Neutrino Oscillation Results from NOvA

Jeremy Hewes, for the NOvA collaboration
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Neutrino oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

PMNS matrix

$$P(\nu_\alpha \to \nu_\beta) = \sum_i U^*_{\alpha i}U_{\beta i}U_{\alpha i}U^*_{\beta i} + \sum_{i\neq j} U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}e^{i\frac{\Delta m^2_{ji}L}{2E}}$$

- Parameterise with two mass terms, three angles and one phase:

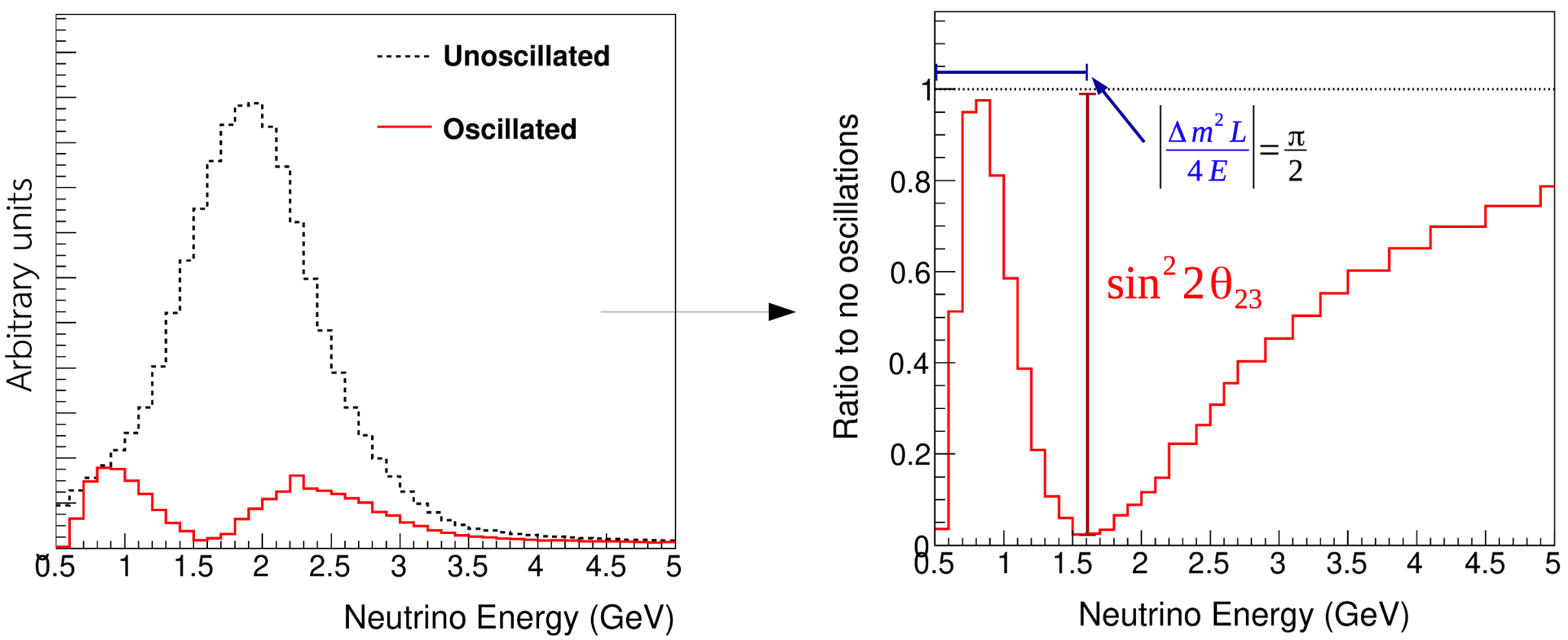
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & s_{13}e^{i\delta}\\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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

ν_μ Disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{32}[\mathrm{eV}^2] L_\nu [\mathrm{km}]}{E_\nu [\mathrm{GeV}]}\right)$$

- Only sensitive to atmospheric mixing parameters **θ_{23}** and **Δm^2_{32}**.
- Mixing angle gives amplitude of oscillation dip, while mass splitting dictates its location in energy.

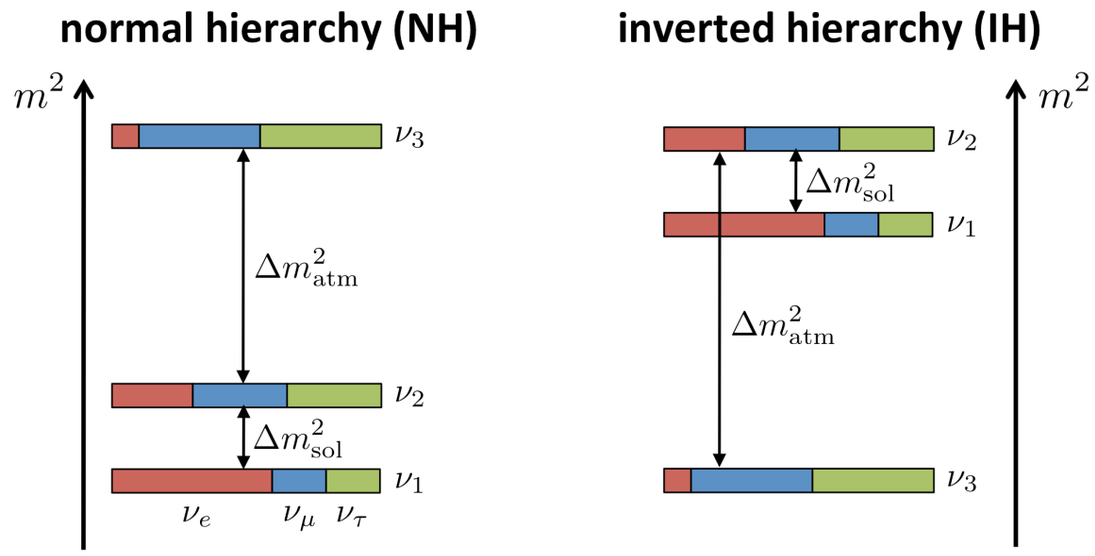


ν_e Appearance

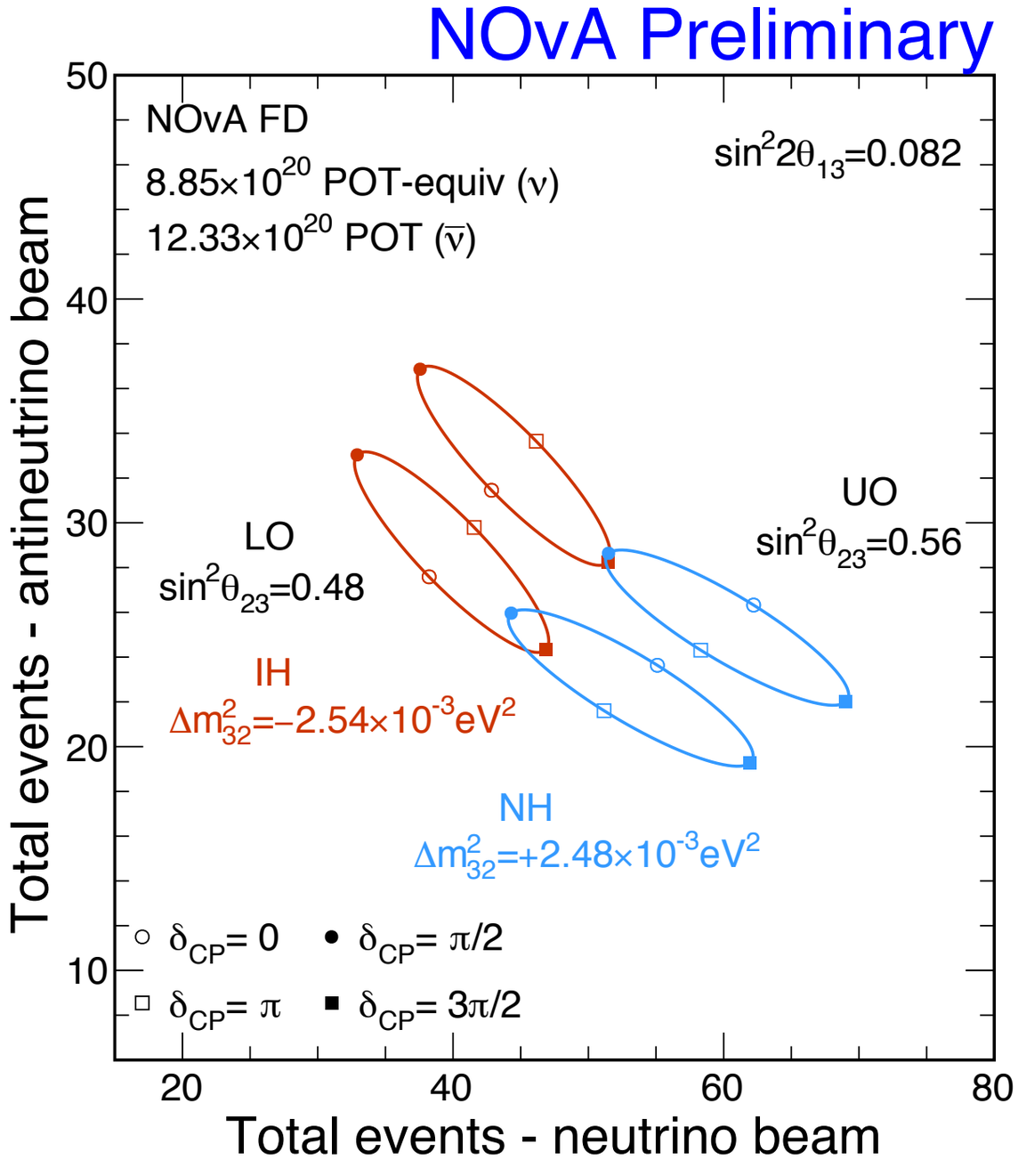
$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2\Delta(1-A)}{(1-A)^2}$$
$$+\alpha \tilde{J} \cos(\Delta \pm \delta_{cp}) \frac{\sin\Delta A}{A} \frac{\sin\Delta(1-A)}{(1-A)}$$
$$+\alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2\Delta A}{A^2}$$

$$\tilde{J} = \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$
$$A = \pm\sqrt{2} G_F n_e E_\nu / \Delta m^2_{13}$$
$$\Delta = \Delta m^2_{31} L_\nu / 4E_\nu$$
$$\alpha = \Delta m^2_{21} / \Delta m^2_{31}$$

- Sensitive to all oscillation parameters.
- **Matter effects** and **δ_{cp}** are **CP-odd** terms, meaning they move in opposite directions for neutrinos and antineutrinos.
- Maximise sensitivity to **δ_{CP}** and **mass hierarchy (MH)** by looking at both neutrino and antineutrino beams, and comparing the two.



Resolving Degeneracies

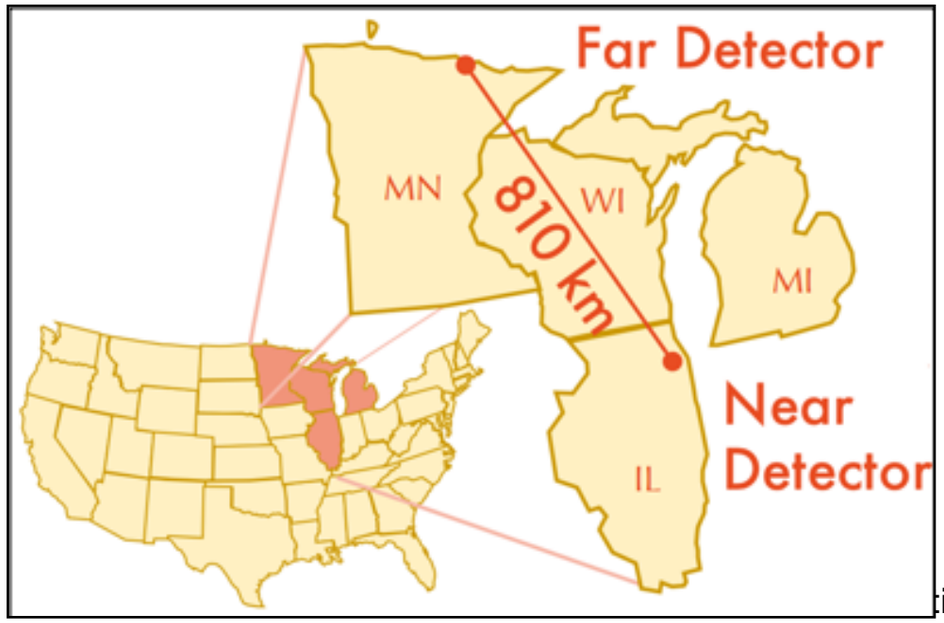


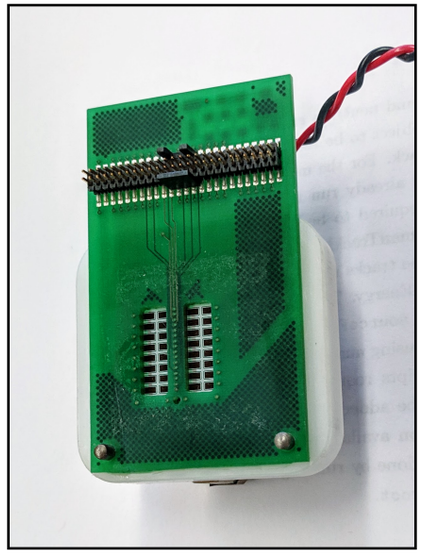
- Both neutrino and antineutrino beam suffer degeneracies due to the interplay of θ_{23}, δ_{cp} and the **mass hierarchy**.

- Measuring both and fitting simultaneously gives us an additional constraint to help break this degeneracy.

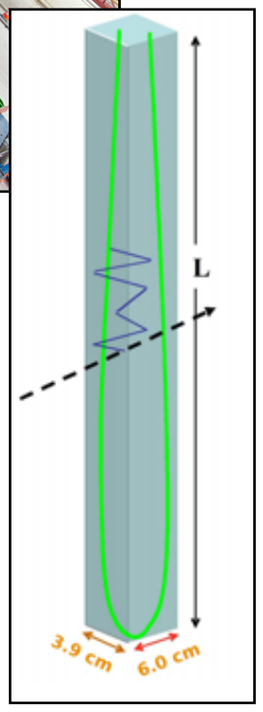
The NOvA Experiment

- **NOvA** is a long-baseline accelerator experiment based at Fermilab.
- Measures neutrinos from Fermilab's **NuMI beam**.
- Functionally identical near and far detectors.
  - Plastic and liquid scintillator **sampling tracking calorimeter**.
  - **ND:** 1km baseline, FNAL, 300 tons.
  - **FD:** 810km baseline, Ash River, 14 kt, 14 mrad off-axis.

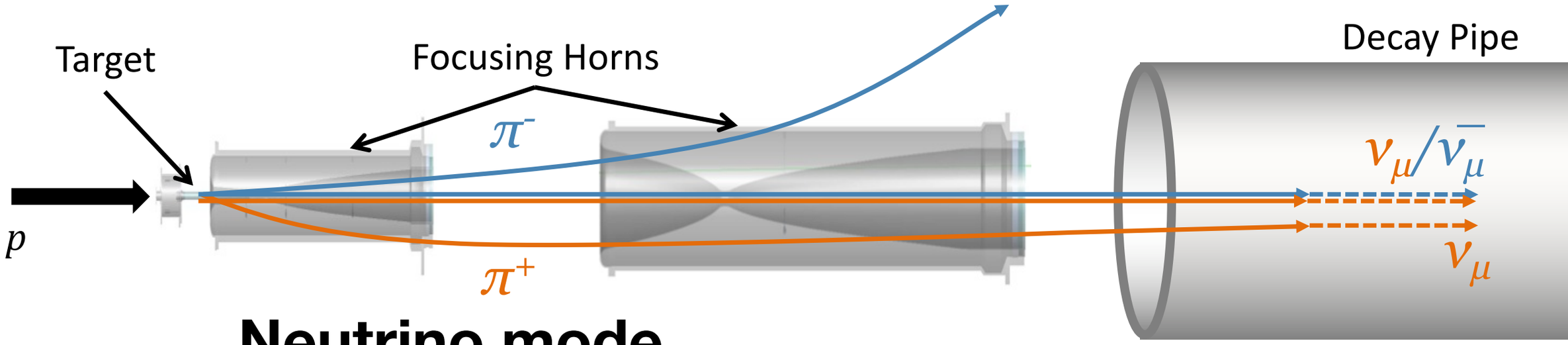




- Charged particles produce light when propagating through scintillator.
- Picked up by wavelength-shifting fibers (right) and amplified by avalanche photodiodes (left).

