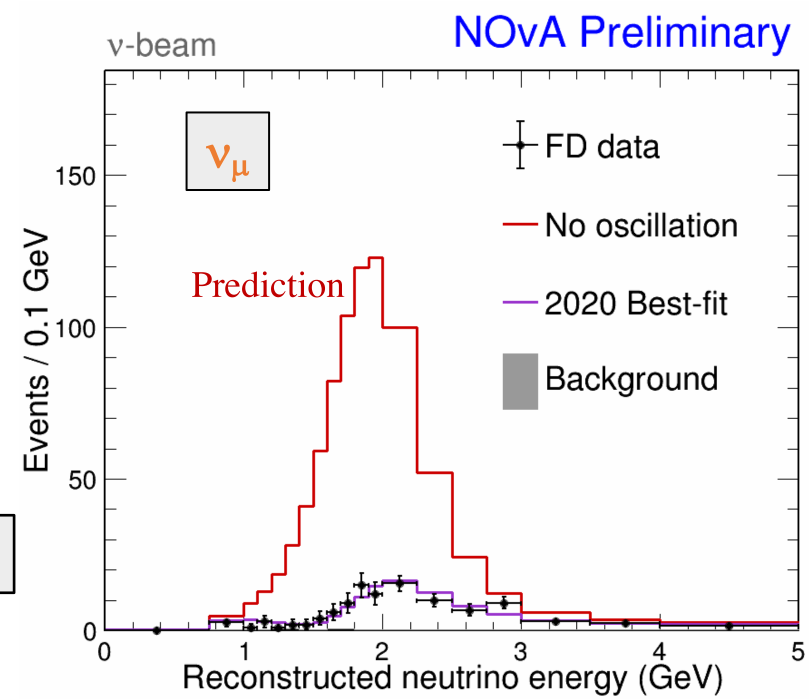


Making Prediction

- To extract oscillation parameters from reconstructed neutrino energy data, we compare it to the null case of no oscillation.
- A simple simulation cannot be directly used as a prediction, since parts of the process are unknown or poorly known (contributing large uncertainties).
- Use ND Data to correct and constrain the Monte Carlo simulation.

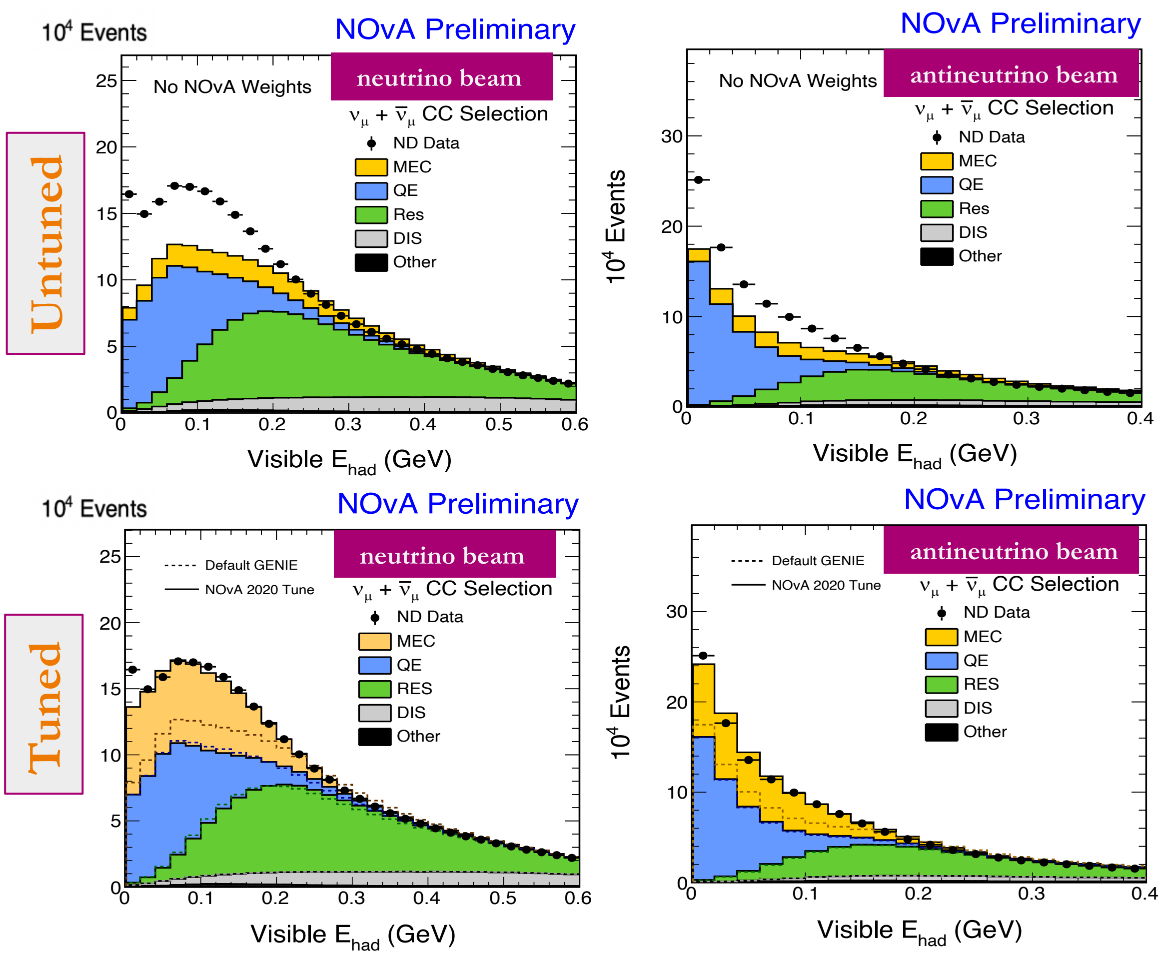
Prediction = ND Data Corrected Simulation





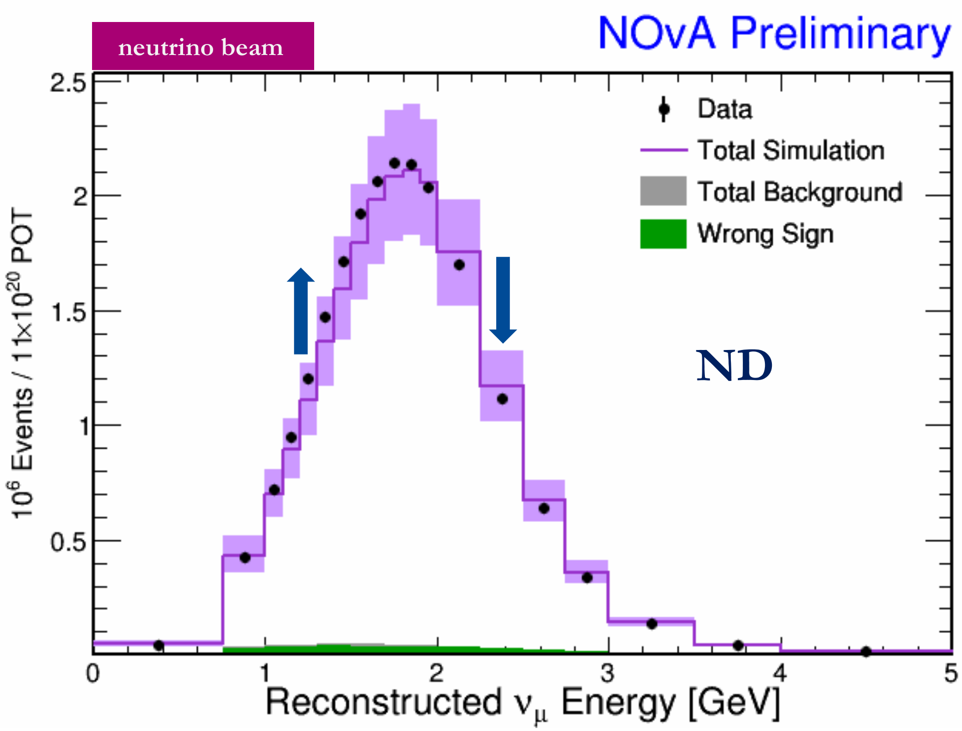
NOvA ND Tune

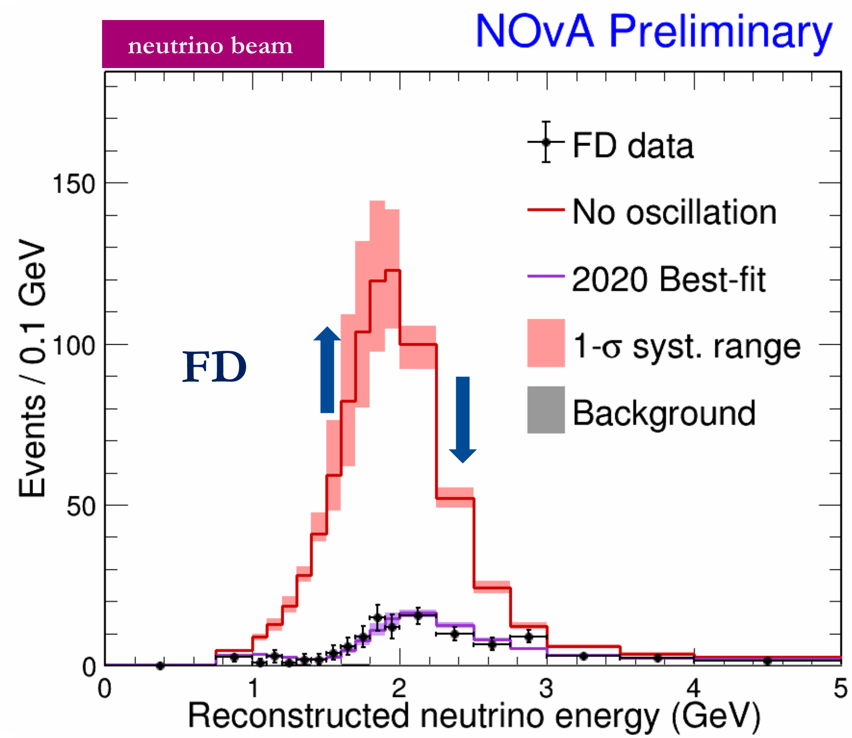
- We use **GENIE**(v3.0.6) for neutrino interaction generation.
- Nuclear effects are still not well-modeled. Out-of-the-box GENIE does not describe ND data well.
- Tuned GENIE by varying the MEC and FSI components.
- Any remaining differences between data and MC are covered by systematic uncertainty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



ND Data Constraint

- Difference in data-MC at ND is propagated to the FD simulation.
- This is done for the central-value Monte Carlo *and* all systematically shifted simulations.