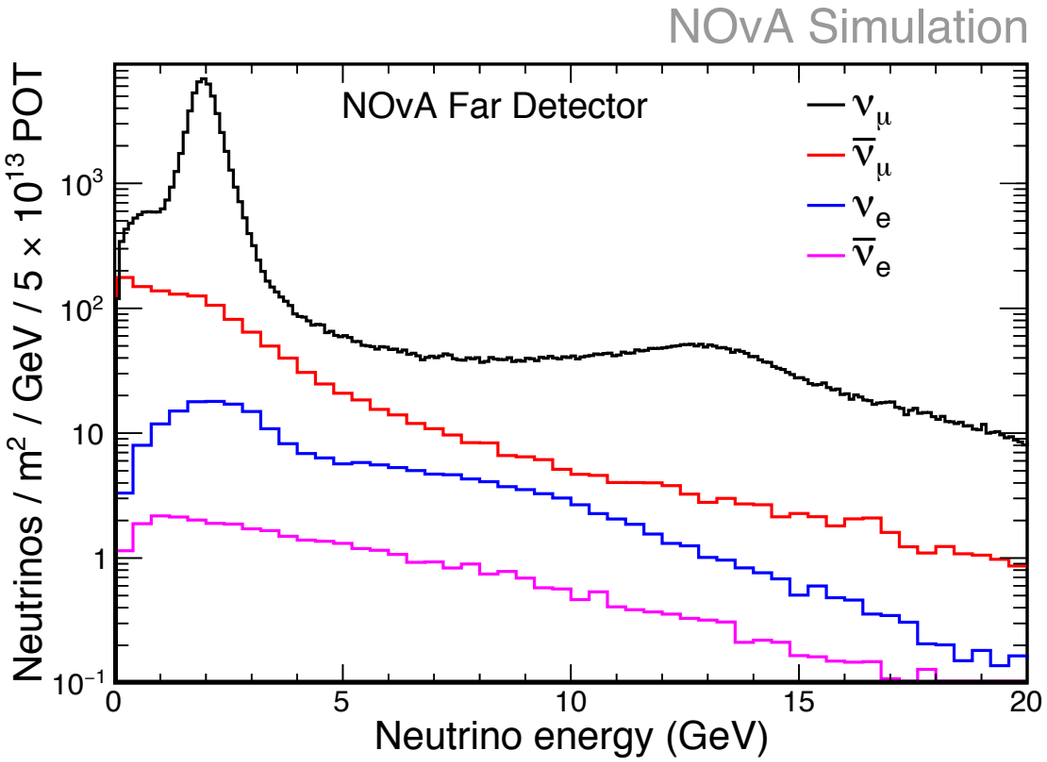


The NuMI Beam

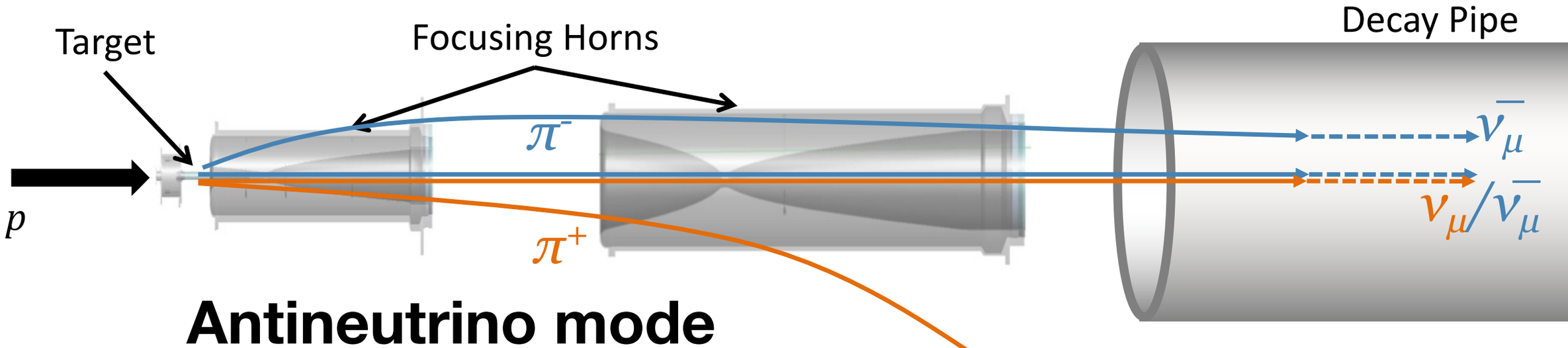


Neutrino mode

- Protons accelerated at Fermilab's Main Injector.
- These protons are incident on a target, and interact to produce **pions** and **kaons**.
- π & κ focused using magnetic horns.
- Focused π & κ decay in flight to neutrinos.
- Magnet polarity allows us to select a primarily **neutrino** or **antineutrino** beam.

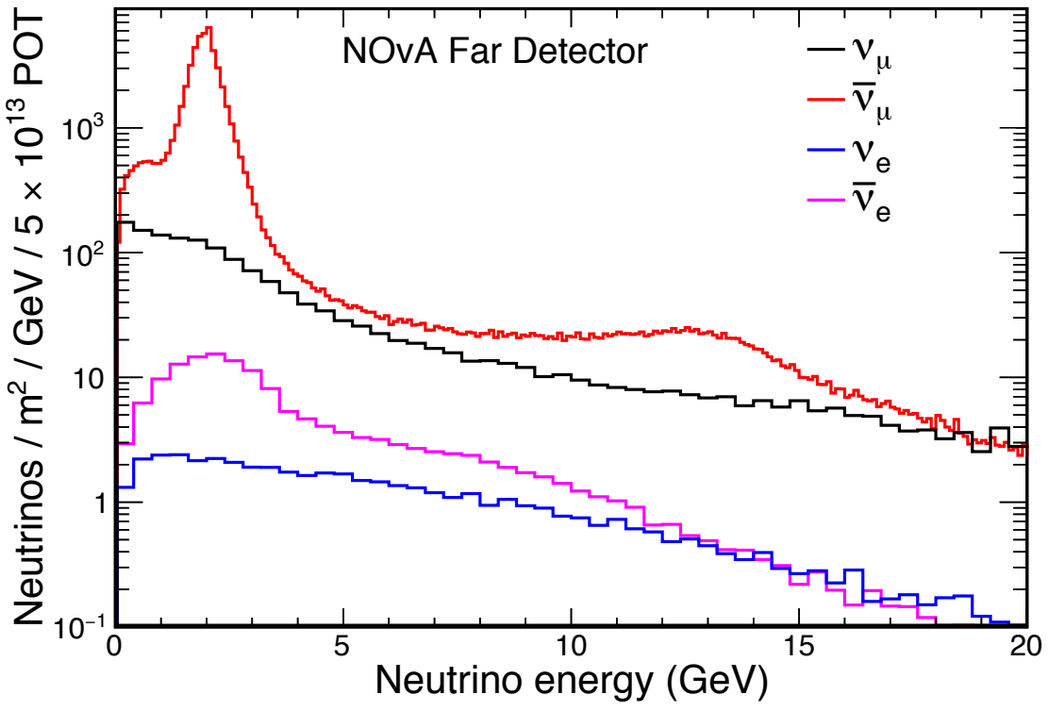


The NuMI Beam

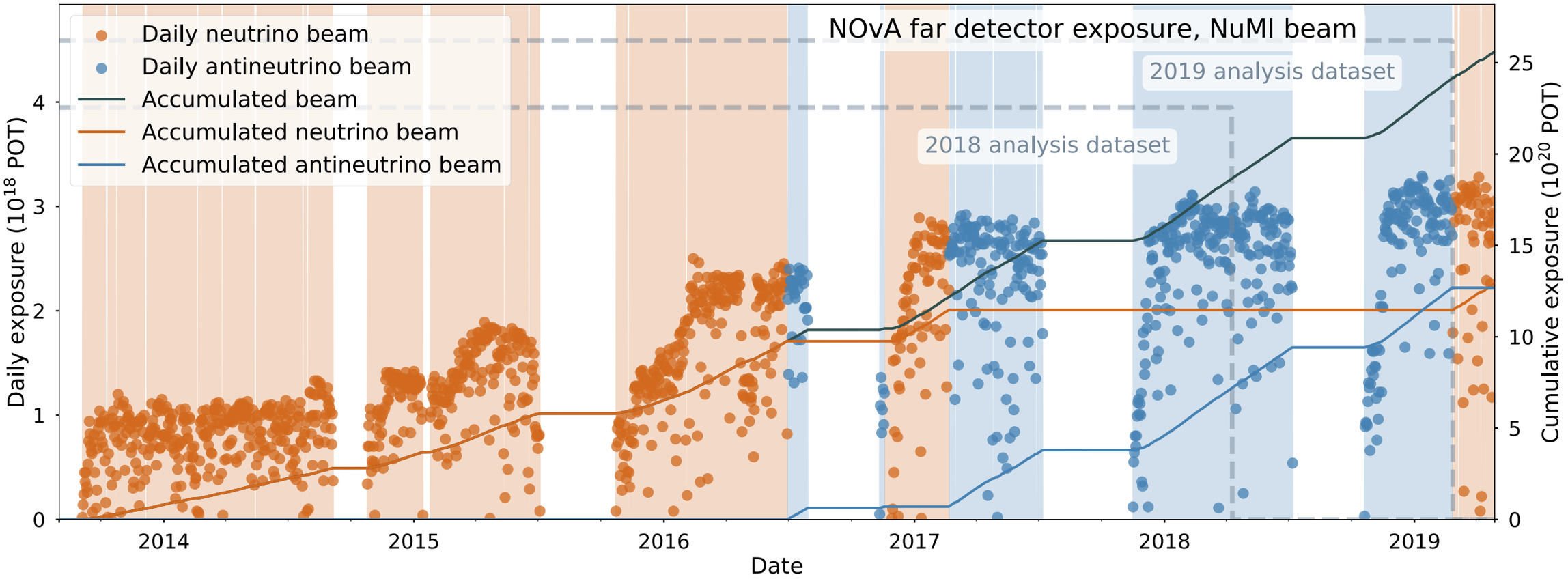


Antineutrino mode

- Protons accelerated at Fermilab's Main Injector.
- These protons are incident on a target, and interact to produce **pions** and **kaons**.
- π & κ focused using magnetic horns.
- Focused π & κ decay in flight to neutrinos.
- Magnet polarity allows us to select a primarily **neutrino** or **antineutrino** beam.



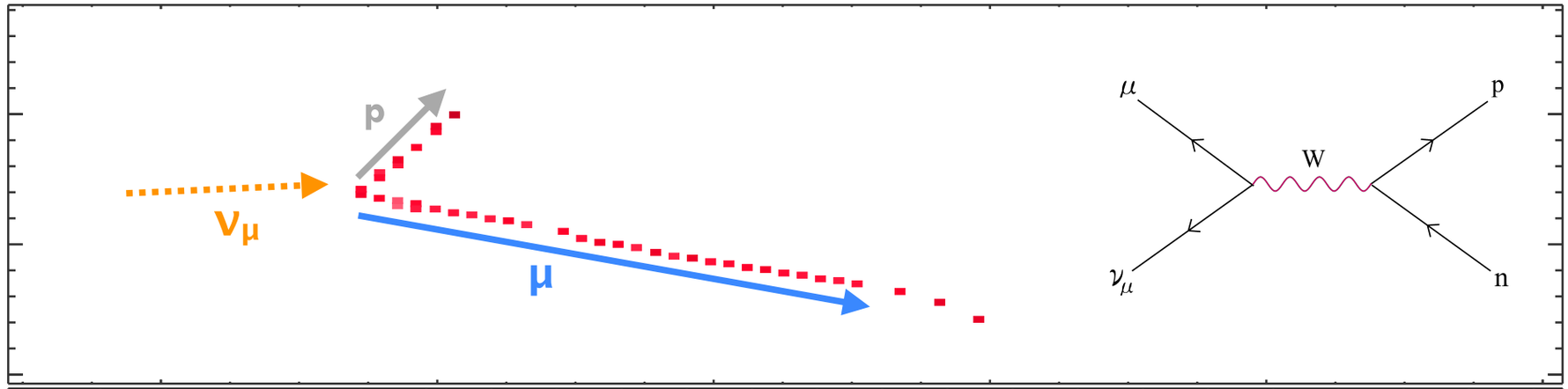
Accumulated Dataset



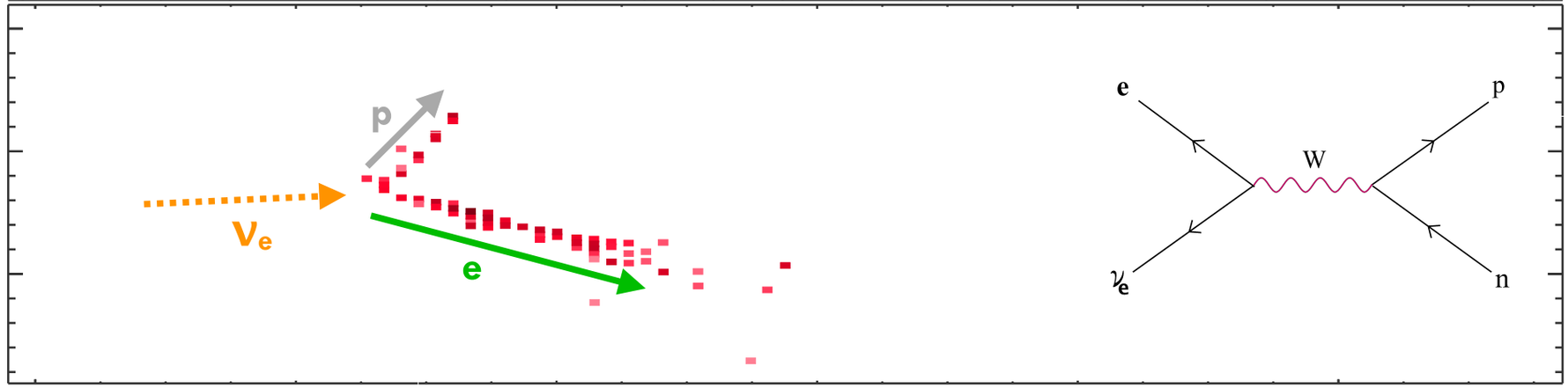
- NOvA has collected data in both neutrino and antineutrino beam modes.
  - In this result we use **8.9 x 10^{20} POT** in neutrino mode and **12.3 x 10^{20} POT** in antineutrino mode.
- NOvA is actively running and accumulating more statistics in neutrino beam mode.

Interaction Topologies

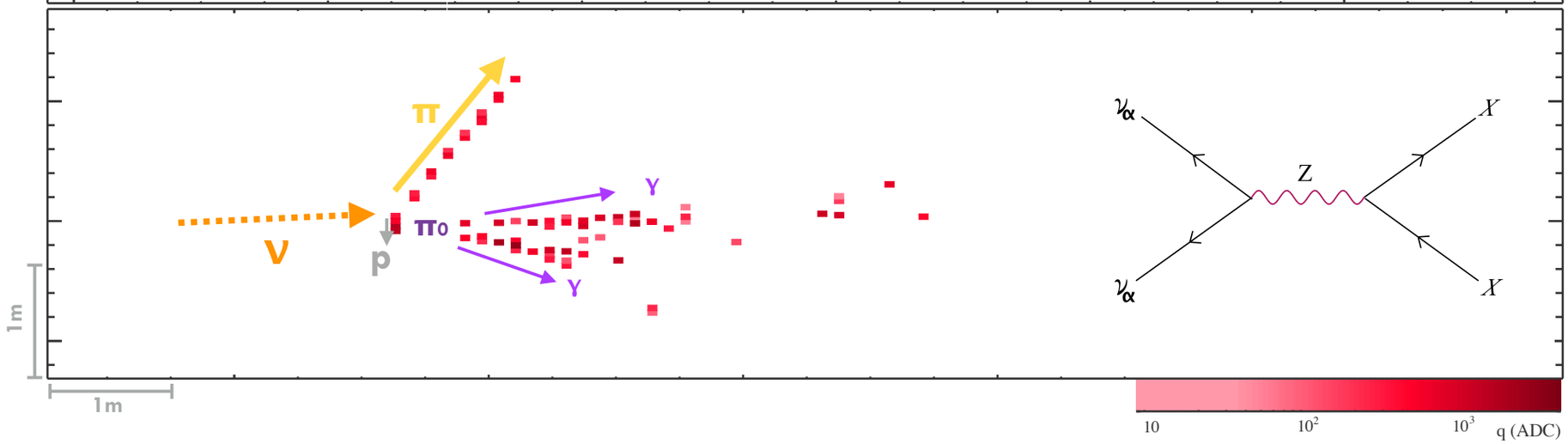
ν_μ CC



ν_e CC

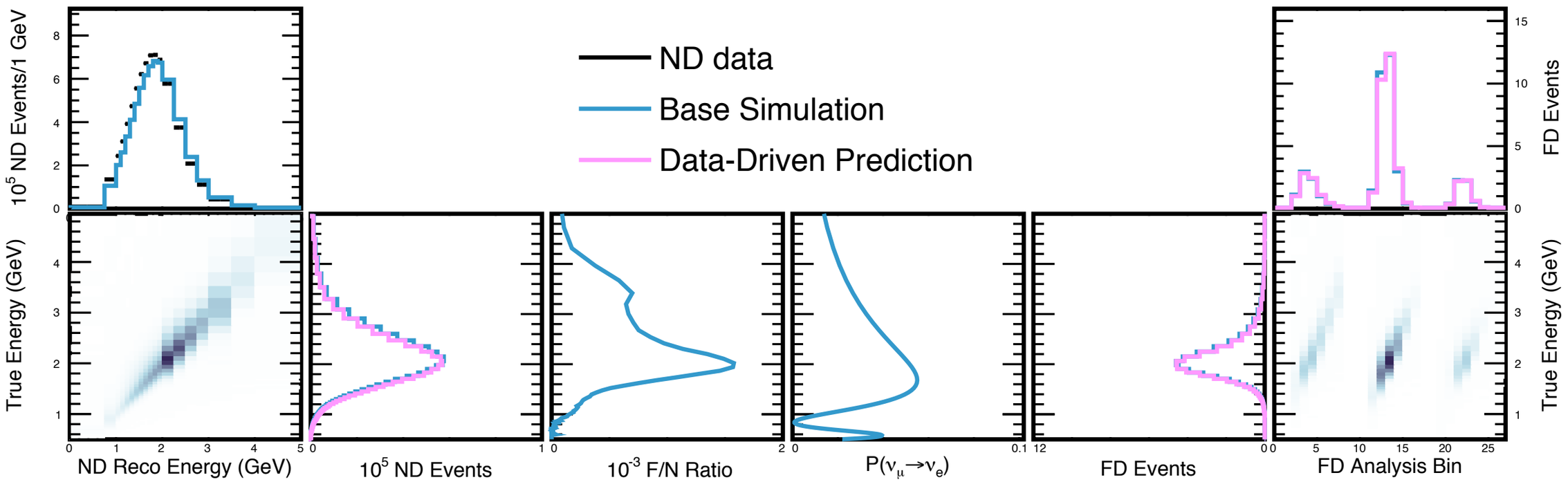


NC

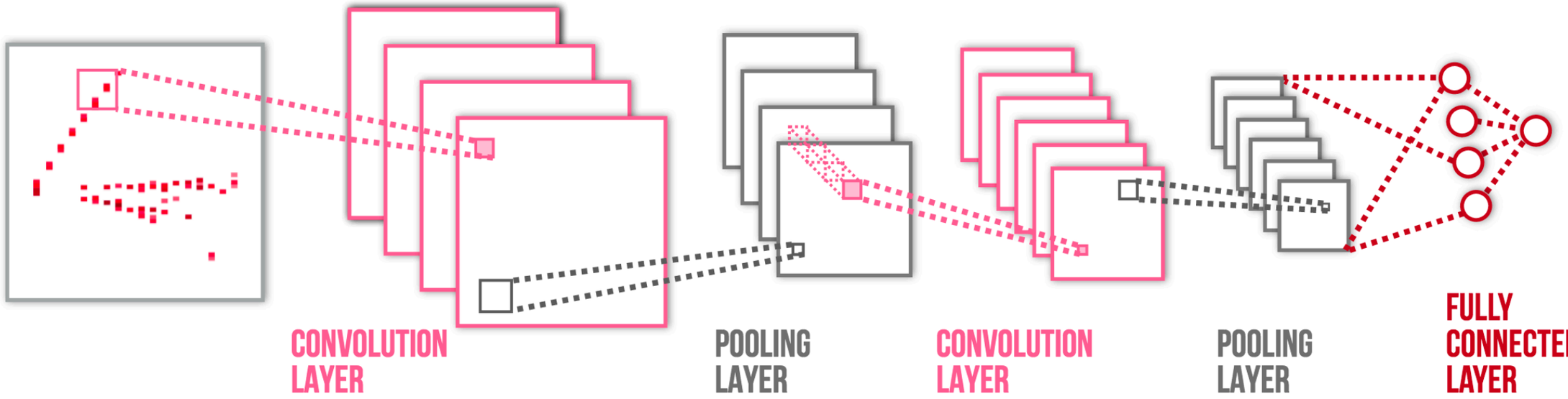


Data-Driven Prediction

- Produce **data-driven Far Detector prediction** using **Near Detector data**.
  - Reweight ND simulated true energy spectrum to match reconstructed energy data spectrum.
  - Apply ratio accounting for beam divergence and detector acceptances.
  - Apply oscillation probabilities.
  - Smear FD prediction from true to reconstructed energy.