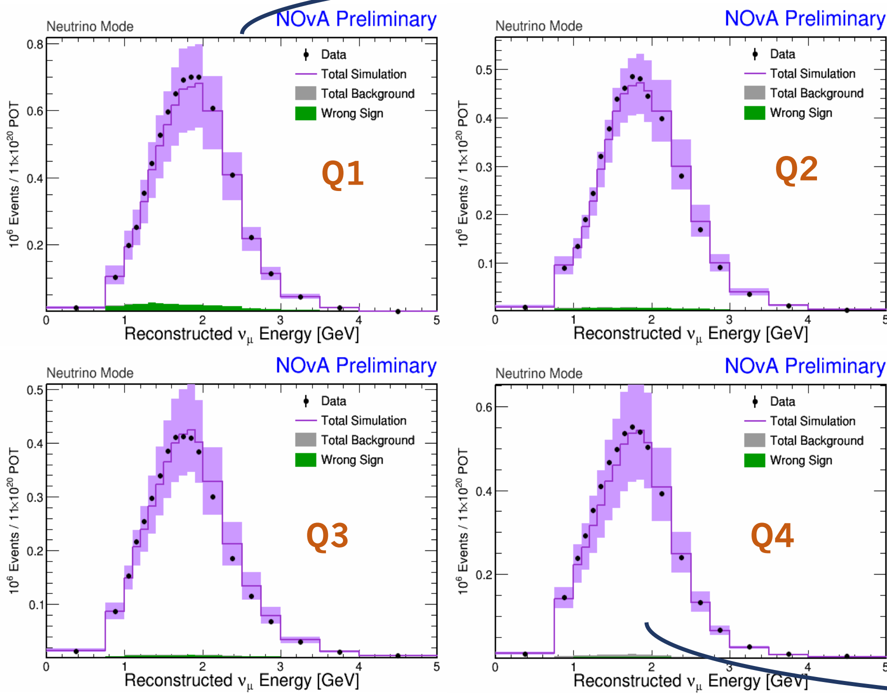




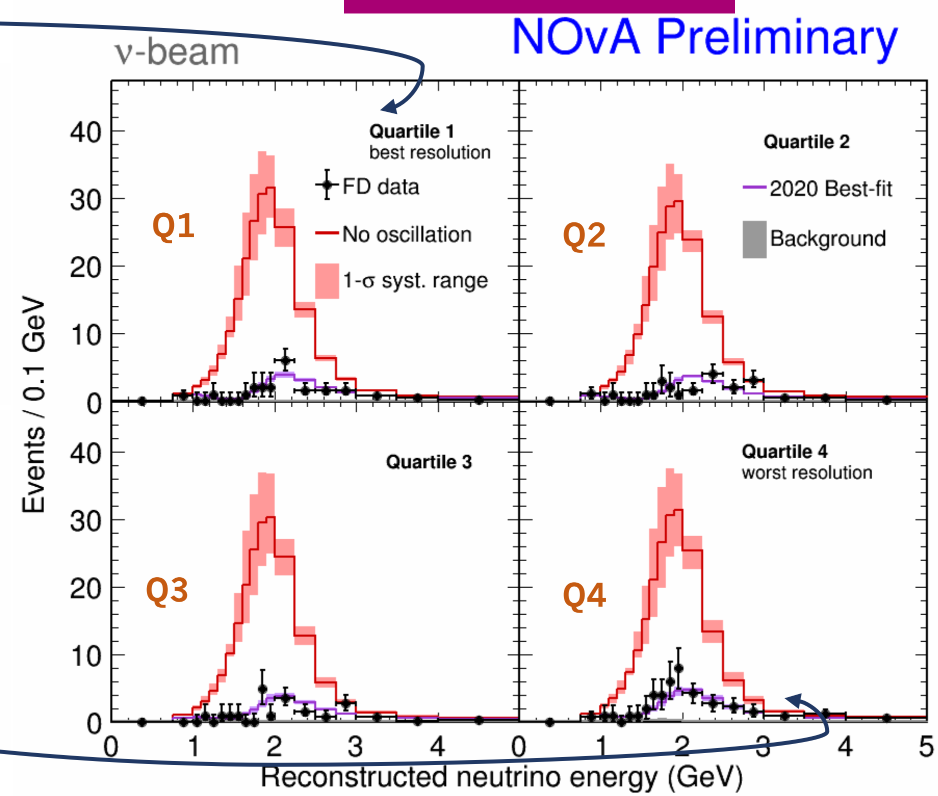
ND Data Constraint : Energy Resolution

- 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.

ND DATA

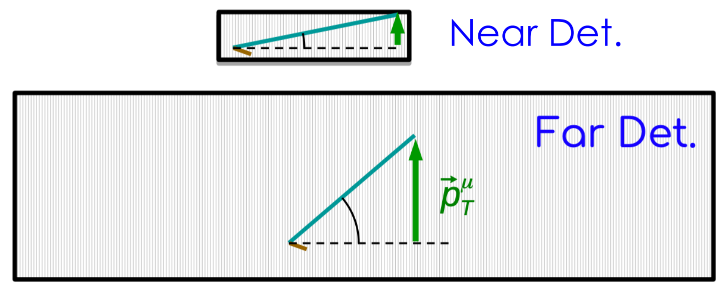


FD PREDICTION

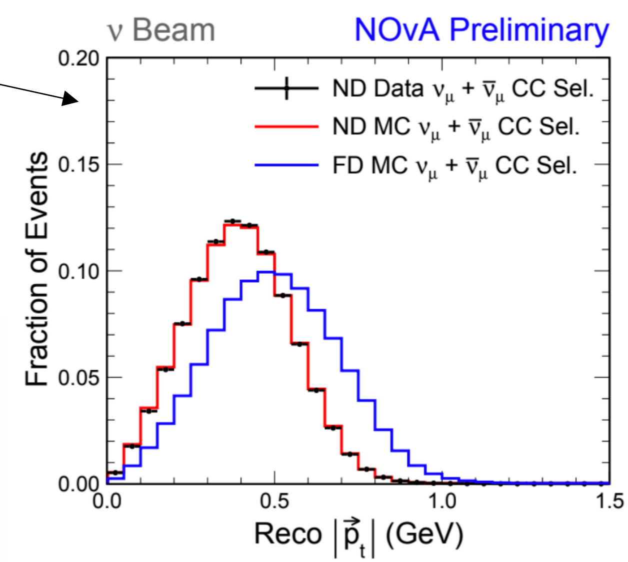


ND Data Constraint : Detector Acceptance

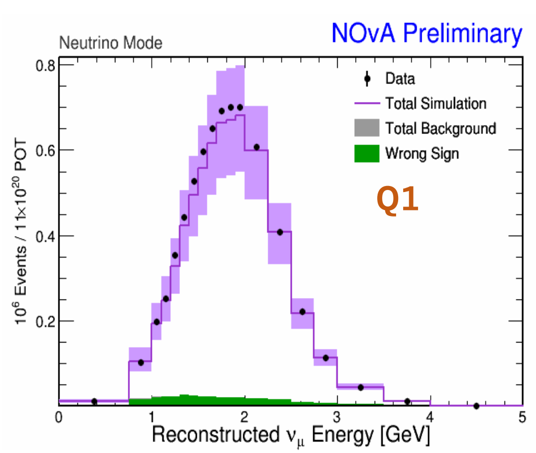
- Due to a large difference in size of the detector, FD has a larger acceptance of the particles going in the transverse direction than the ND.

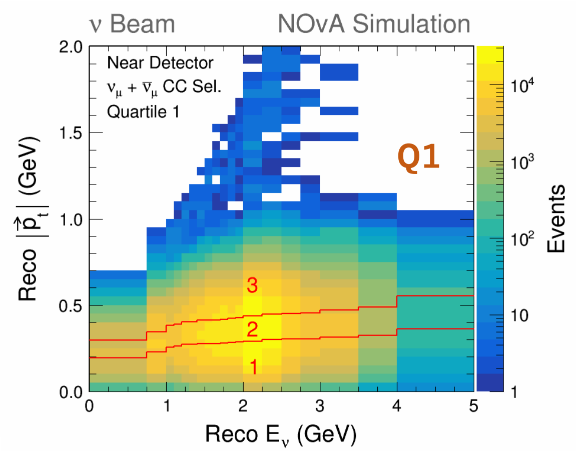


- This difference can be seen in the lepton $|\vec{p_t}|$ distributions.

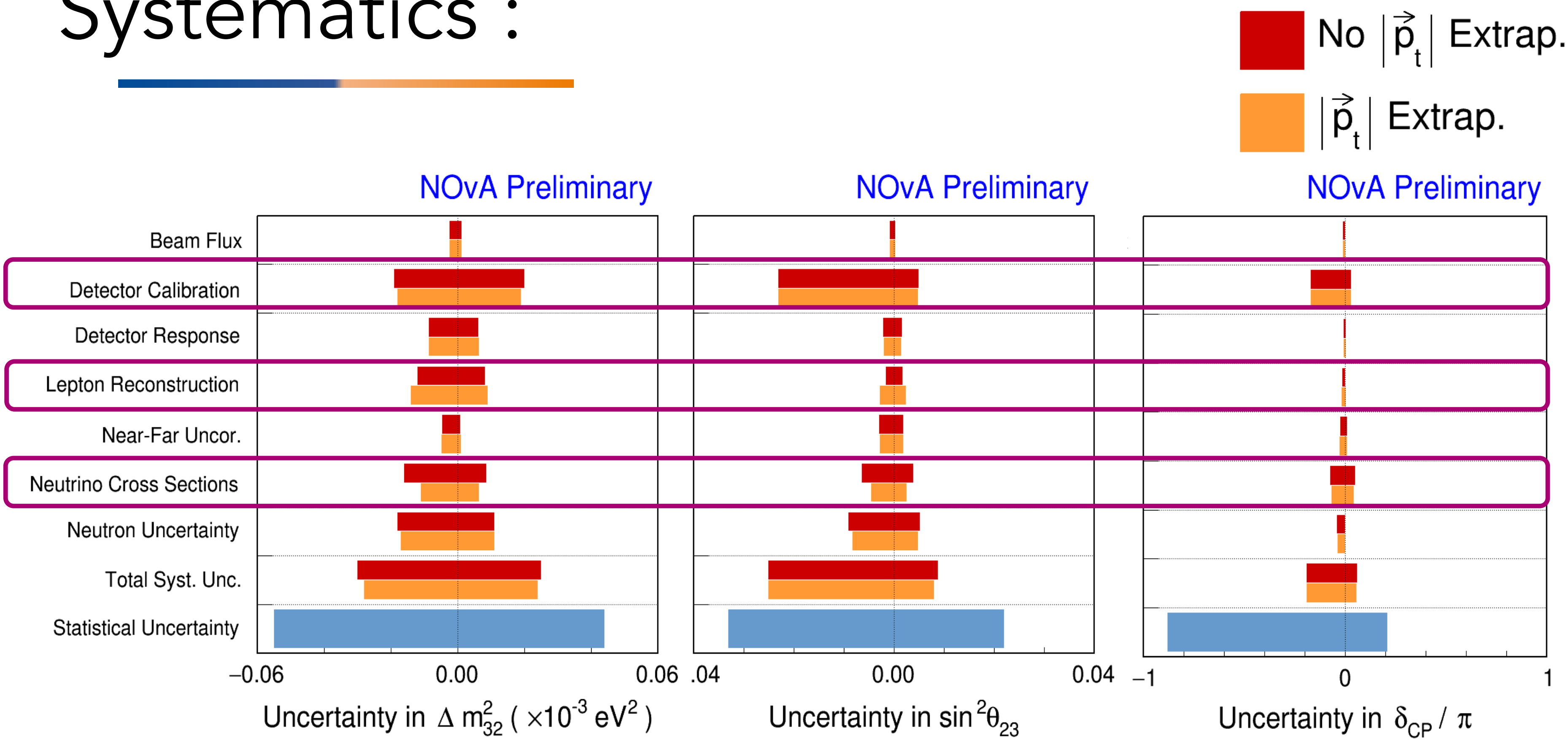


- **Sub-divide the sample in 3 bins of lepton $|\vec{p_t}|$** to better match the samples applying the constraint between the two detectors.



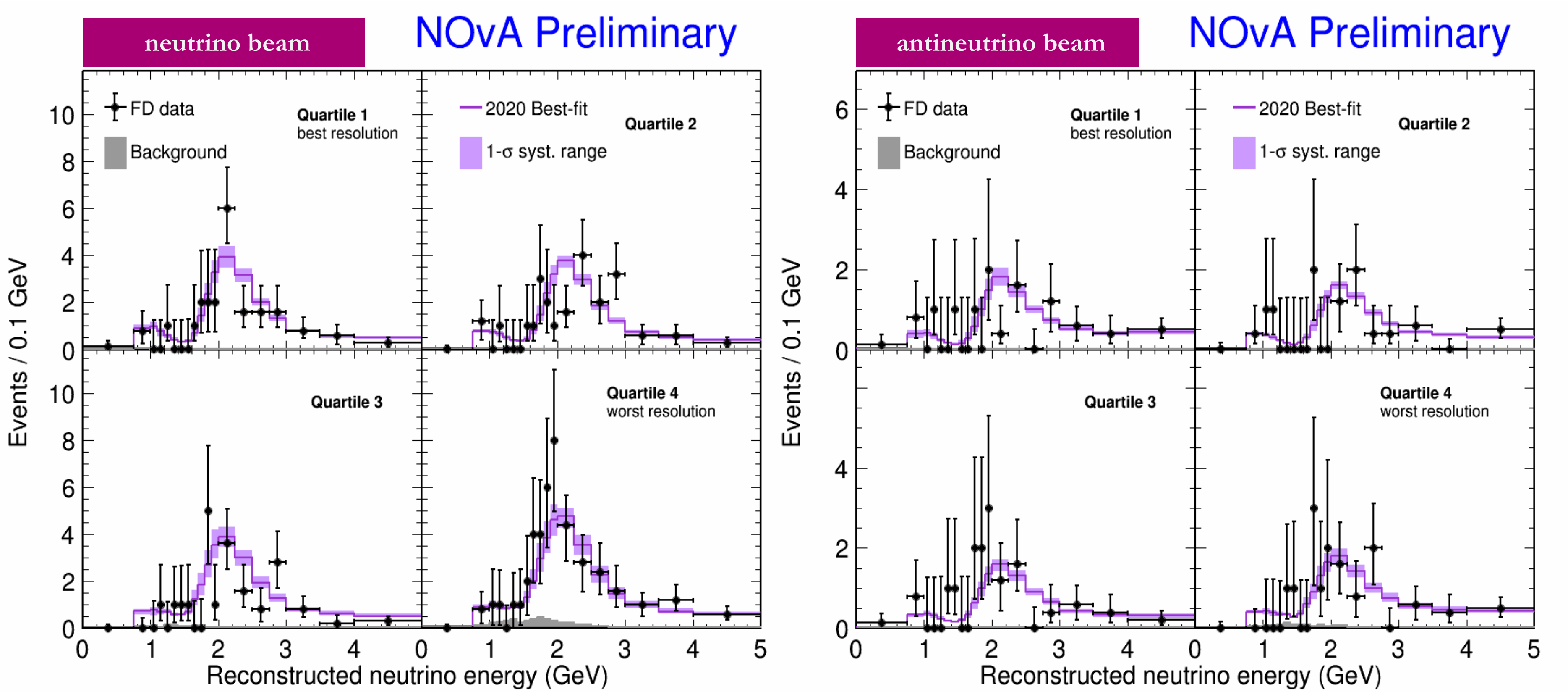


Systematics :



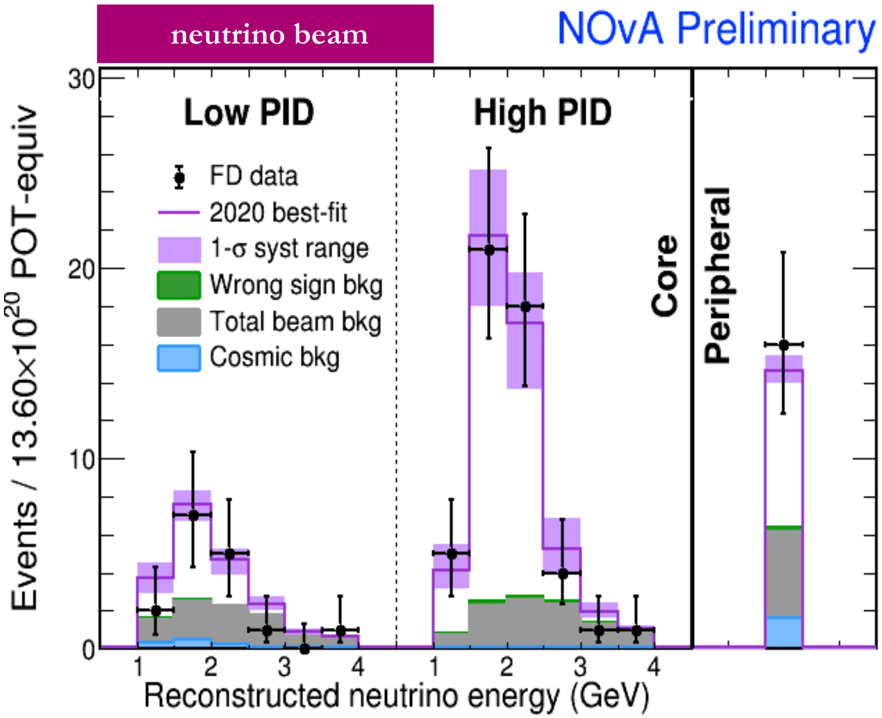
- Adding extrapolation in $|\vec{p}_t|$ further constrains neutrino cross section systematics by 30% and makes the analysis more resilient to "unknown-unknowns" error.
- It also leads to a slight increase in lepton reconstruction systematics. However, lepton reconstruction uncertainty is well-understood.
- All measurements are statistics-limited and our systematics budget is dominated by Detector Calibration and Response uncertainties.