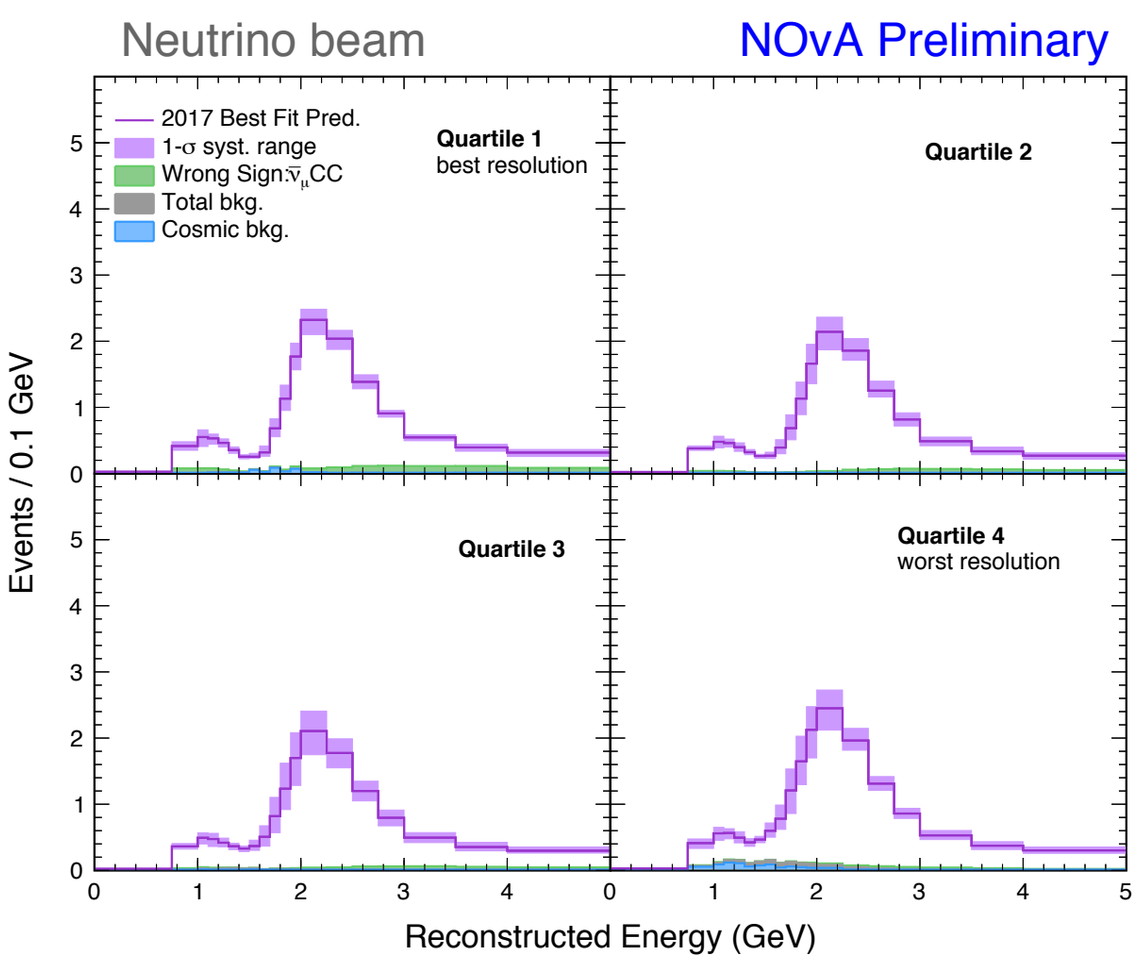
Convolutional Visual Network

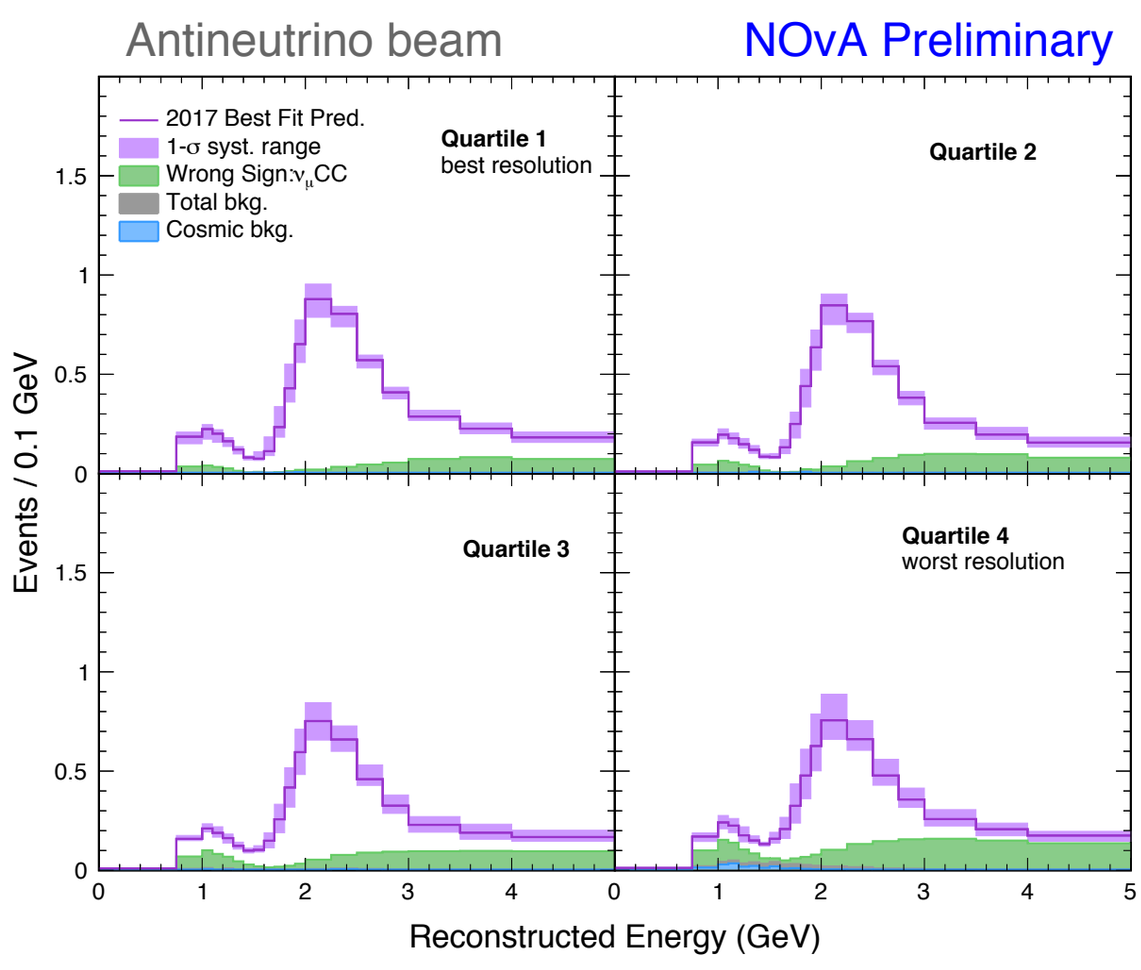


- Event identification is performed by our **CVN** (Convolutional Visual Network).
- CVN is an **event classifier** that employs a convolutional neural network in the "image recognition" style.
- The network is **trained on two-dimensional views** of the event's **calibrated hits**.
- Information from each view is then combined in the final layers of the network.
- CVN is **trained separately on neutrinos and antineutrinos**.

ν_μ Disappearance Prediction

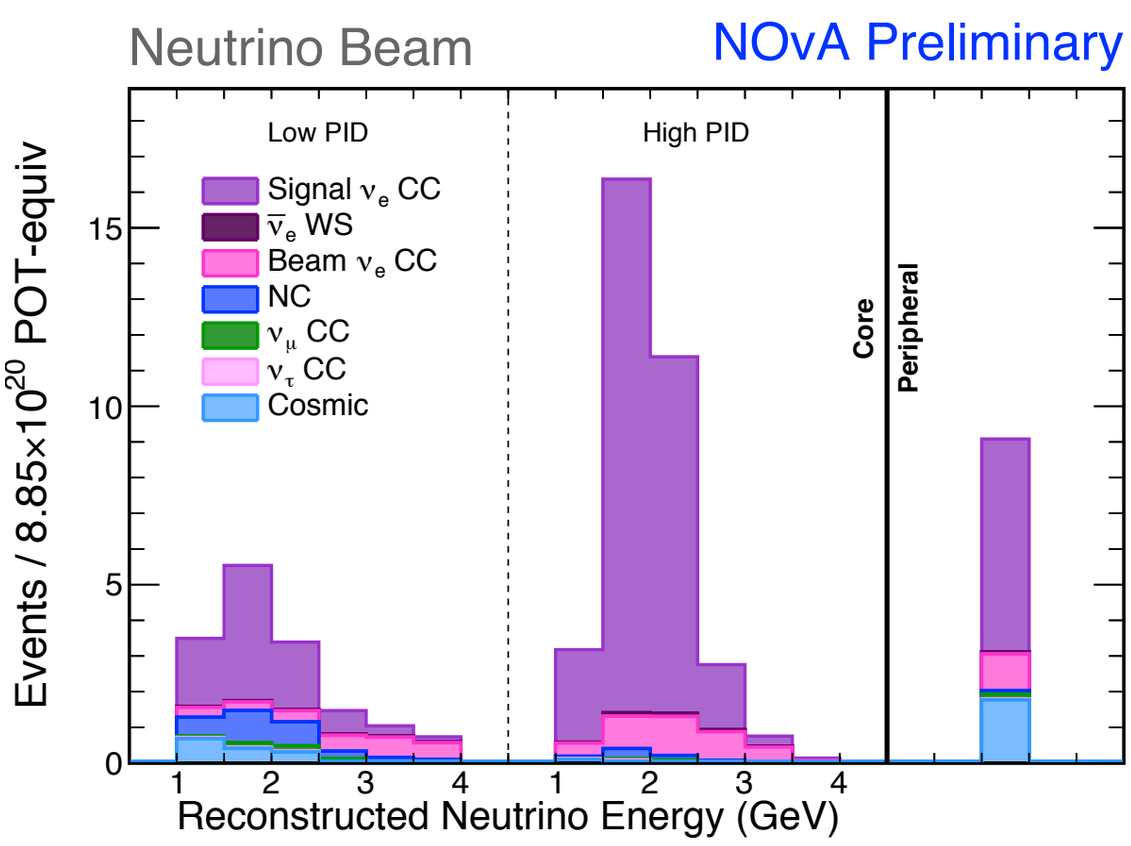
- Apply low-level quality cuts and Boosted Decision Tree (BDT) for cosmic rejection.
- Select ν_μ events using kNN muon ID and CVN classification.
- Spectrum divided into **four quantiles** according to hadronic energy fraction.

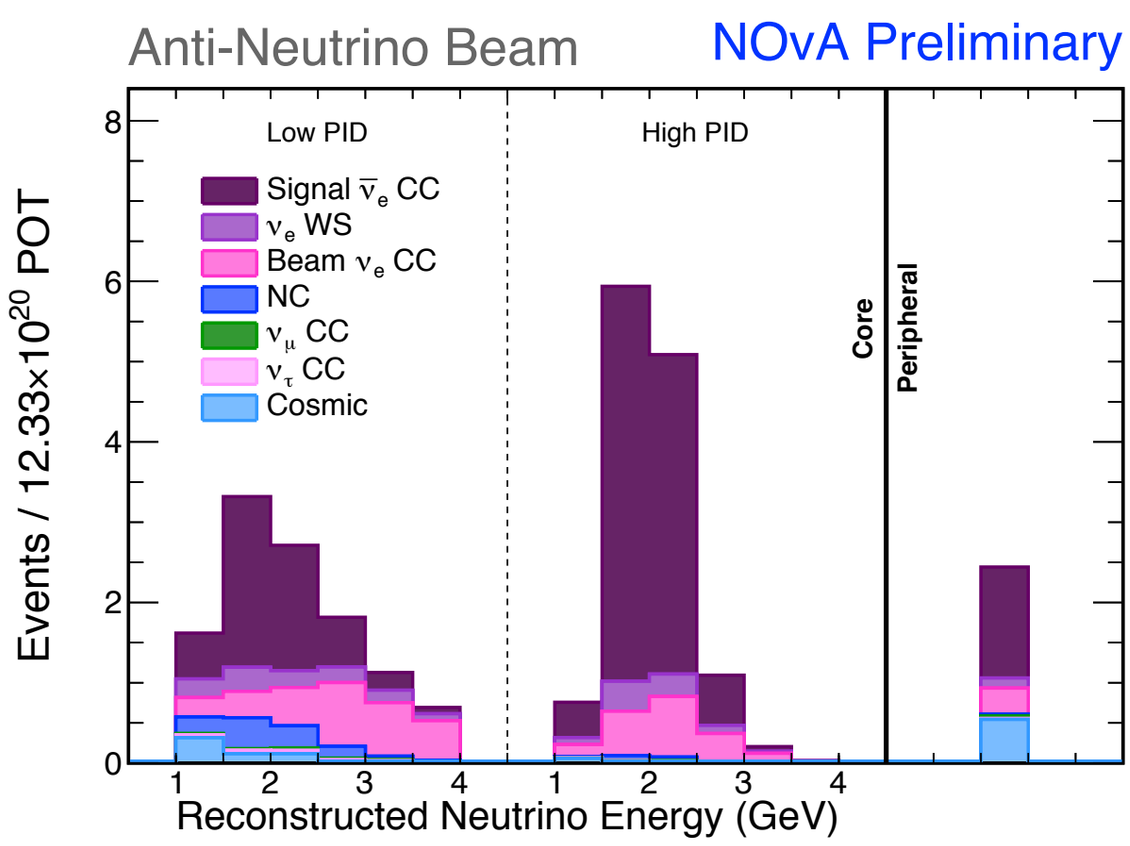




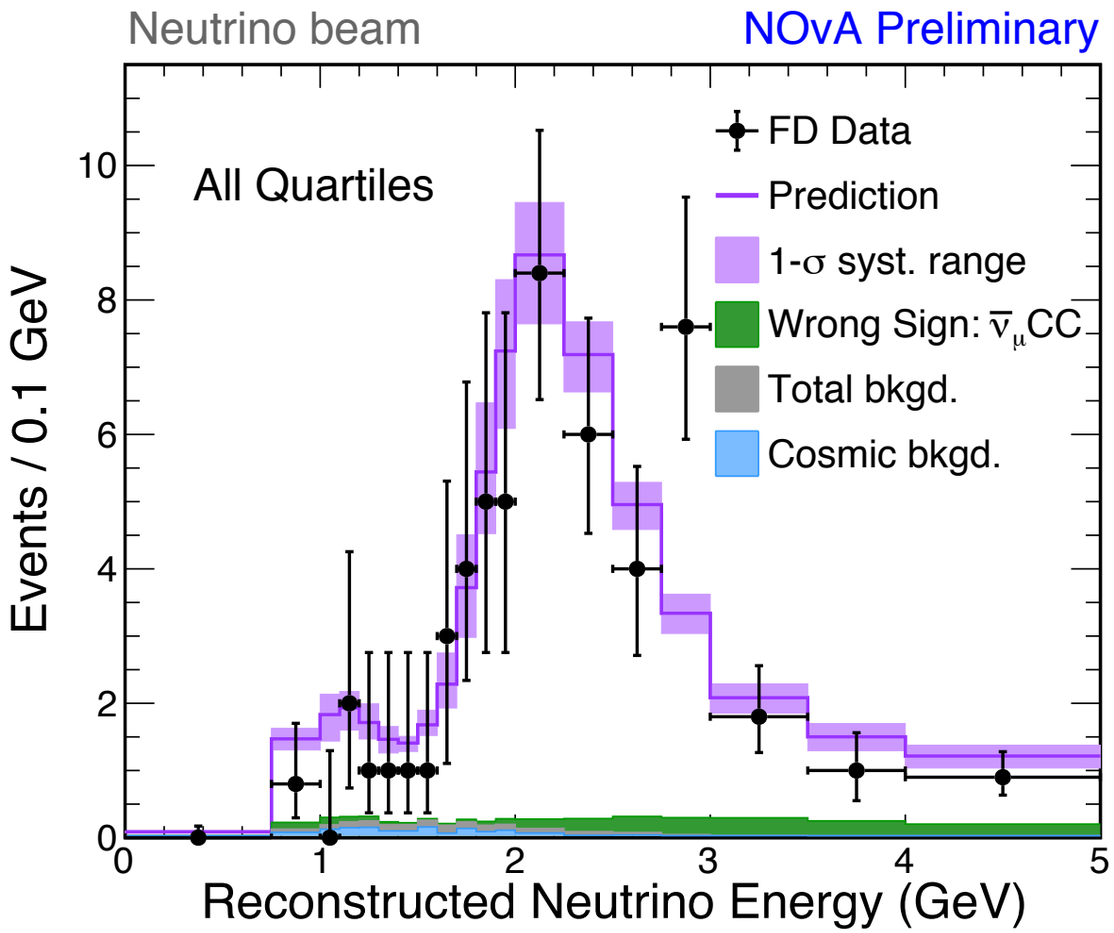
ν_e Appearance Prediction

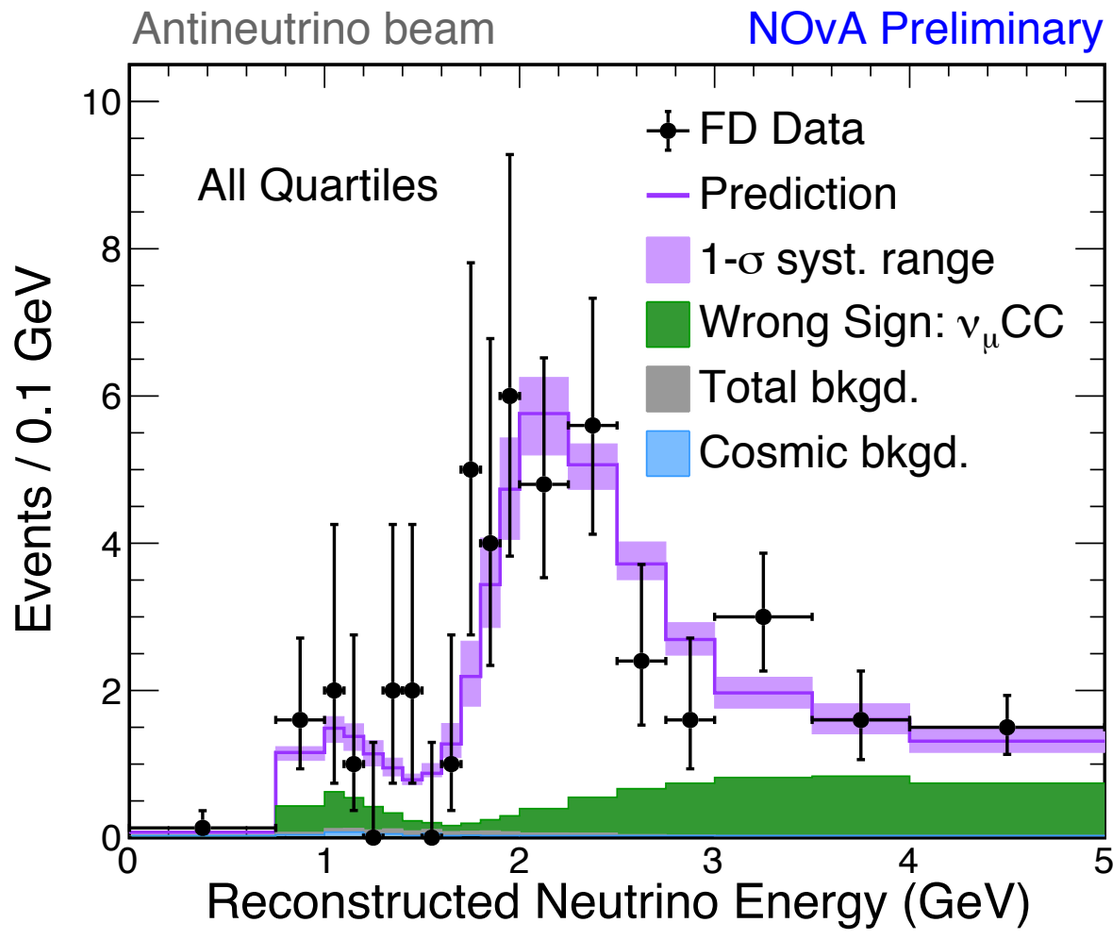
- Apply low-level quality cuts and Boosted Decision Tree (BDT) cosmic rejection.
- ν_e spectrum separated into **high PID** and **low PID** bins using CVN.
- An additional peripheral sample is included which adds events that fail lower-level cuts if their PID score is sufficiently high.





ν_μ Disappearance Results



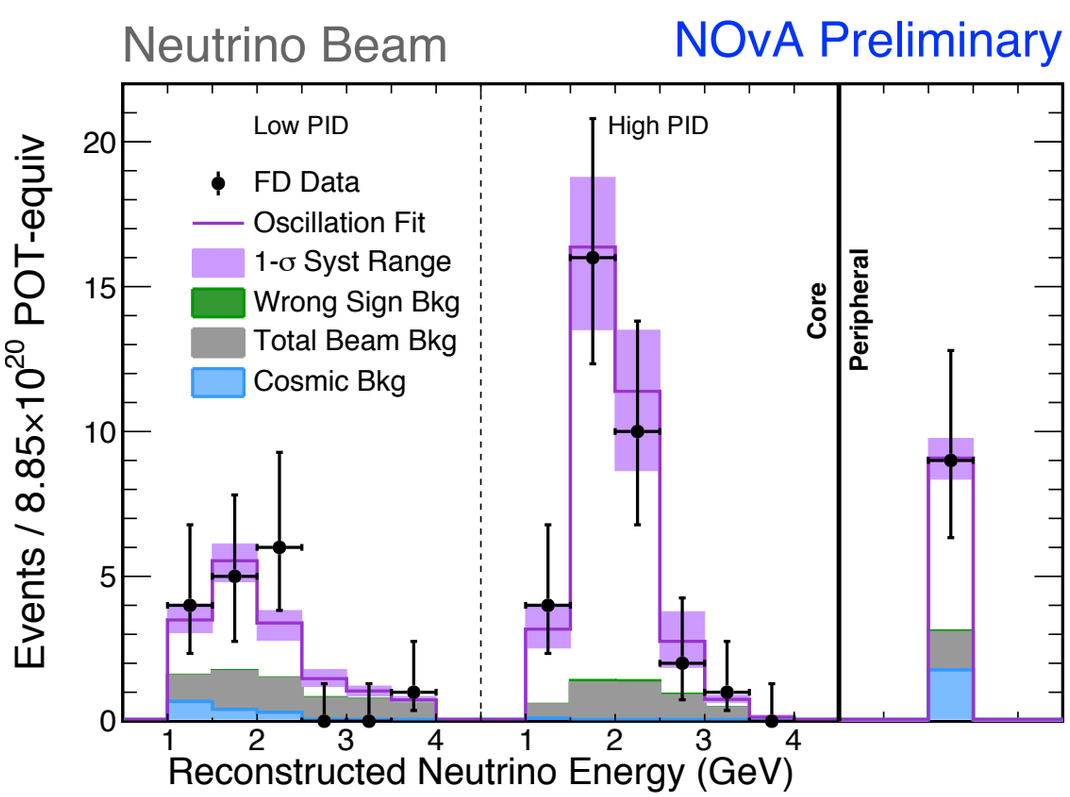


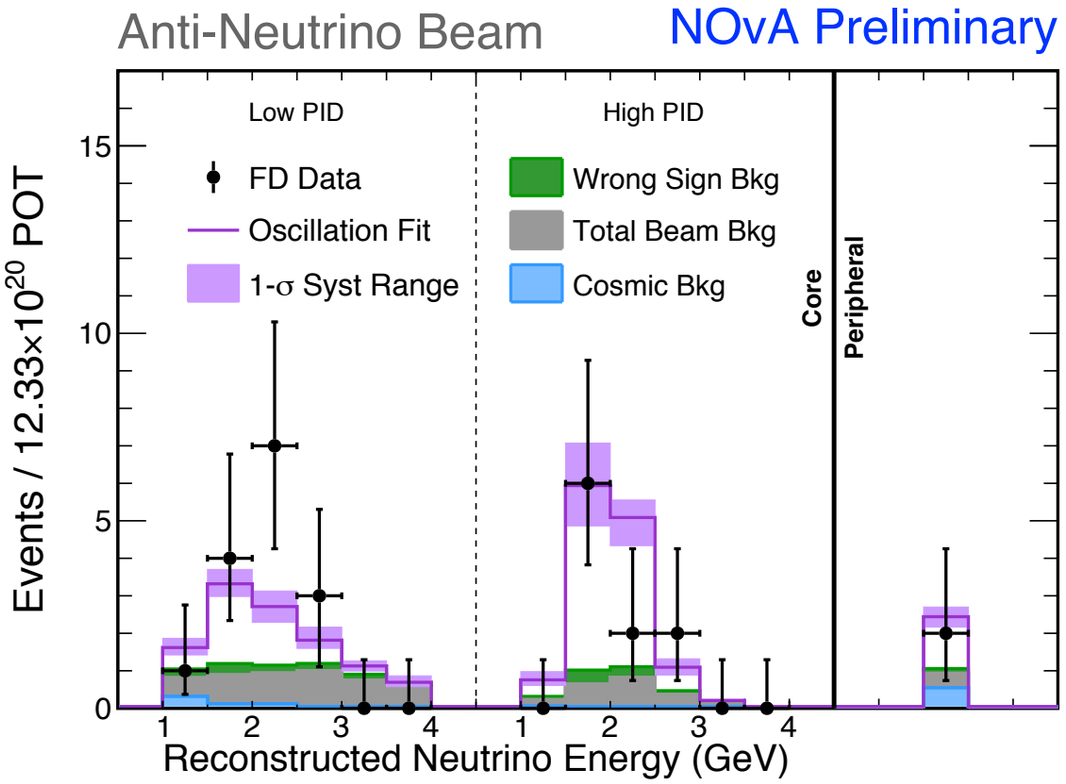
Observed	113
Total prediction (best fit)	123.9
Cosmic background	2.1
Beam background	1.4
Unoscillated prediction	730.2

Observed	102
Total prediction (best fit)	96.2
Cosmic background	0.8
Beam background	0.8
Unoscillated prediction	475.6

ν_e Appearance Results

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



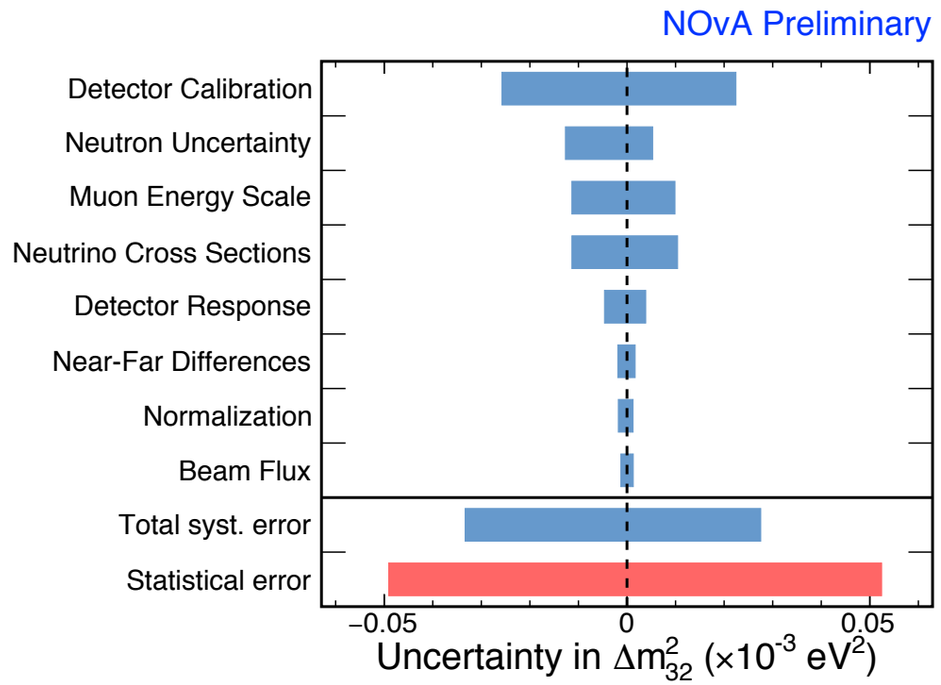


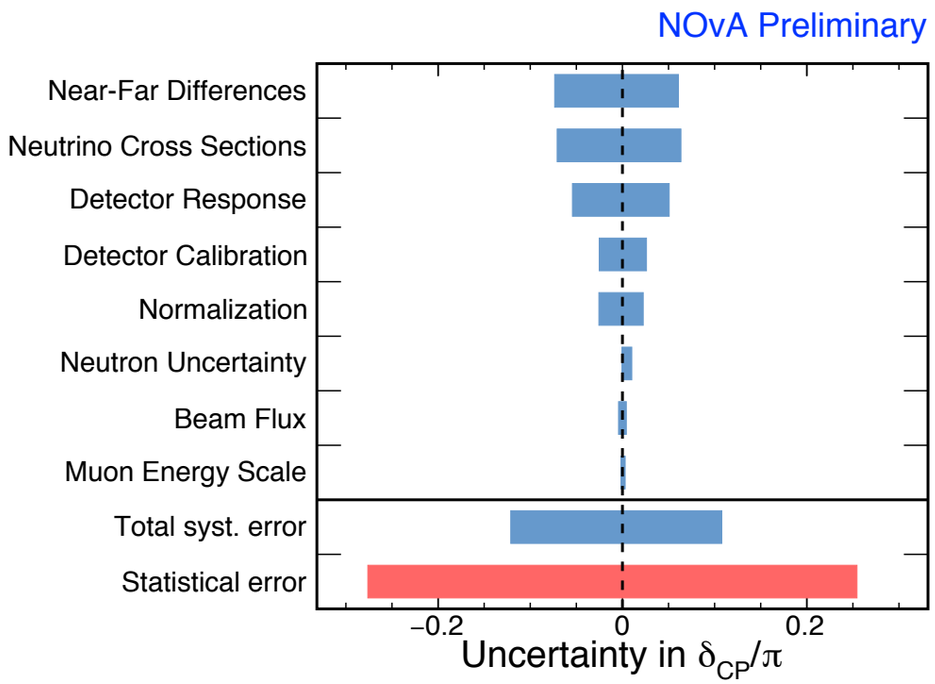
Observed	58
Total prediction (best fit)	59.3
ν_e	44.3
$\bar{\nu}_e$	0.6
Beam background	10.8
Cosmic background	3.3

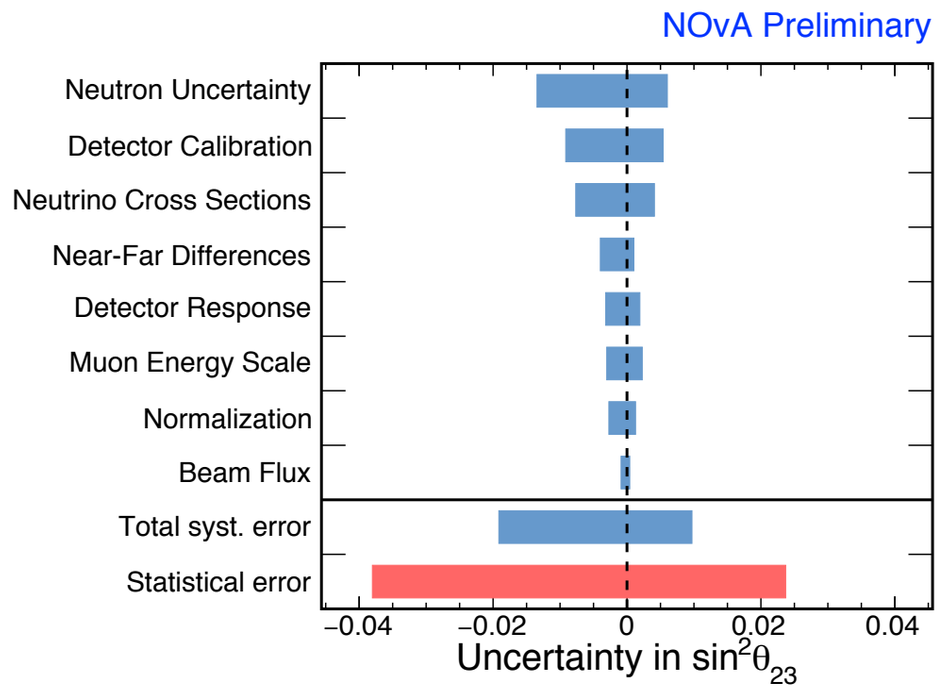
Observed	27
Total prediction (best fit)	26.8
$\bar{\nu}_e$	16.6
ν_e	2.2
Beam background	6.7
Cosmic background	1.1