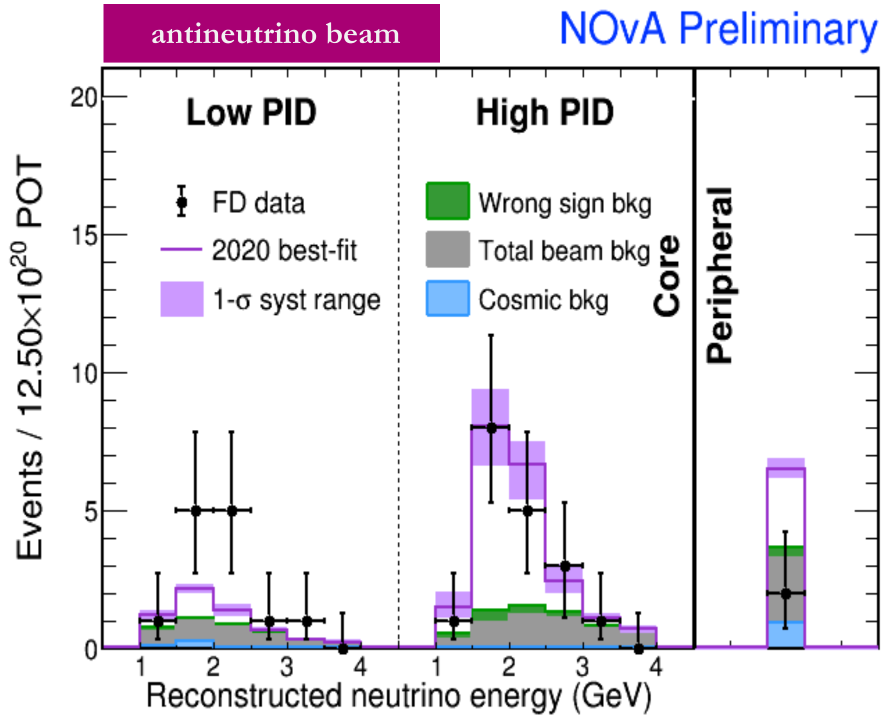
FD Data Samples : ν_μ disappearance



- 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





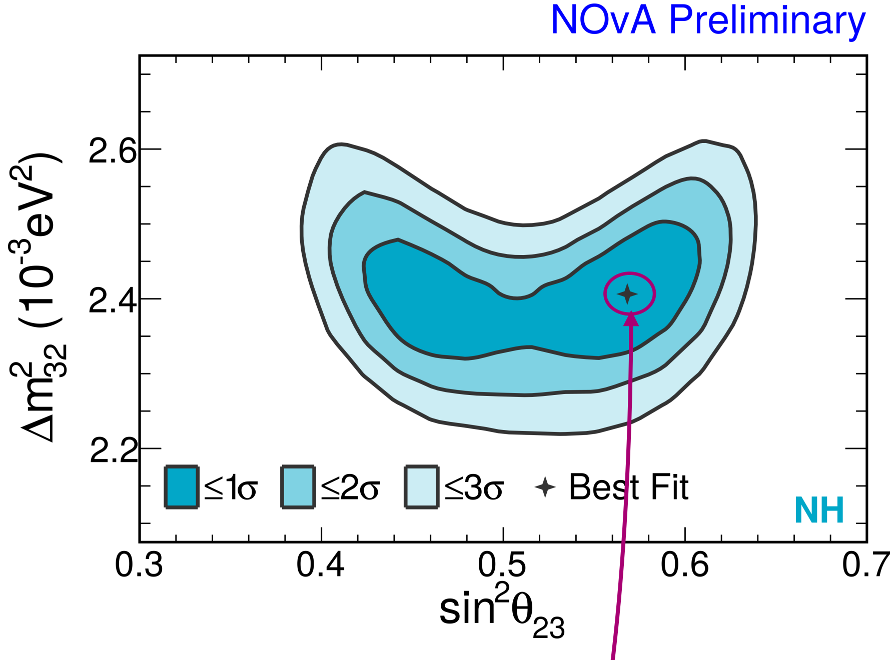
Observed : 82 events

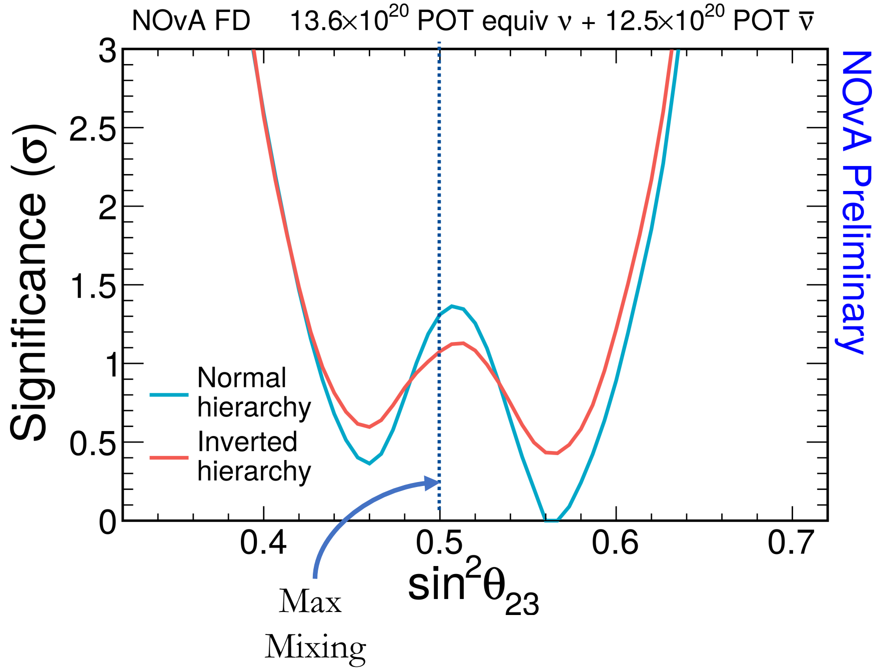
Observed 33 events : > 4σ $\bar{\nu}_e$ appearance

- 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.

Extracting Oscillation Parameters

Oscillation parameters are extracted by a simultaneous joint fit of both datasets in neutrino and antineutrino mode.





Best Fit:

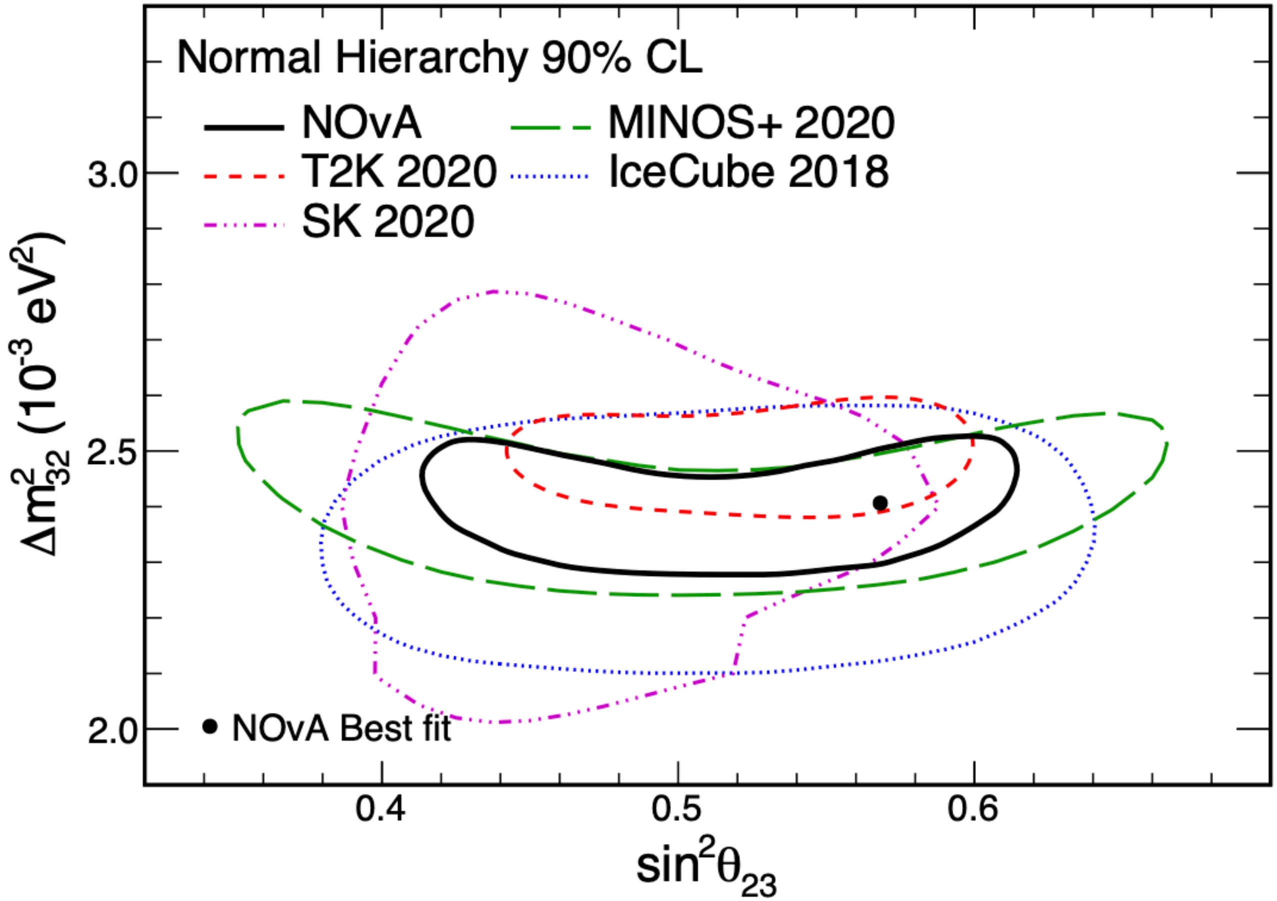
$$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$$

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

~ 2.9% Precision

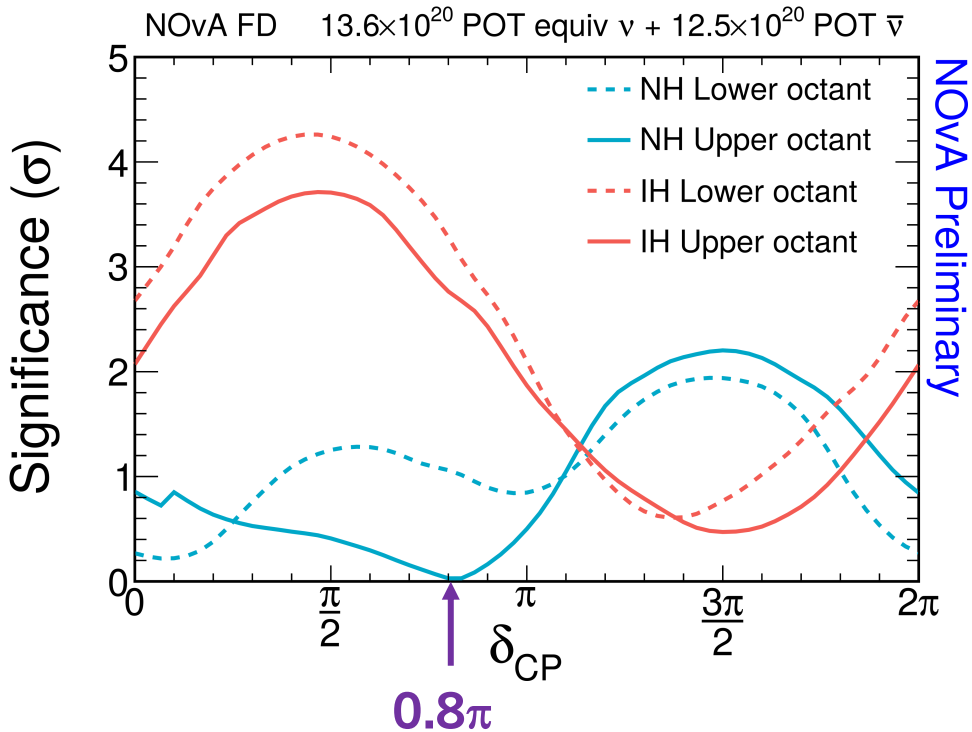
- Maximal Mixing is disfavored at 1.1σ
- Upper Octant is preferred at 1.2σ

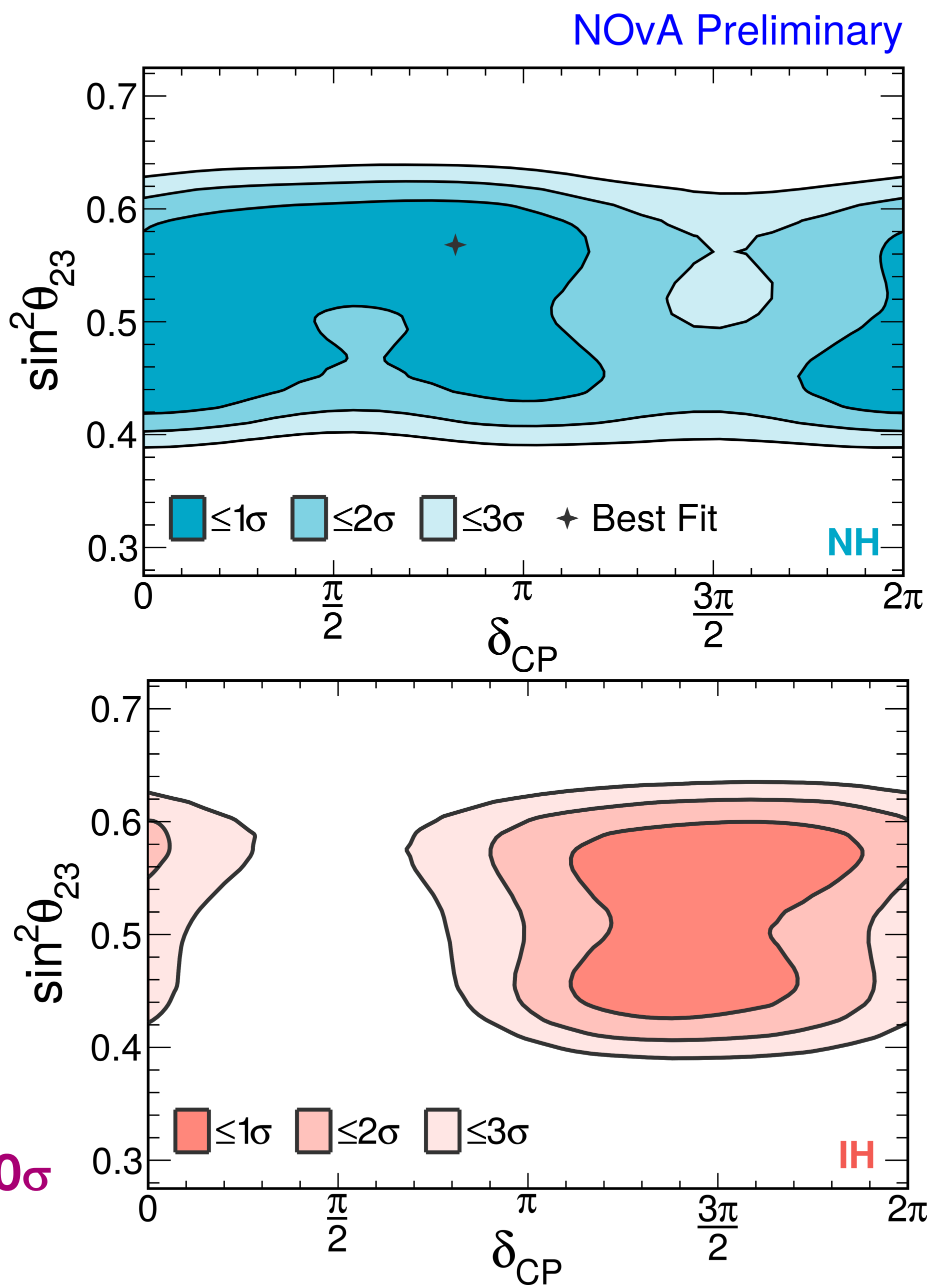
NOvA vs Others



- These measurements are consistent across many experiments.