Systematic Uncertainties

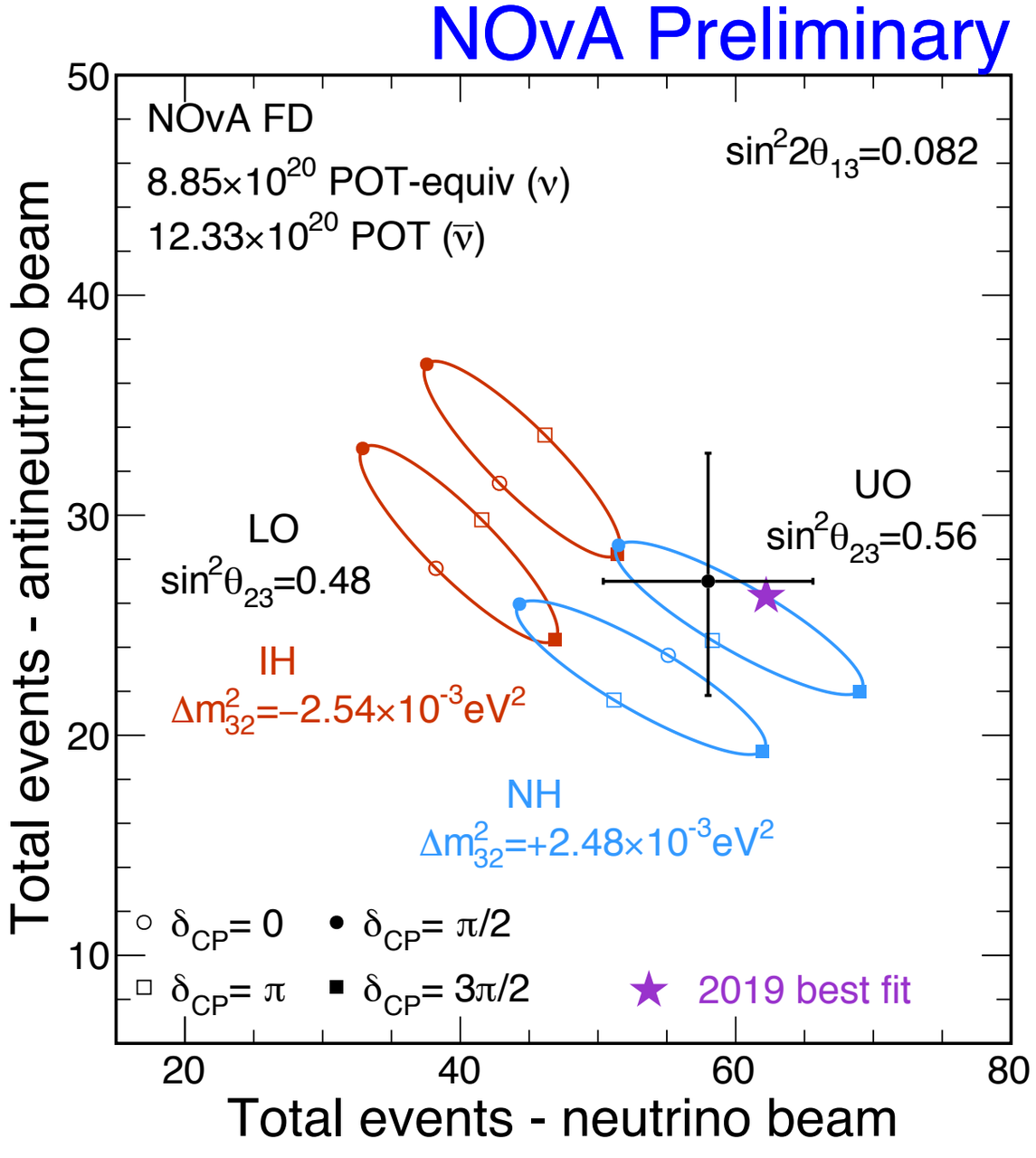
- Statistically limited.
- Dominant sources of systematic uncertainty are:
  - **Detector calibration**
  - **Neutrino interactions**
  - **Neutron detection**







Resolving Degeneracies

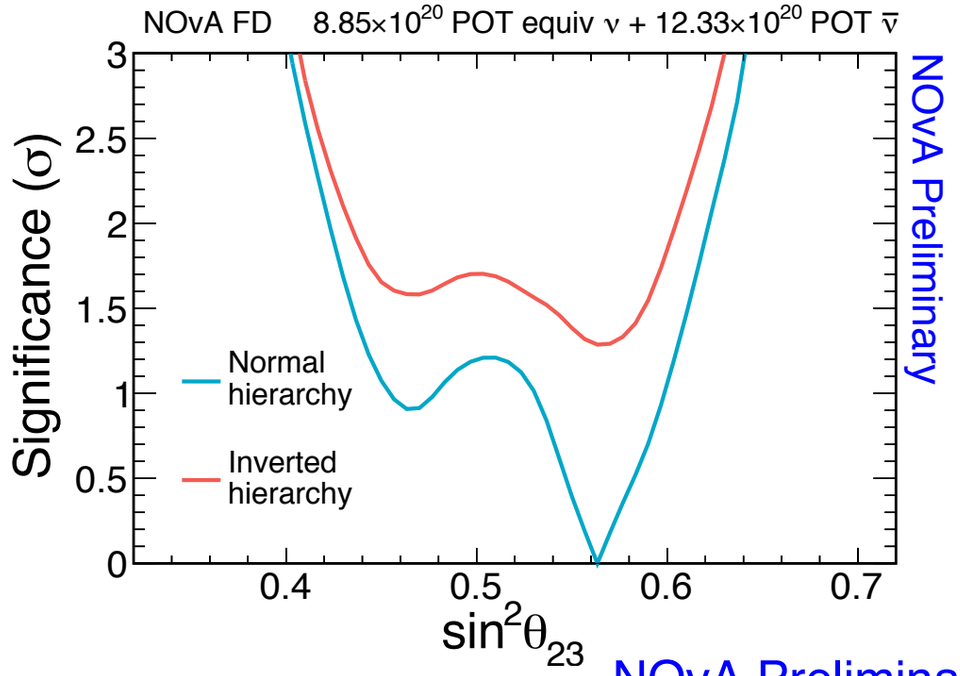


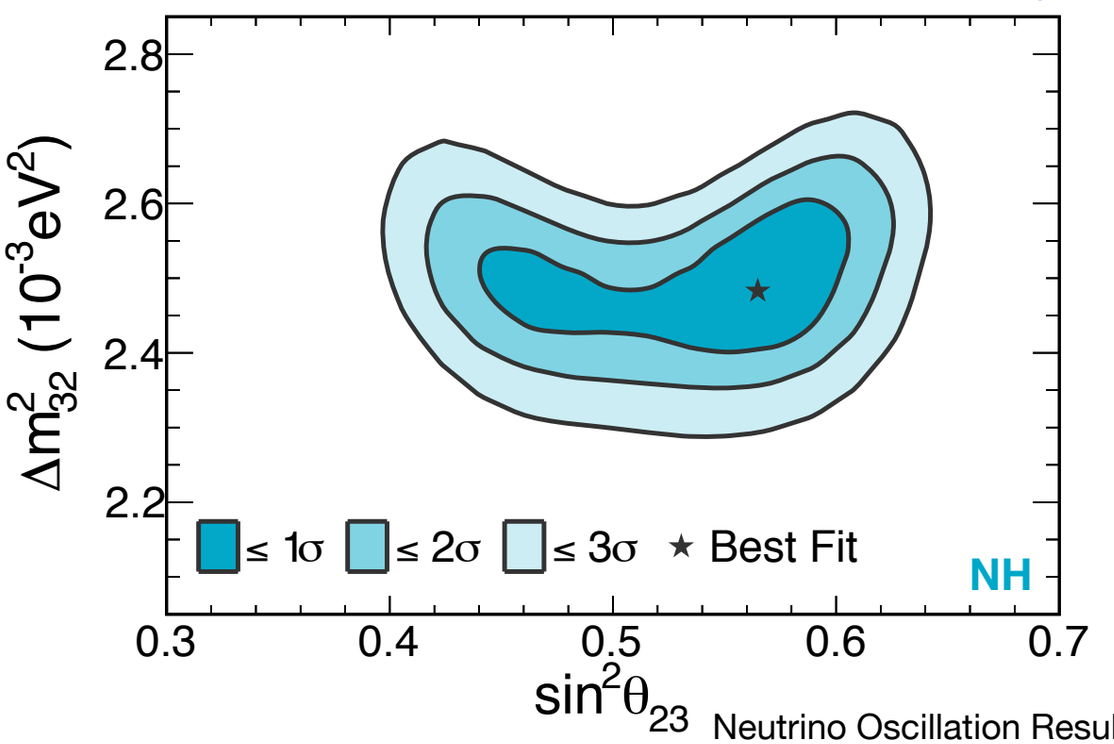
- Both neutrino and antineutrino beam suffer degeneracies due to the interplay of θ_{23}, δ_{cp} and the **mass hierarchy**.

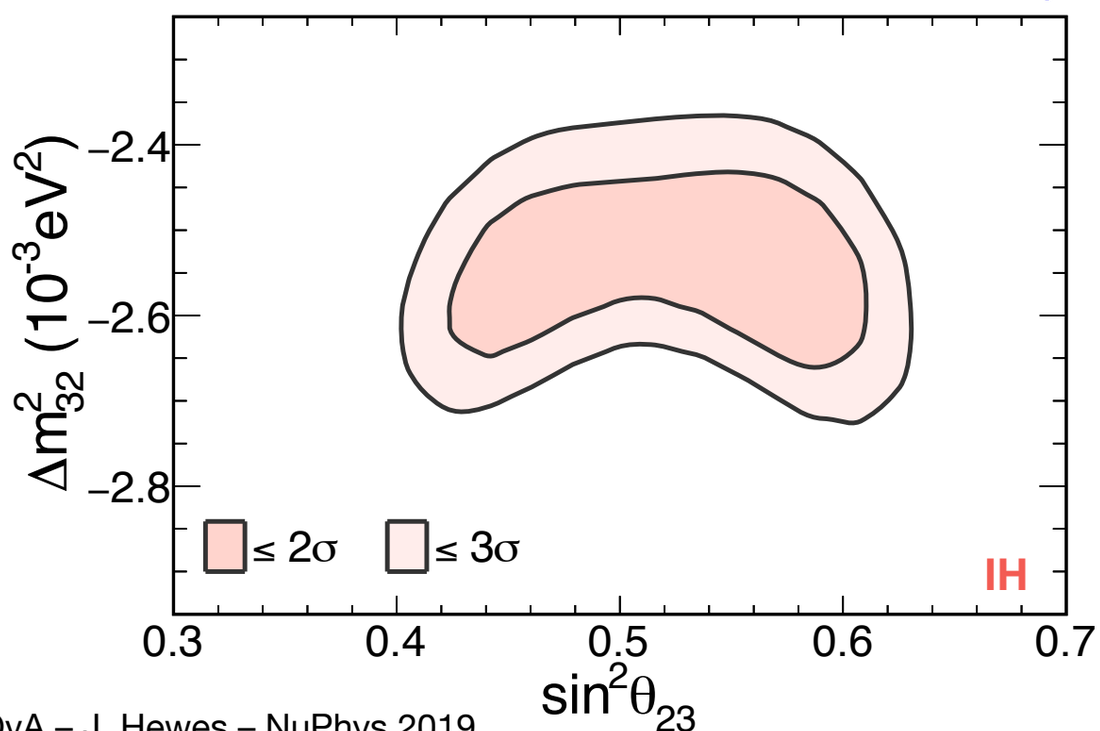
- Measuring both and fitting simultaneously gives us an additional constraint to help break this degeneracy.

ν_μ & ν_e Joint Fit: θ_{23} & Δm^2_{32}

- All systematic uncertainties, FC corrected.
- Prefer **upper octant of θ_{23}** at **1.6σ**.
- Prefer **normal mass hierarchy** at **1.9σ**.
- Best fits:
  - **$\Delta m^2_{32} = 2.48\ (+0.11/-0.06) \times 10^{-3}\ eV^2$**
  - **$\sin^2\theta_{23} = 0.56\ (+0.04/-0.03)$**

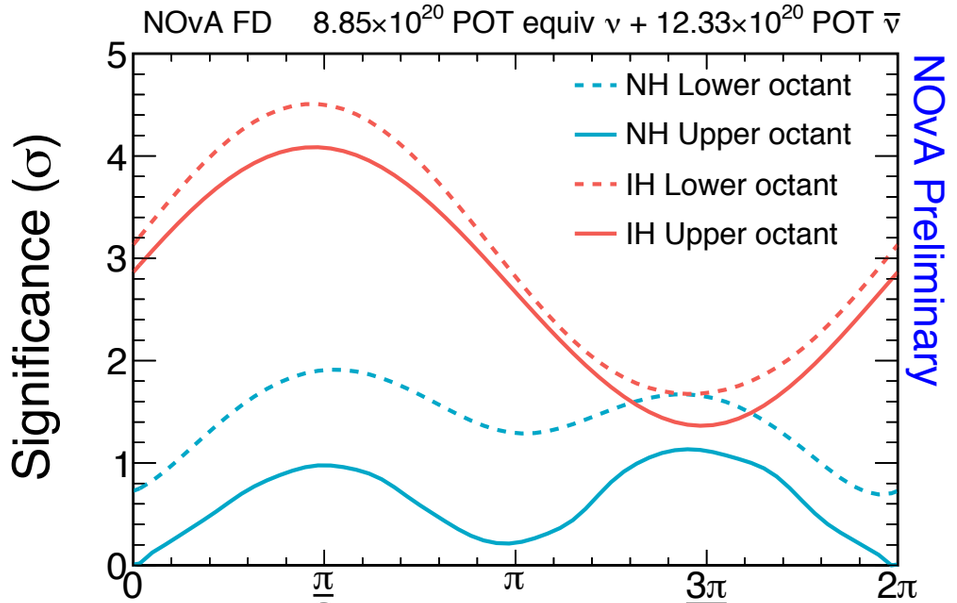


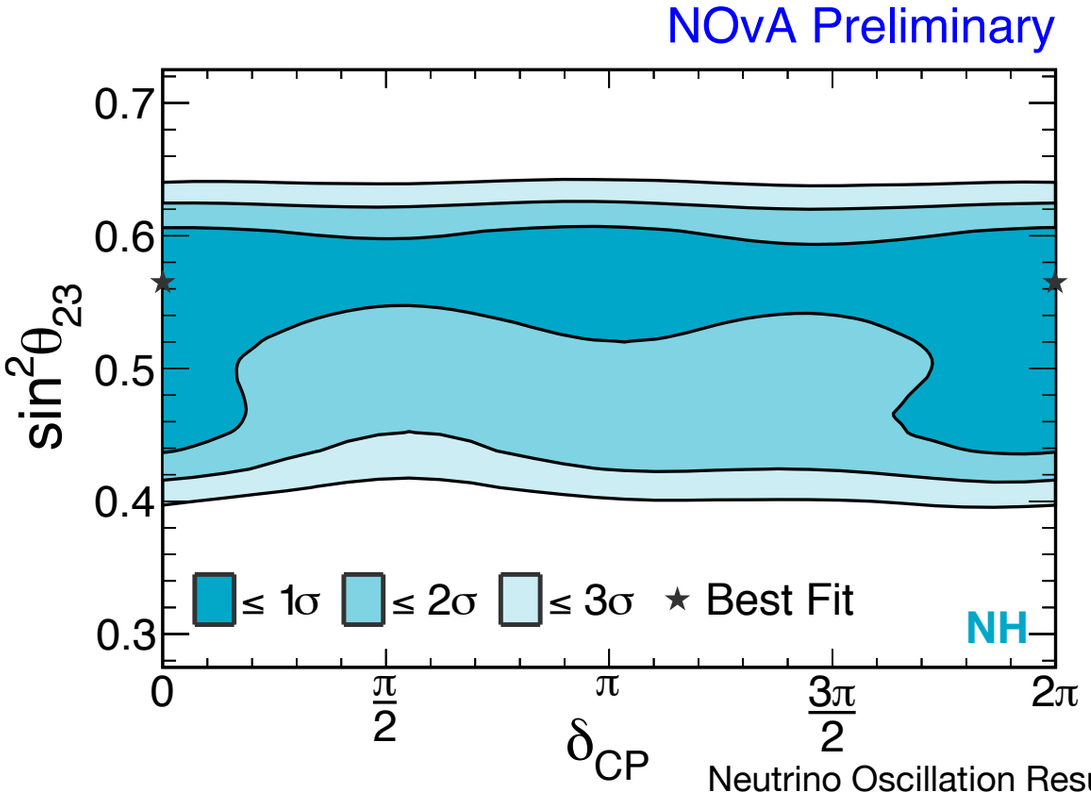


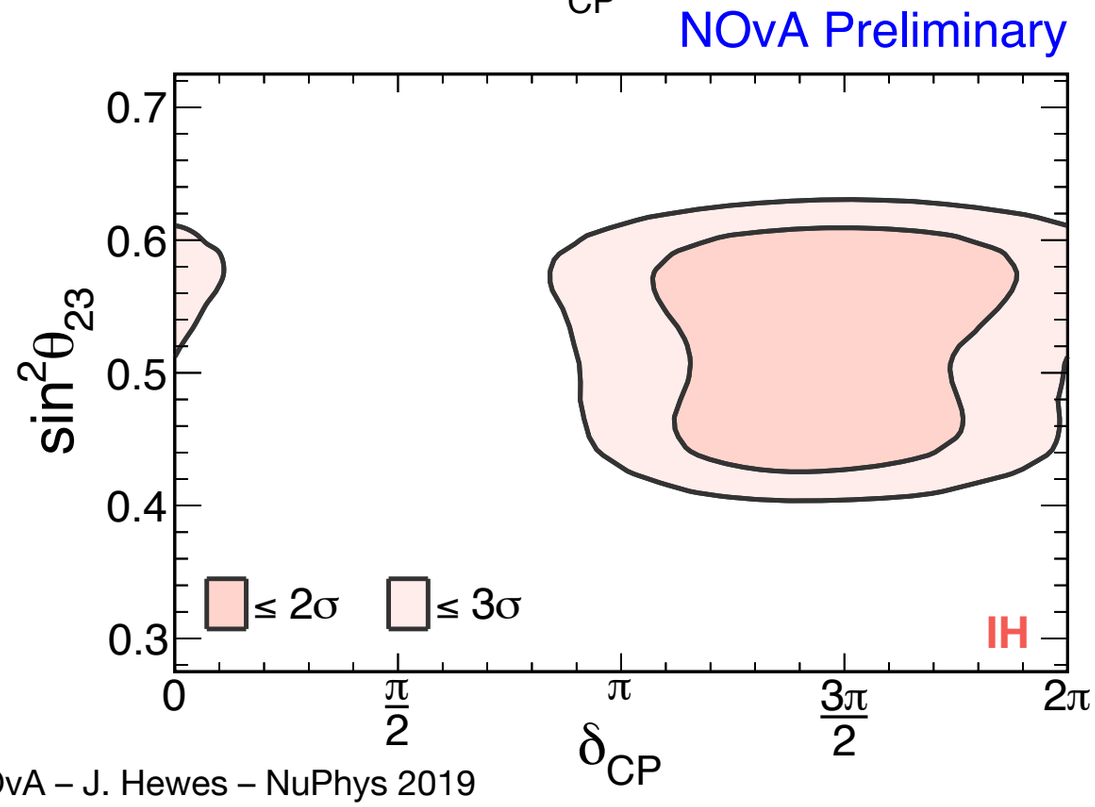


ν_μ & ν_e Joint Fit: δ_{cp}

- All systematic uncertainties, FC corrected.
- For **inverted hierarchy**, $\delta_{cp} = \pi/2$ excluded at **>3σ**.
- Best fits:
  - **$\Delta m^2_{32} = 2.48\ (+0.11/-0.06) \times 10^{-3}\ eV^2$**
  - **$\sin^2\theta_{23} = 0.56\ (+0.04/-0.03)$**
  - **$\delta_{cp} = 0.0\ (+1.3/-0.4)\ \pi$**

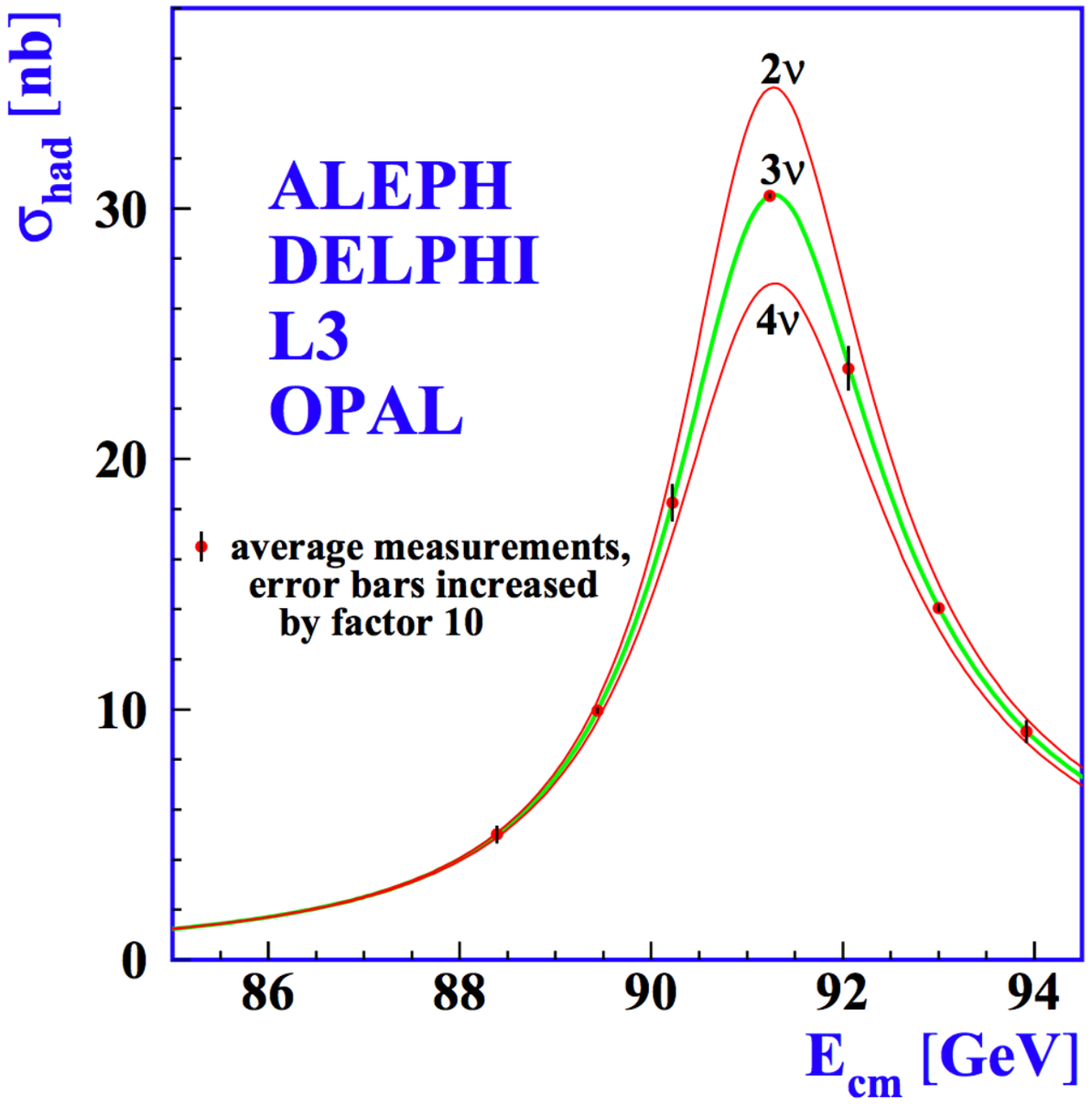






Sterile neutrino searches

- We know there are **three active neutrino states** from the LEP experiments' precise measurements of the width of the Z boson.
- Any additional light neutrinos must be **sterile**, ie. not couple to the weak force.
- We cannot measure these sterile neutrinos directly, but we can look for the active neutrino states oscillating in and out of them.



3+1 sterile neutrino oscillations

- NC events are insensitive to standard three-flavor oscillations.
- In NOvA, look for **active neutrino states** (ν_e, ν_μ, ν_τ) to **disappear into sterile state** (ν_s) using **NC events**.

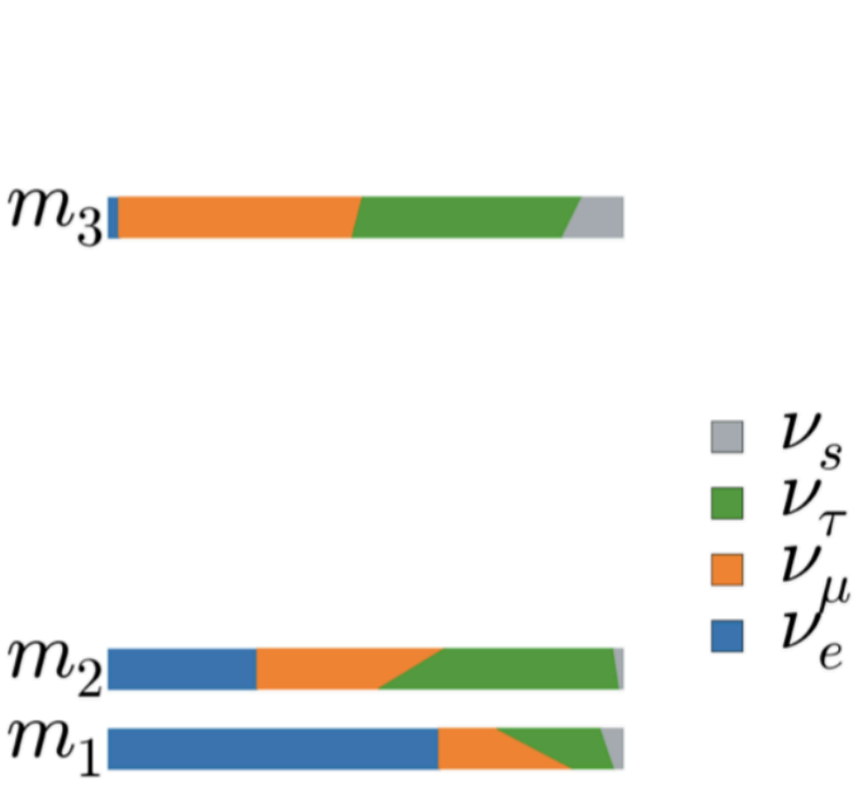
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

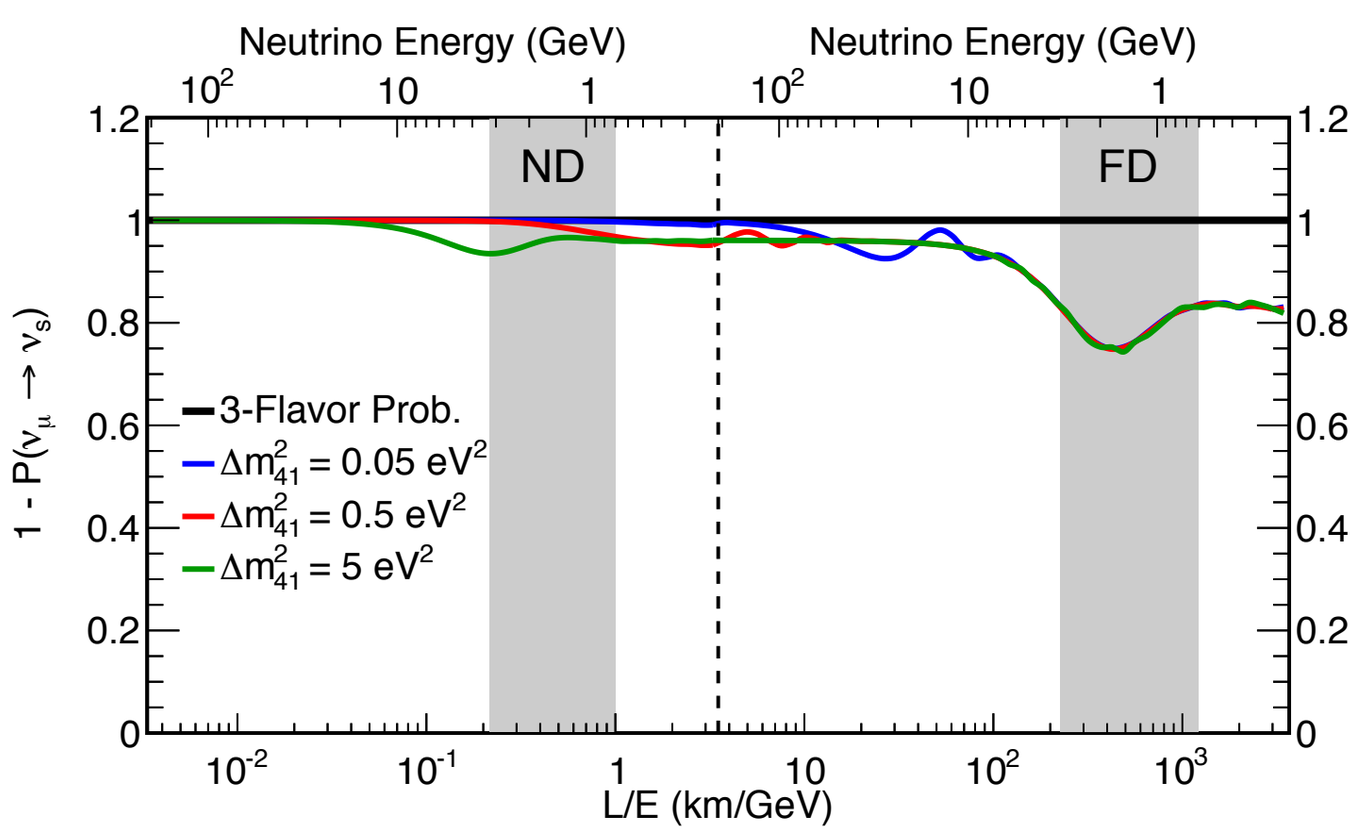
$$1 - P^{LBL,3+1}_{\nu_\mu \to \nu_s} \approx 1 - \frac{1}{2}\cos^4\theta_{14}\cos^2\theta_{34}\sin^2\theta_{24} + \sin^2\theta_{34}\sin^2 2\theta_{23}\Delta_{31} + \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{34}\sin 2\theta_{23}\Delta_{31}$$

(Exact formalism used in fit)

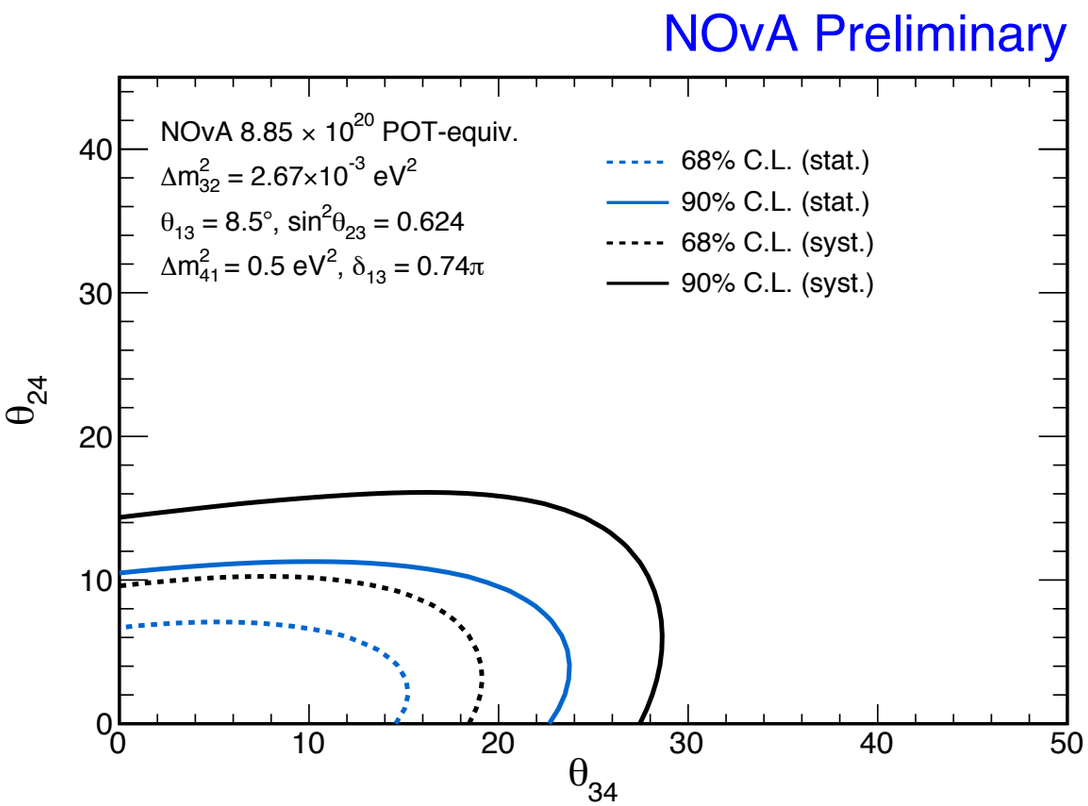
3+1 sterile neutrinos

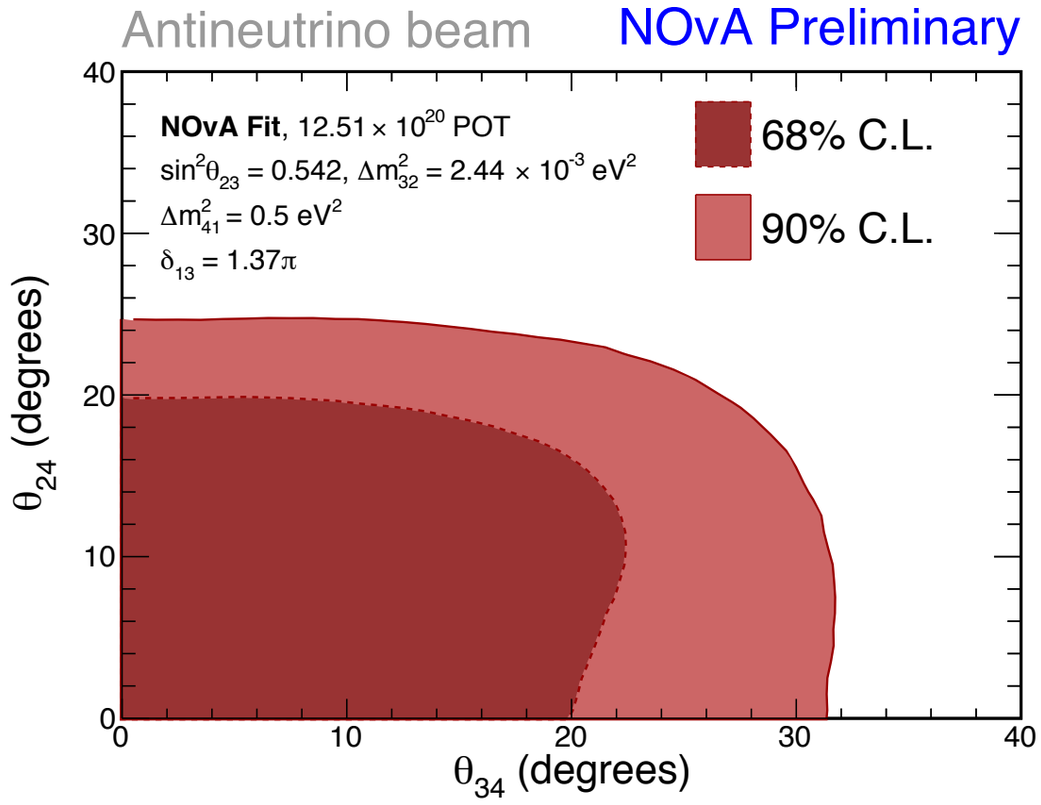
- Signal is always a **deficit**, never an excess.
- ~1 eV^2 sterile neutrino produces rapid oscillations in far detector, which manifest as overall normalisation shift.
- Sensitive to parameters θ_{24}, θ_{34}, Δm^2_{41} and δ_{24}.