δ_{CP} Measurement

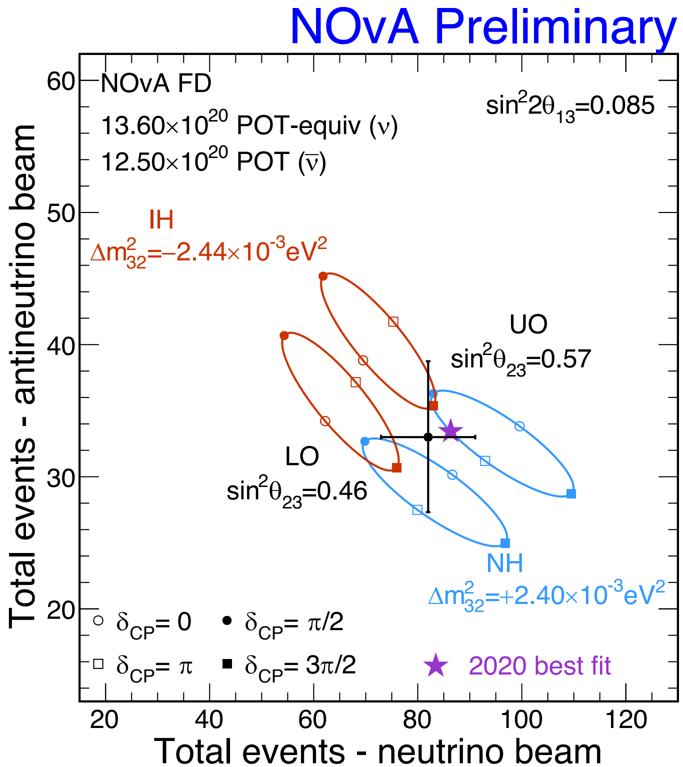


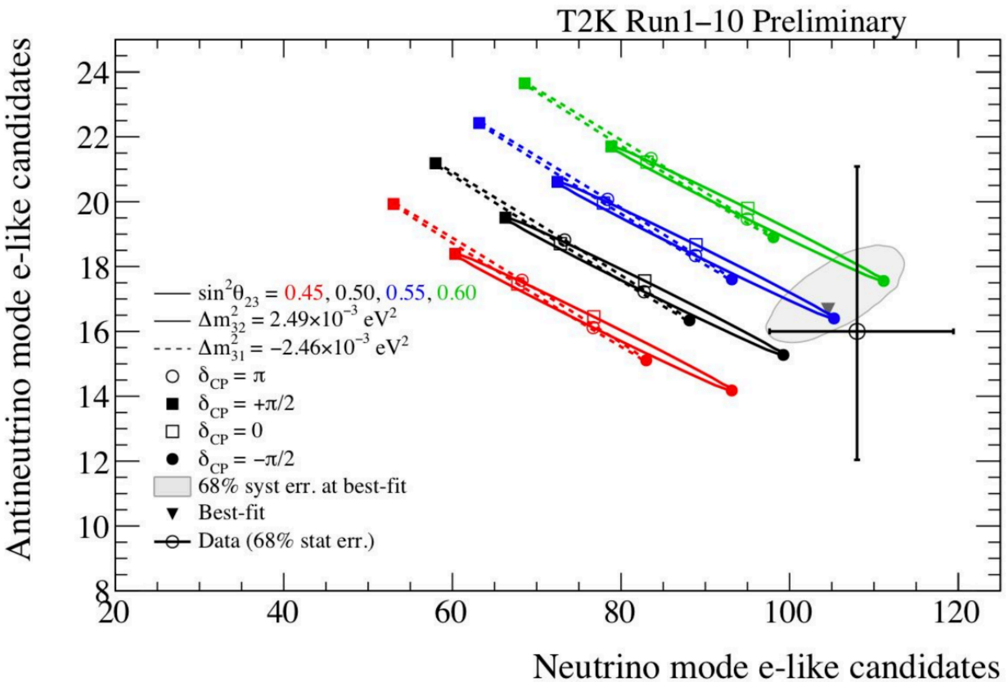


- Excludes {IH, $\delta_{CP} = \pi/2$ at > 3σ} & {NH, $\delta_{CP} = 3\pi/2$ at ~2σ}

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

NOvA & T2K





T2K plot from [P. Dunne's talk at Neutrino 2020]

- **NOvA data disfavors strong asymmetry in rates of ν_e and $\overline{\nu}_e$ appearance.**
- **T2K sees a larger ν_e appearance than $\overline{\nu}_e$ appearance and their best fit is consistent with large CP violation for Normal Hierarchy.**

Looking Ahead

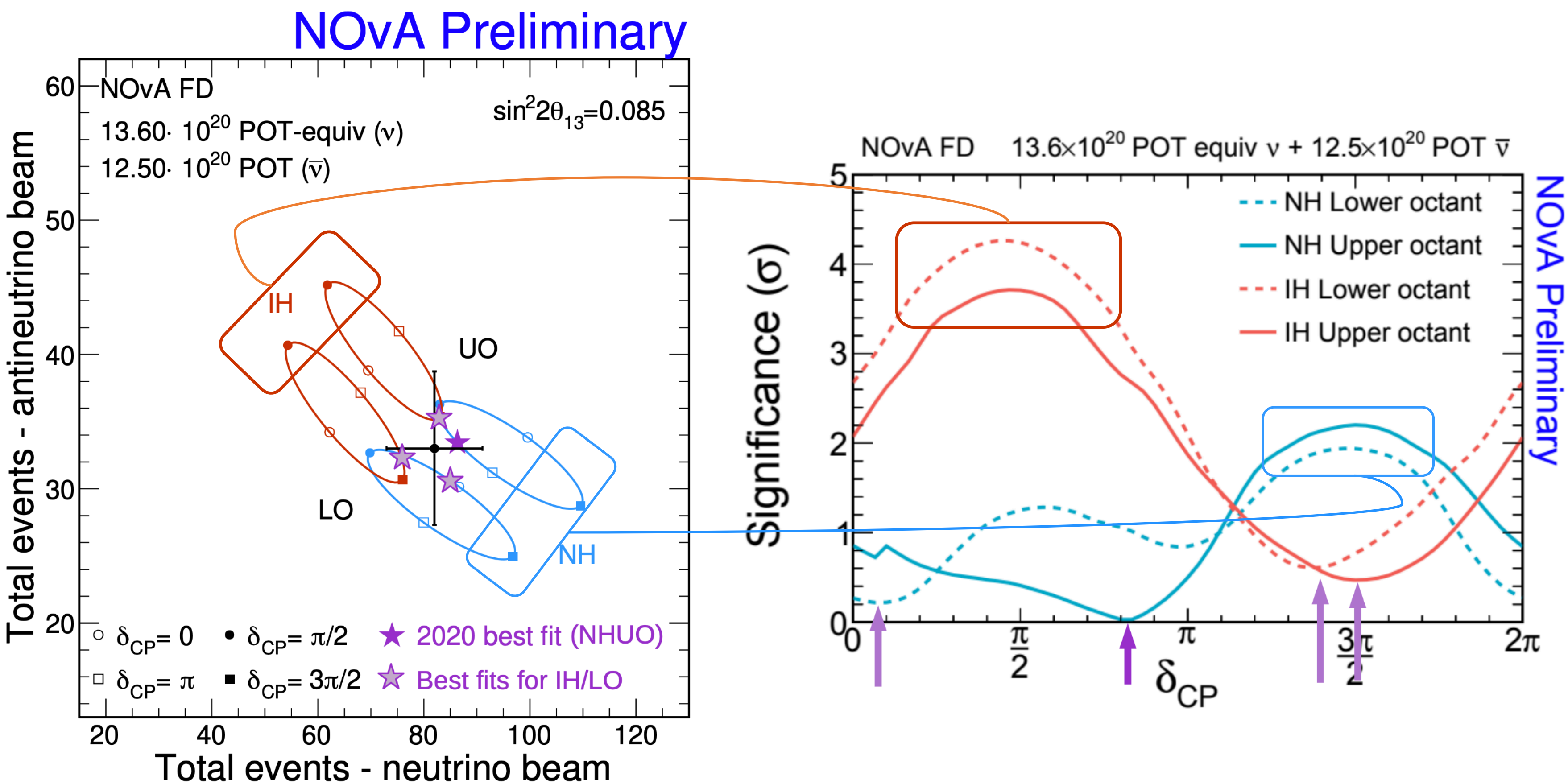
- Detector energy scale and response systematics dominate systematic uncertainty.
- **NOvA Test Beam** at Fermilab Test Beam Facility to study hadronic response.
- NOvA is currently taking ν beam data and the experiment is expected to run until 2025.
- **A 3σ hierarchy measurement is likely for 30-50% values of δ_{CP} parameter.**
- **NOvA-T2K joint analysis** is progressing with regular working group meeting and bi-annual workshops.

T2K-NOvA Joint Analysis Workshop, Fermilab

Irvine, California
February 2020

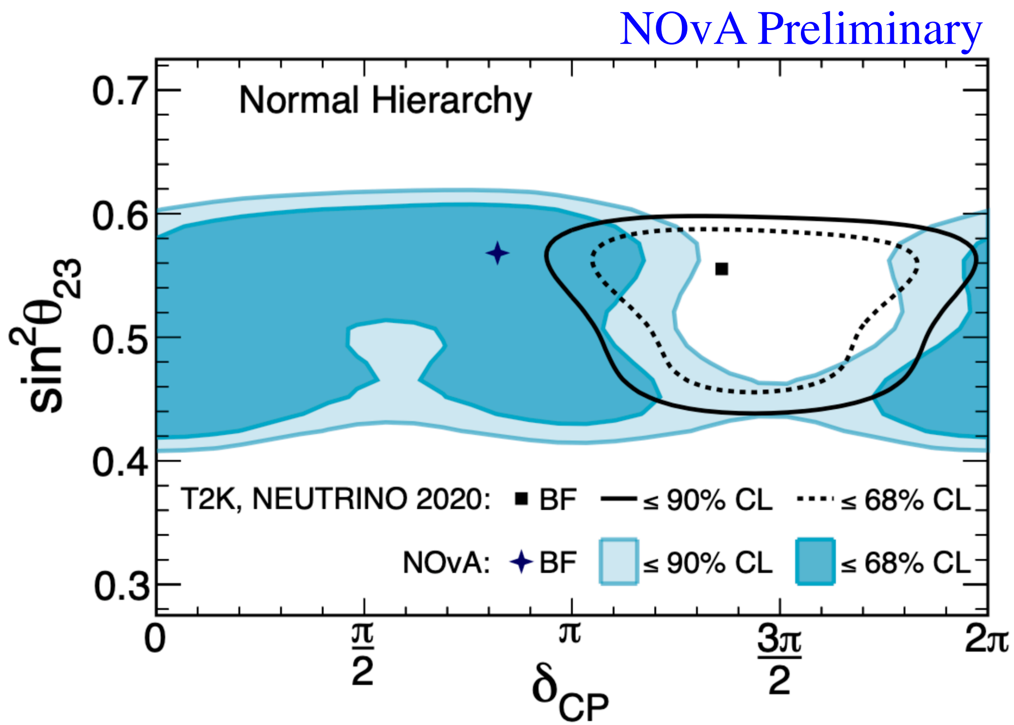
Supplementary Slides

Extracting Oscillation Parameters



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

NOvA and T2K



- T2K sees a large asymmetry in their ν_e and $\overline{\nu}_e$ appearance so their δ_{CP} best fit value is in *tension* with NOvA's best fit.
- NOTE : In the above plot, NOvA's contours are Feldman-Cousin corrected while T2K's are not. Not an exact comparison.