NOvA 3+1 results



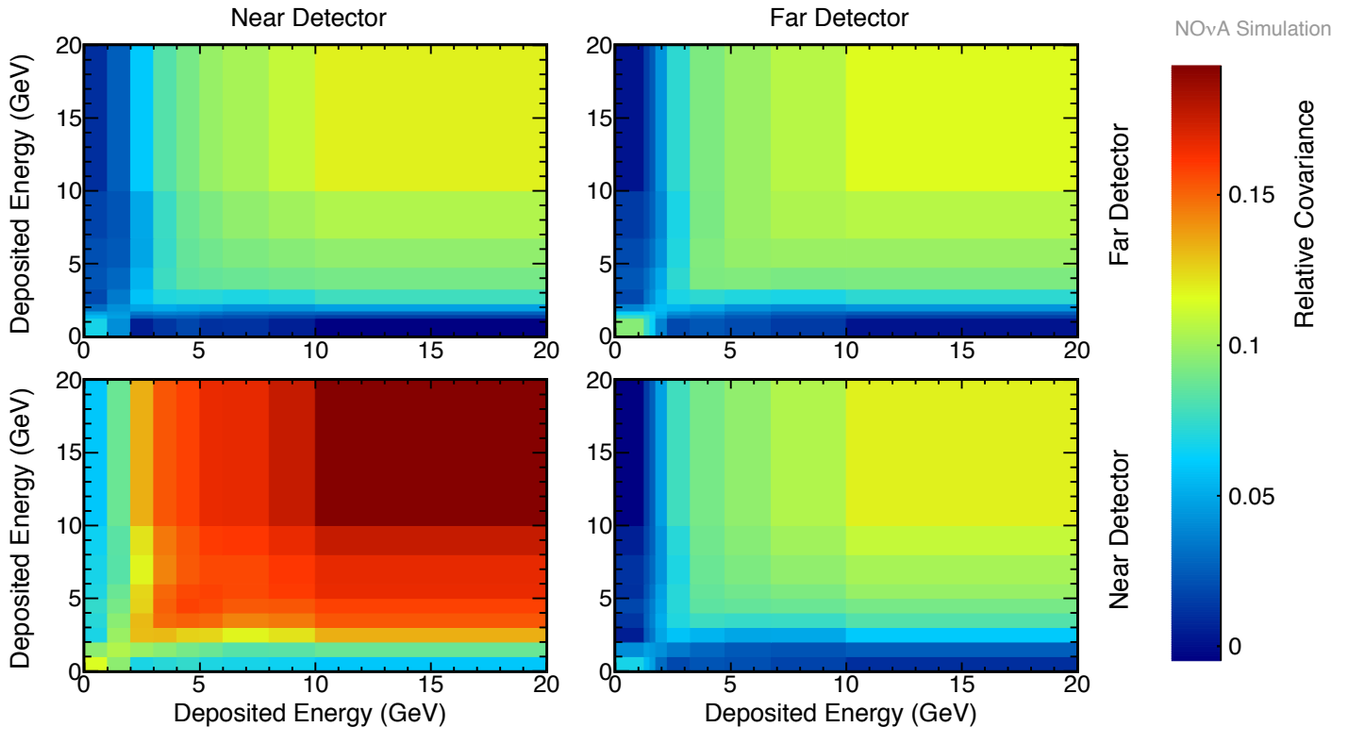


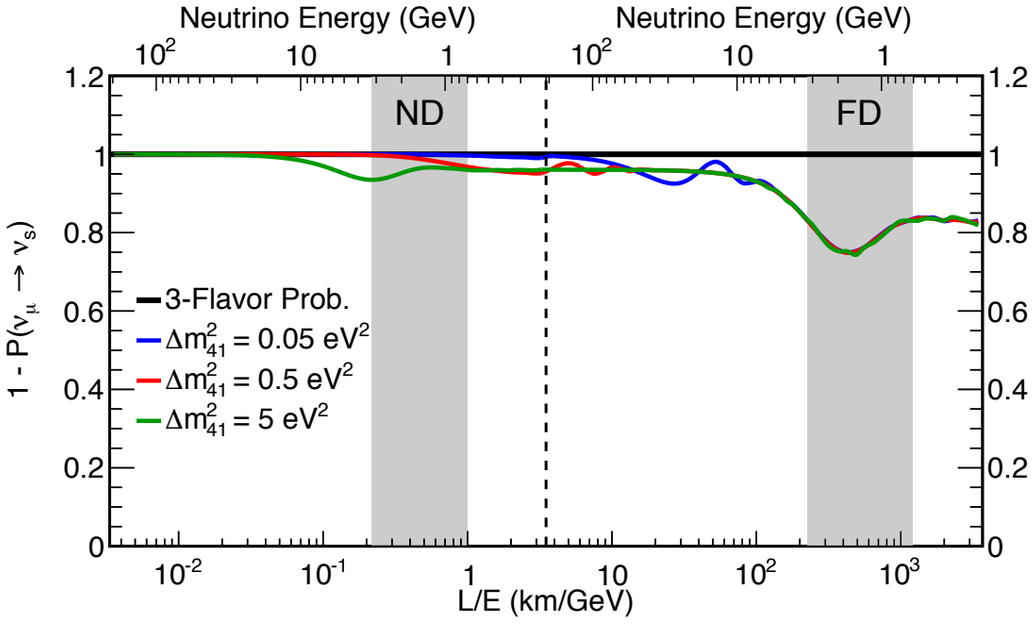
- 1D limits at 90% CL, $\Delta m_{41}^2 = 0.5$ eV^2:
  - **$\theta_{24} < 16.2°$**
  - **$\theta_{34} < 29.8°$**

- 1D limits at 90% CL, $\Delta m_{41}^2 = 0.5$ eV^2:
  - **$\theta_{24} < 24.7°$**
  - **$\theta_{34} < 31.7°$**

Future sterile searches

- At high sterile mass splitting Δm_{41}^2, extrapolation method breaks down due to disappearance in near detector.
- Use covariance matrix to **fit in both detectors simultaneously**, while still cancelling systematic uncertainties.





$$V_{ij,\text{syst}} = \frac{\sum_{n=1}^{U}(S_{n,i} - \mu_i)(S_{n,j} - \mu_j)}{U - 1}$$

$$\chi^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}(x_i - \mu_i)[V^{-1}]_{ij}(x_j - \mu_j)$$

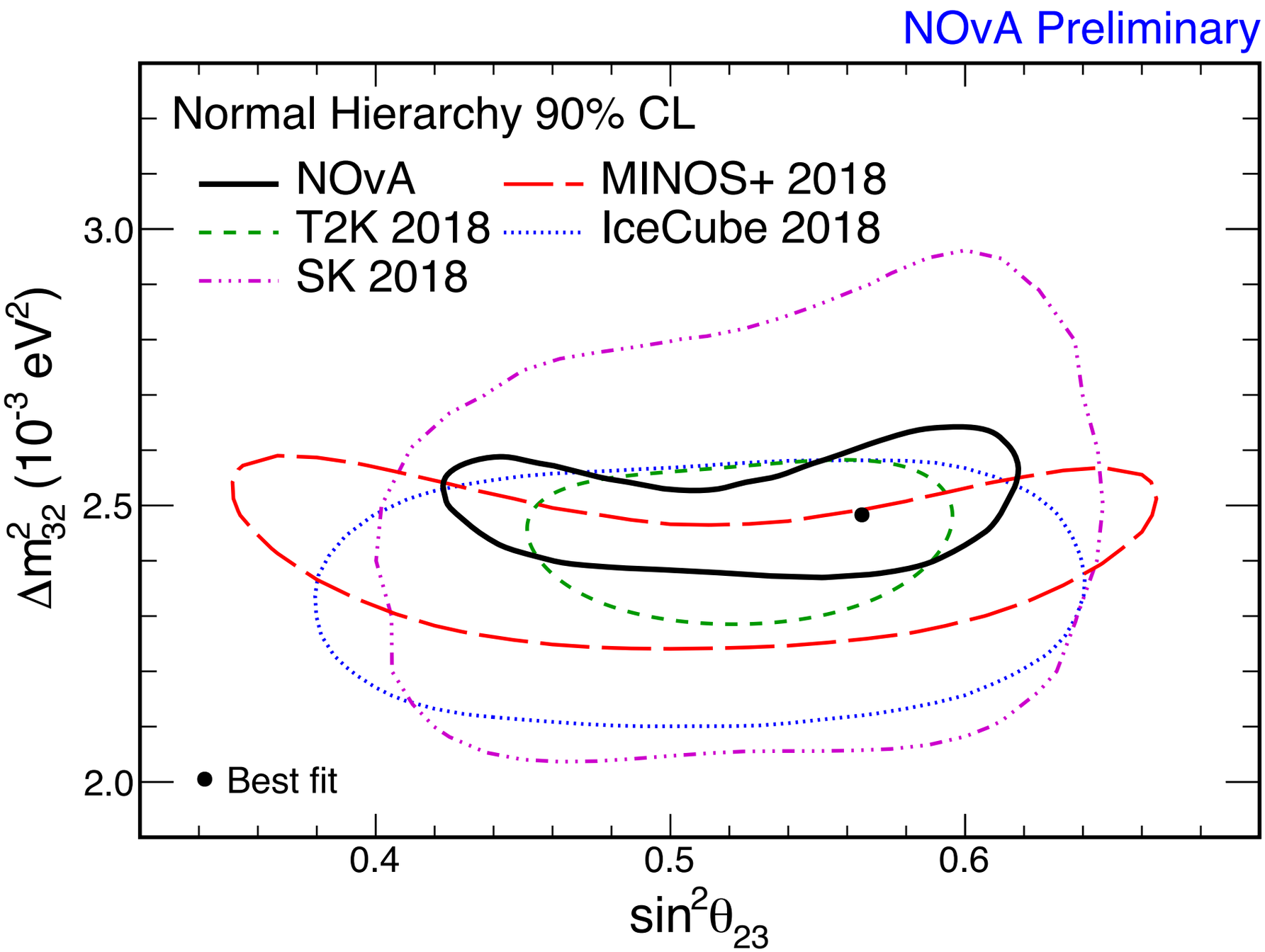
Summary

- **NOvA's second joint analysis with neutrino and antineutrino beam.**
- **Evidence for $\bar{\nu}_e$ appearance observed at 4.4σ.**
- **1.9σ preference for NH and 1.6σ preference for upper octant θ_{23}.**

- **Thank you!**

Backups

Contour (with friends)



Reducing NOvA detector uncertainties

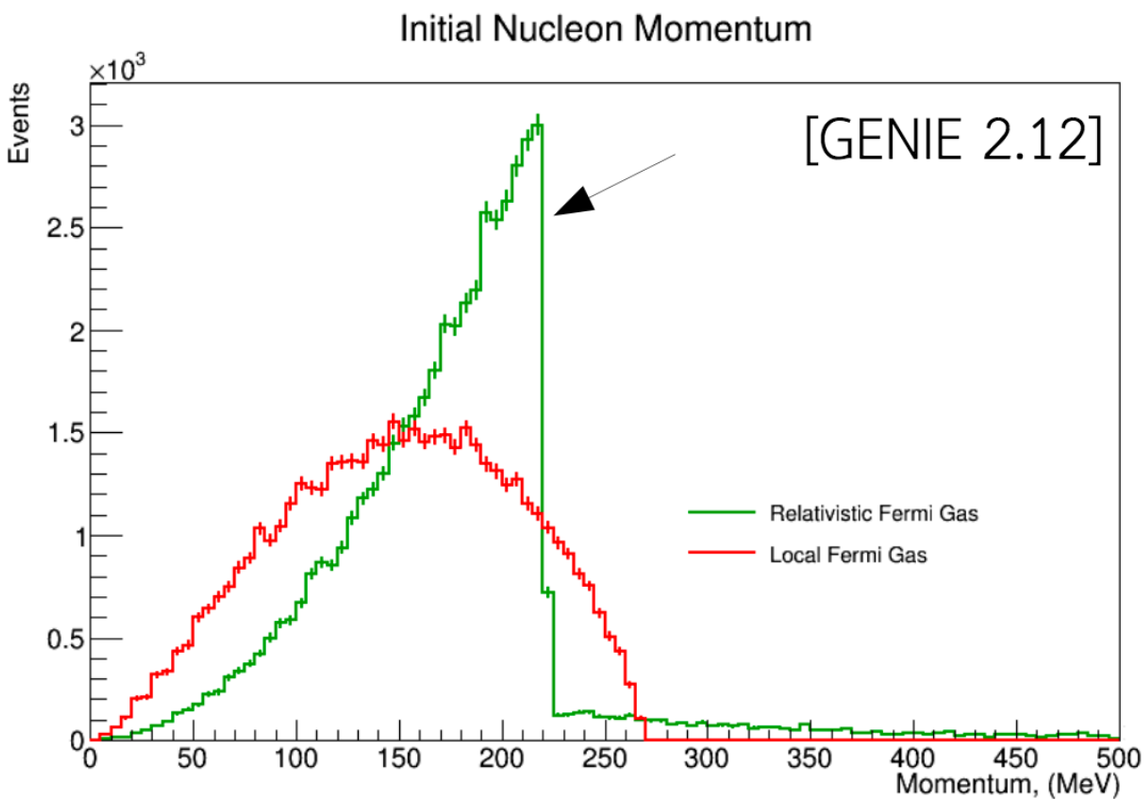
- Dominant source of systematic uncertainty is **detector calibration**.
- NOvA is currently operating a **test beam program** to measure beams of charged particles in a 30 ton NOvA detector, improving understanding of detector response and improving NOvA's physics potential.
- Data-taking began in 2019 & will continue into 2020.

QE interactions

GENIE 2.12 default:

global relativistic Fermi gas

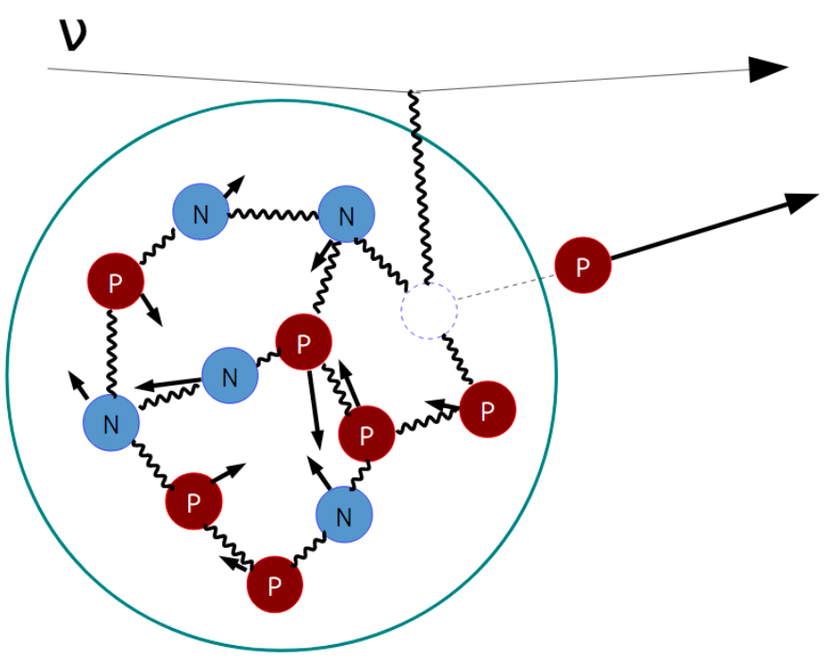
(+ “Bodek-Ritchie tail”)



Local Fermi gas

+

Nuclear polarization / long-range collective response (“RPA”)



Supported by eA data;

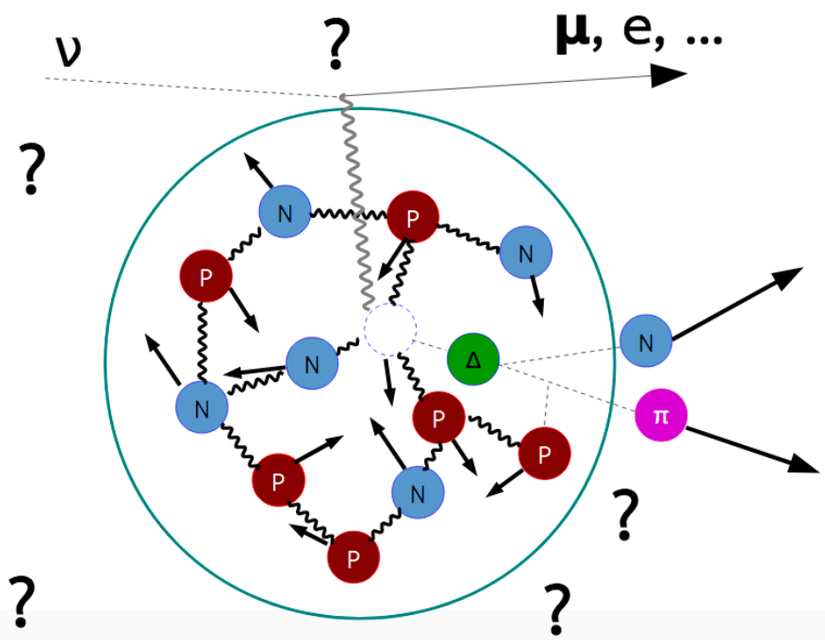
MINERvA νA data (PRD 116, 071802; PRL 121, 022504),

T2K νA data (PRD 98, 032003), …

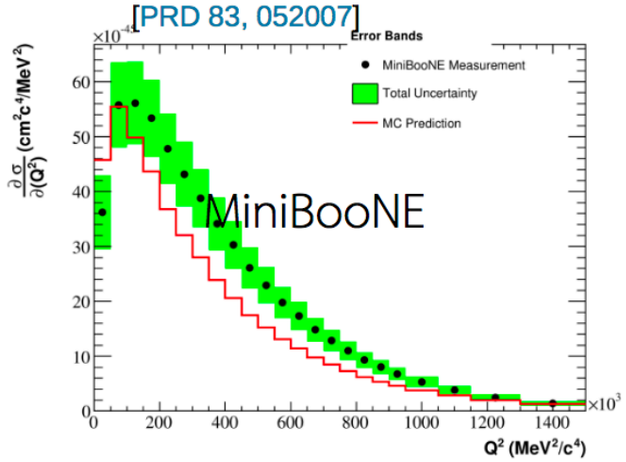
1π interactions

Apparent **suppression at low momentum transfer (Q^2)** relative to model...
(except in $\bar{\nu}A \rightarrow \mu^+\pi^-$?...)

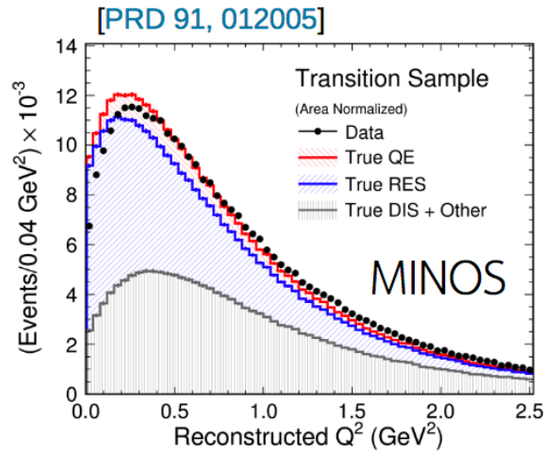
No theory guidance here.
Reminiscent of LFG+RPA correction in elastic though....