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

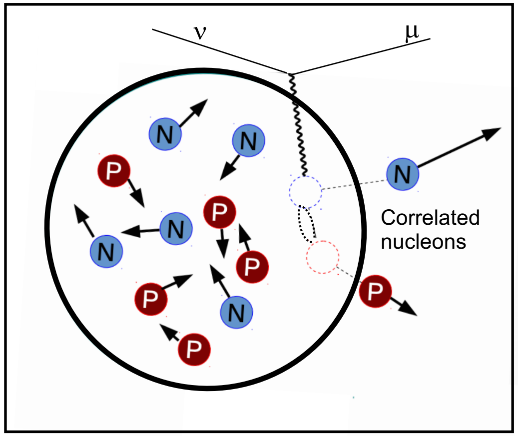
GENIE N1810j_0211a *

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

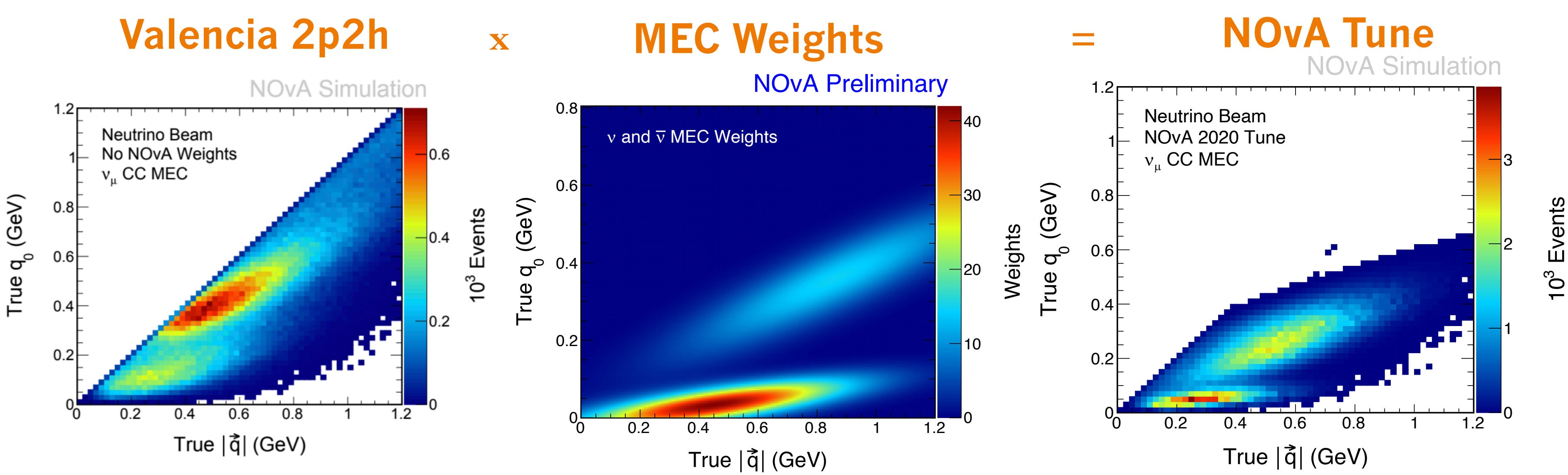
NINJA GENIE

*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

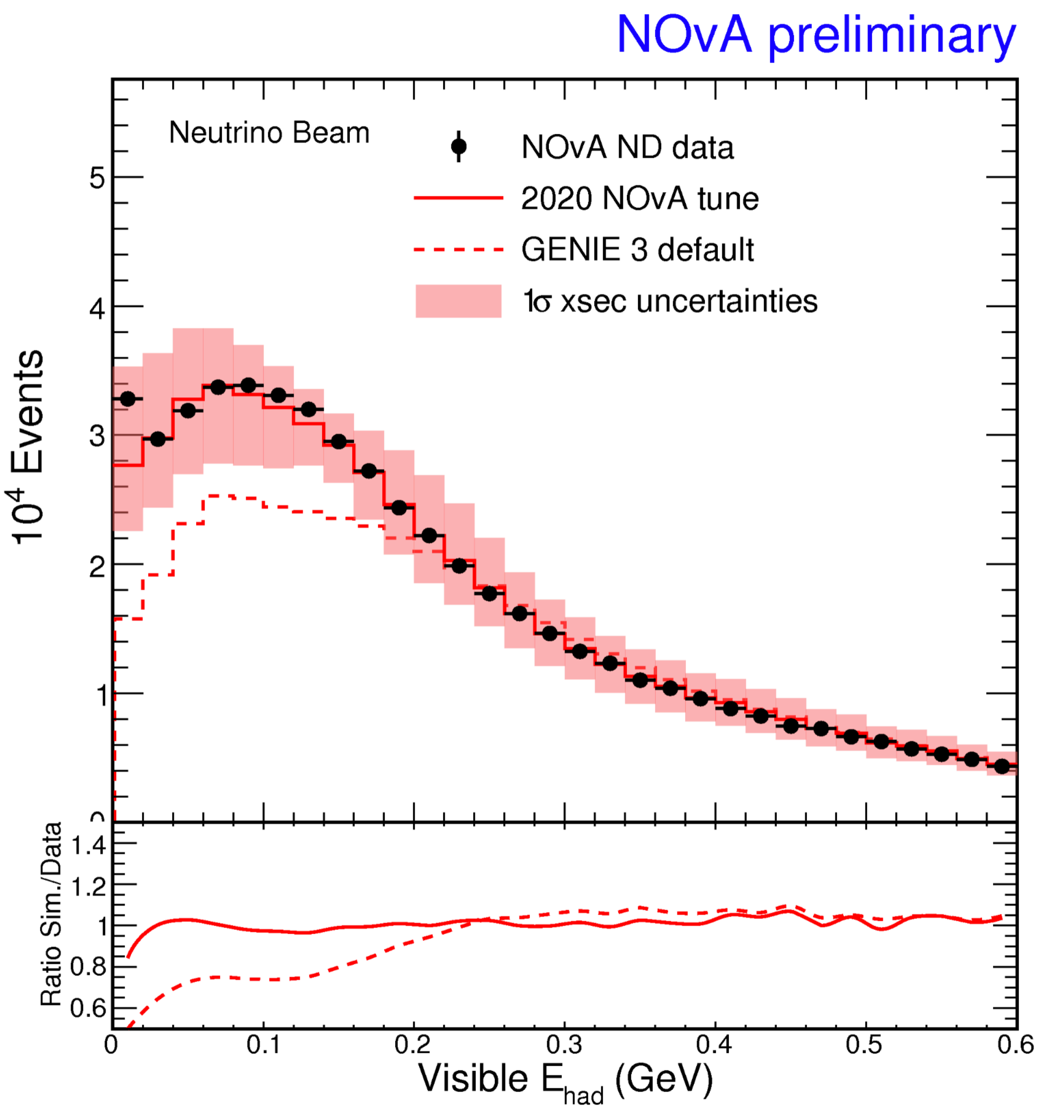
2p2h Tune



- "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.

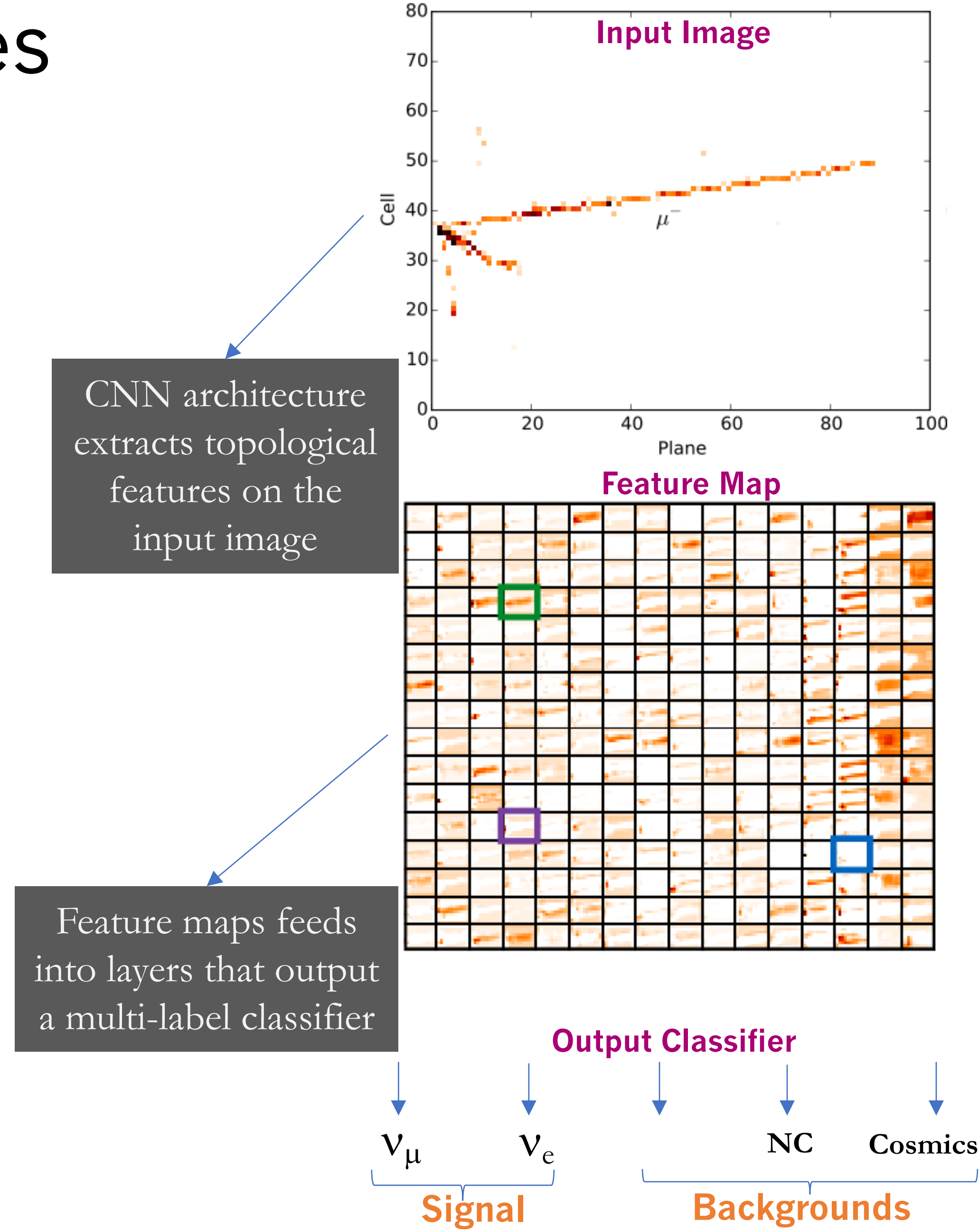


2p2h Tune : Systematics

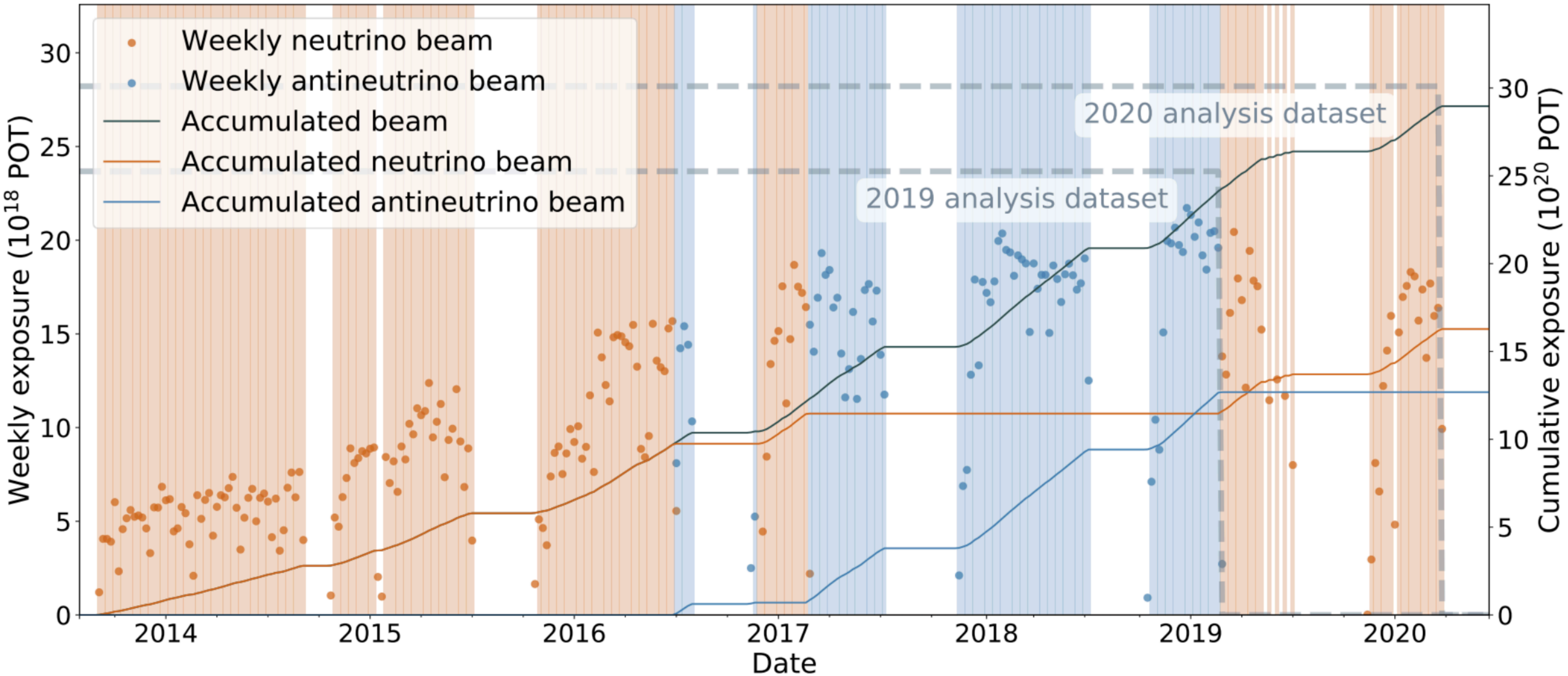


Identifying Particles

- A Convolution Neural Network called **Convolution Visual Network (CVN)** is used to ID particles.
- Calibrated Hits in various events topologies are provided to network as input pixel maps.
- The network classifies these events in desired output categories.
- FHC and RHC modes are trained separately.
- Cosmic data is included in the training sample.

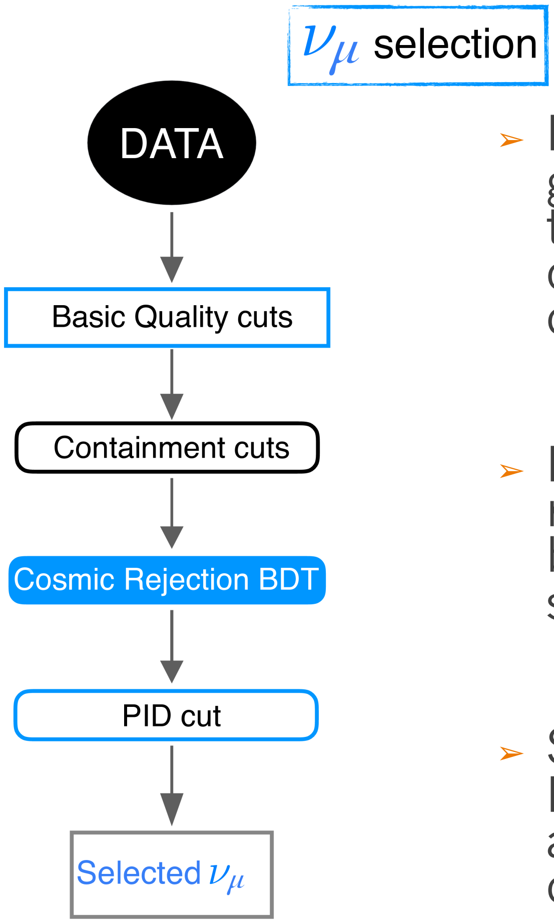


NuMI Beamline

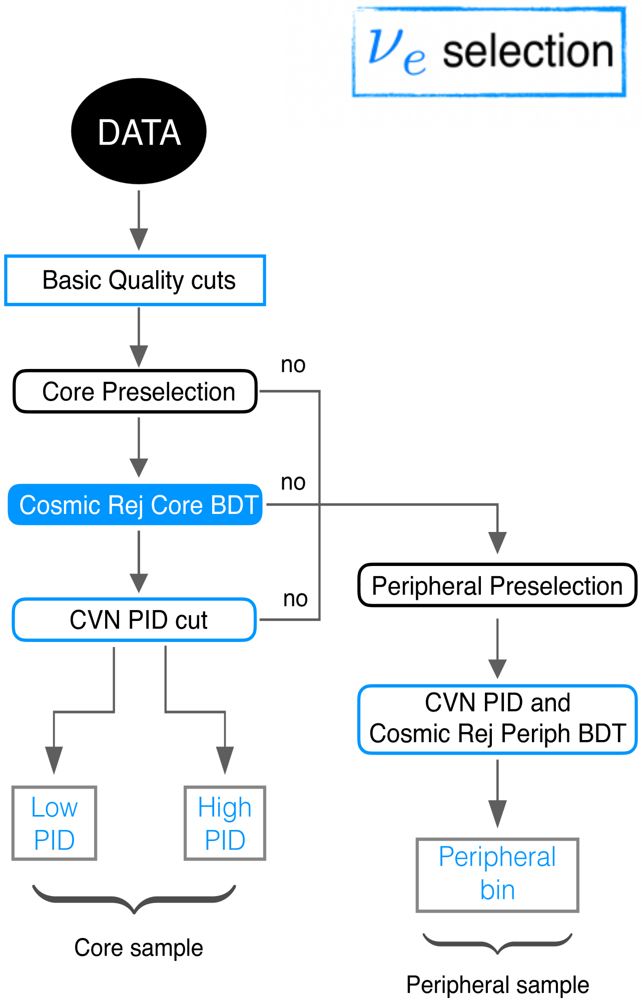


- The data analyzed for this analysis:
  - 13.6×10^{20} POT neutrino beam
  - 12.5×10^{20} POT anti-neutrino beam

Selecting ν_μ and ν_e events



- Pulsed beam along with good timing resolution of the detector and basic quality cut removes $O(10^5)$ cosmics.
- Further cosmic rejection is required to suppress this background compared to signal.
- Specially trained Cosmic BDTs and CVN particle IDs aid in achieving $O(1)$ cosmic events for $O(10)$ ν_e and $O(100)$ ν_μ signal events.



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!** Previous run from Jan – March 2020.