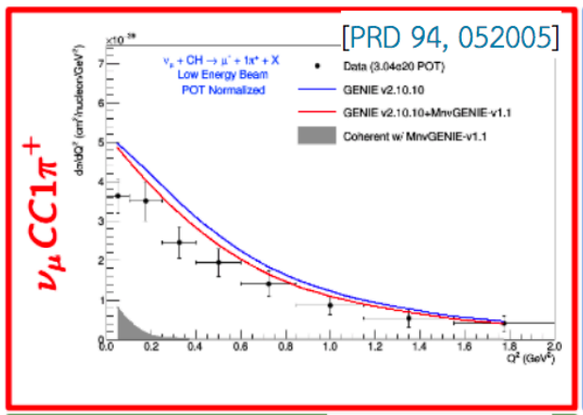
[PRD 83, 052007]



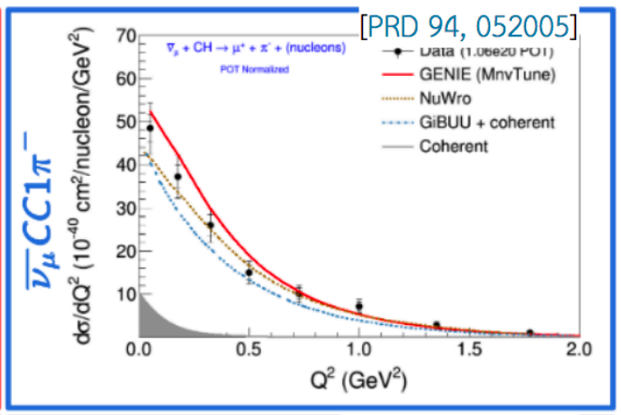
[PRD 91, 012005]



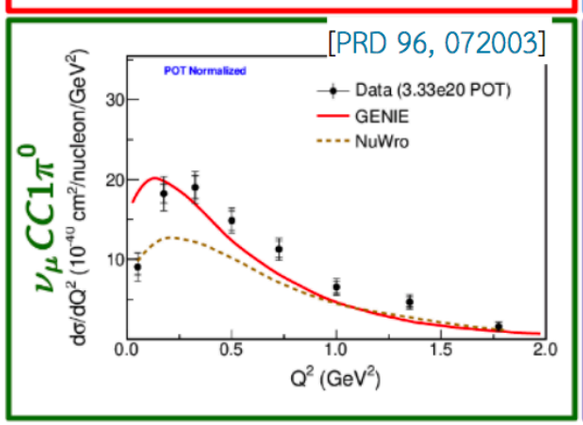
[PRD 94, 052005]



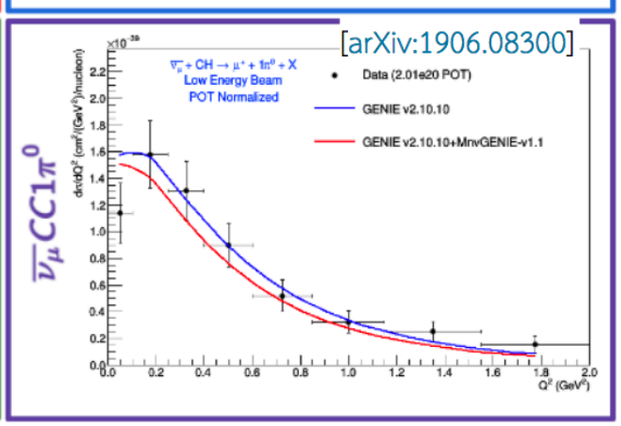
[PRD 94, 052005]



[PRD 96, 072003]

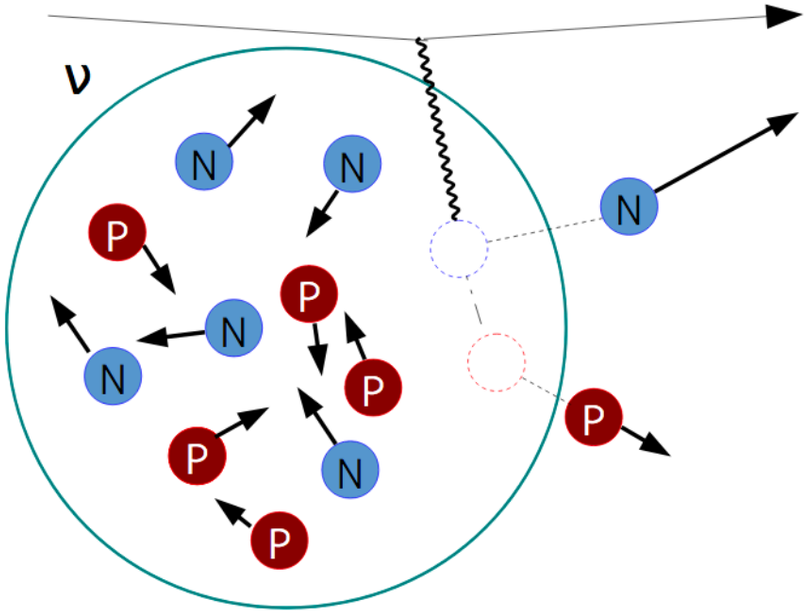


[arXiv:1906.08300]



MINERvA

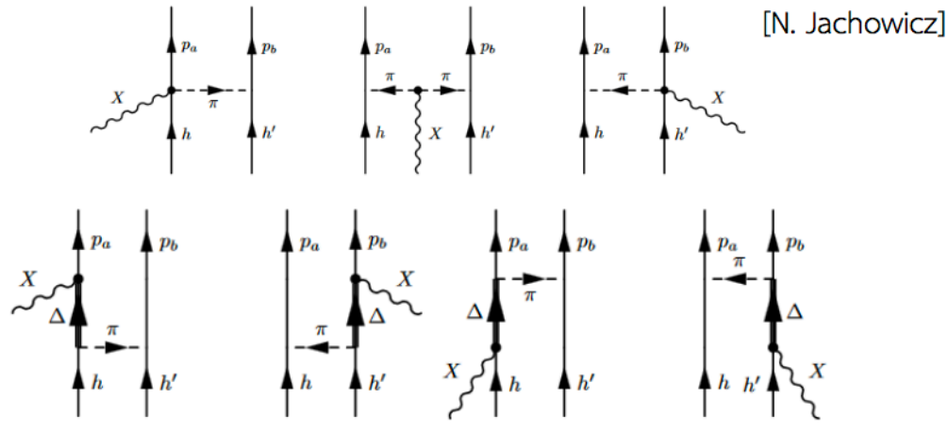
2p2h interactions



"2p2h"

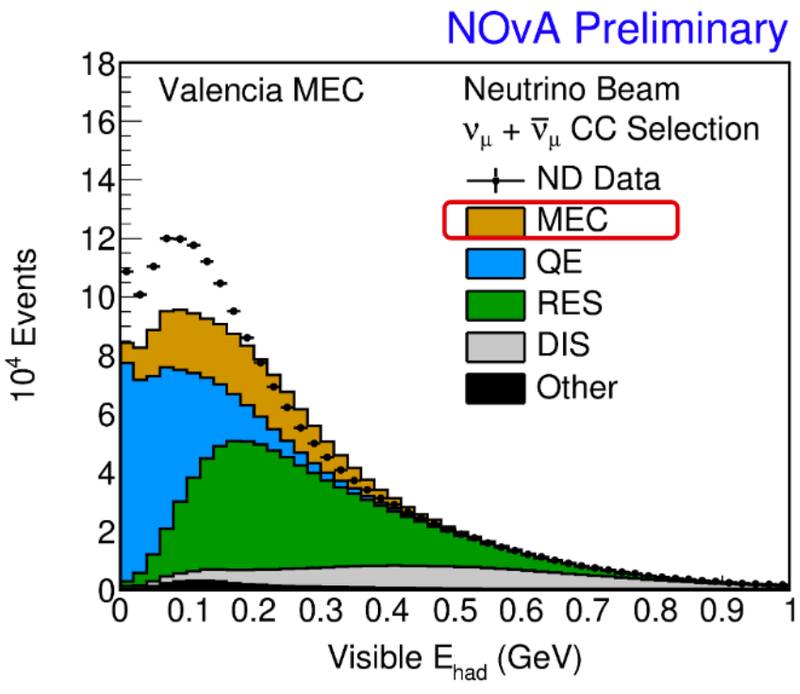
Knock out two nucleons with an elastic-like interaction

[N. Jachowicz]



Meson Exchange Current (MEC) theory for **ν**A is a work in progress.

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 …**



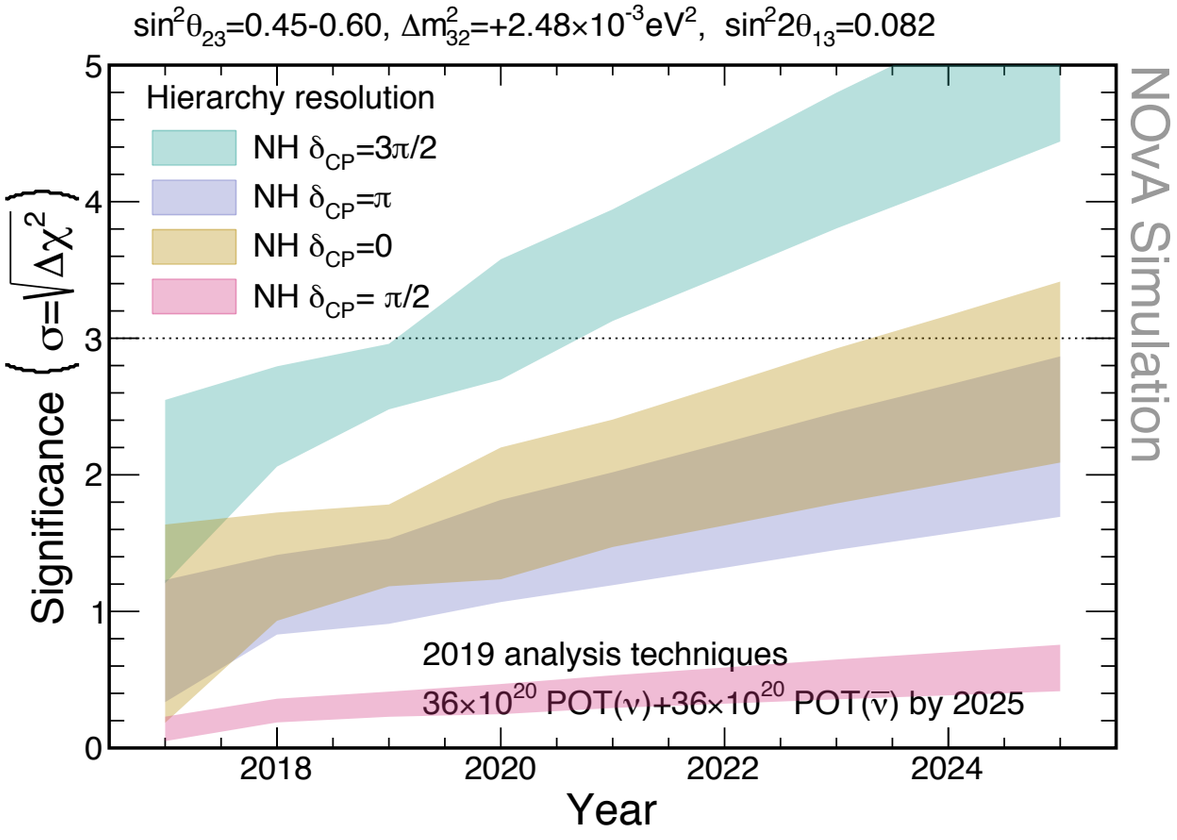
Prospects for T2K Joint Fit

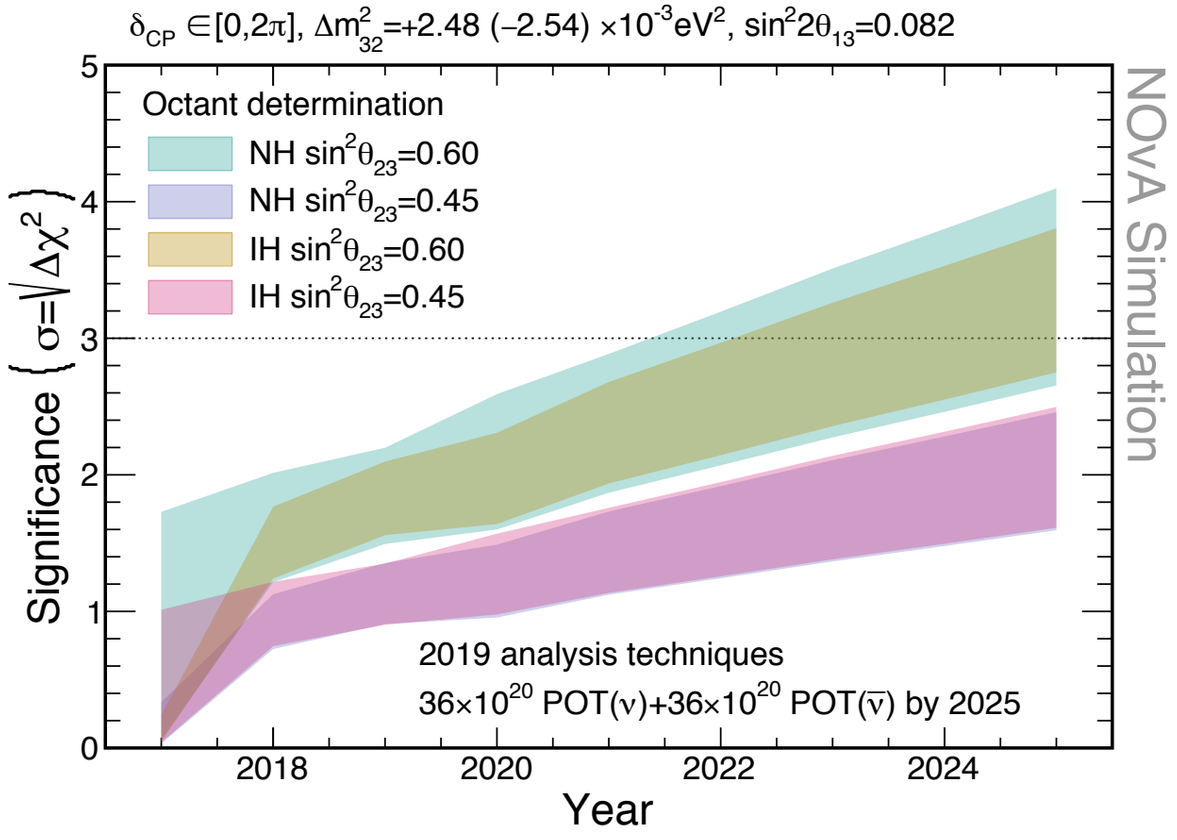
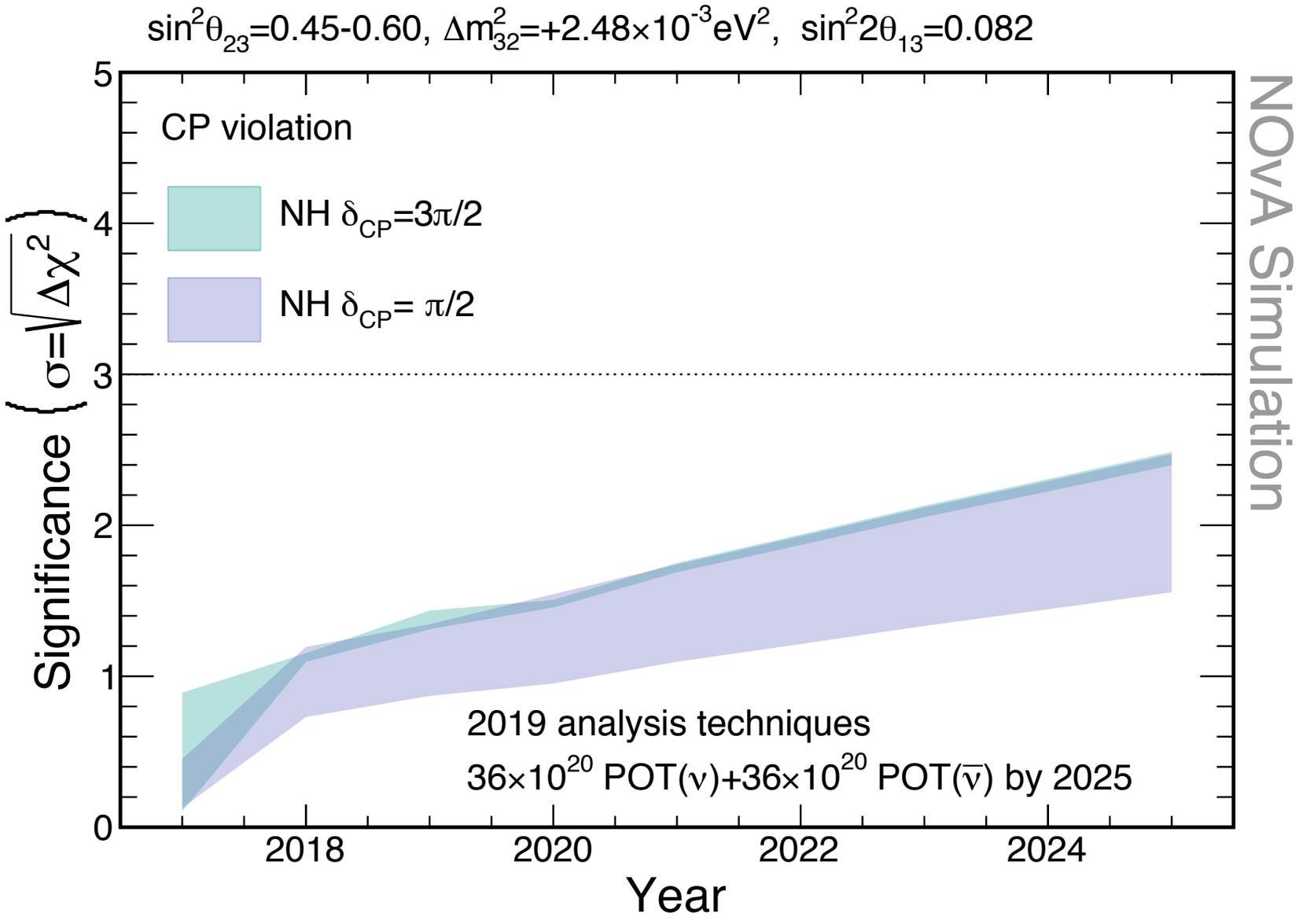
- NOvA and T2K's oscillation results are complementary, since they utilise different baselines and neutrino energy regimes but probe the same region of L/E.
- The two collaborations have met five times (twice in 2019) since 2016 to discuss a joint fit.
- First joint result targeted for **2021**.
- The full scope of this is still under consideration, and will be clarified in **2020**.

NOvA/T2K Statistical Issues

- Two different approaches to fitting:
  - **NOvA** uses **profiling** for nuisance parameters, and uses Minuit to minimize them.
  - **T2K** uses **marginalization** for nuisance parameters, and integrates using MCMC.
- These can be combined into a joint likelihood, but this may present computational challenges.

NOvA Sensitivities





NOvA Sensitivities