

New Perspectives 2022

# **NOvA in 10 minutes** **(or your neutrino is free!)**

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June 21<sup>st</sup>, 2022

# Neutrino Oscillations

- In the 20<sup>th</sup> century many experiments studying neutrinos saw discrepancies in neutrino rates.
- Eventually it was proposed that neutrino oscillations were to blame for these discrepancies.
- Oscillations are governed by the PMNS matrix.

$$\begin{array}{c} \text{Flavor states} \\ \left( \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right) = \left( \begin{array}{ccc} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{array} \right) \left( \begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \right) \\ \text{Mass states} \end{array}$$

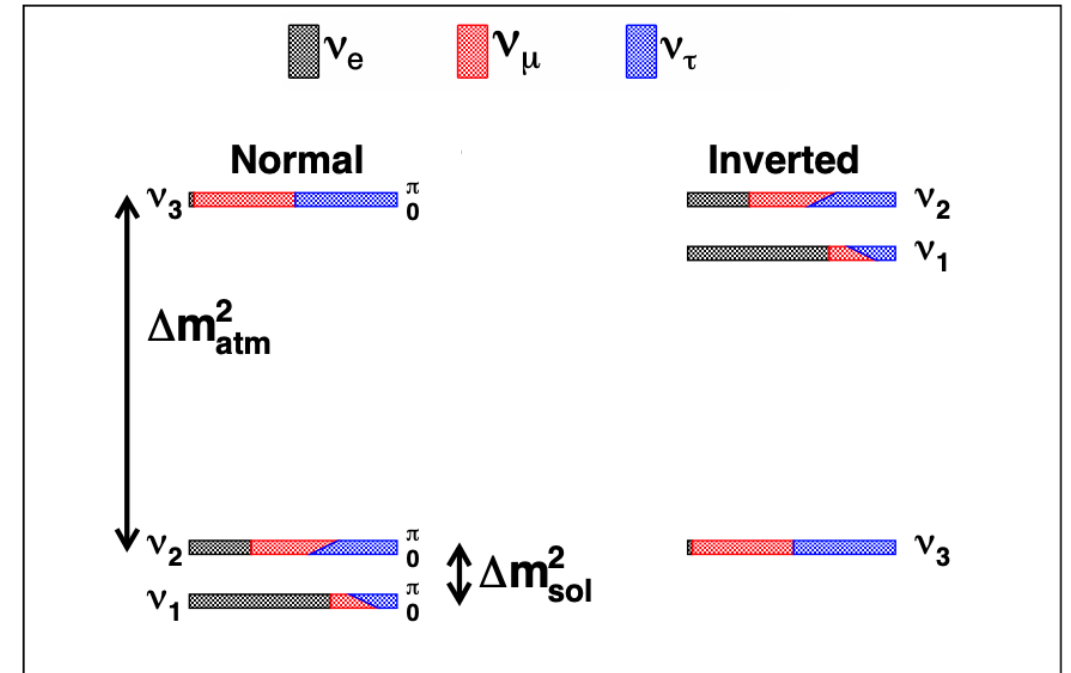
**Pontecorvo-Maki-Nakagawa-Sakata  
(PMNS) Matrix**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix} \begin{pmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{i\delta} & 0 & \cos(\theta_{13}) \end{pmatrix} \begin{pmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ -\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

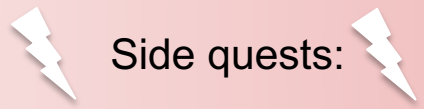
$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U_{\beta i} U_{\alpha i}^* e^{\frac{-im_i^2 L}{2E}} \right|^2$$

# NOvA: Physics Goals

1. **CP:** Are neutrinos CP violating particles?  
What is the value of  $\delta_{CP}$ ?
2. **Mass Hierarchy:** Is  $m_3$  heavier or lighter than  $m_{2/1}$ ?
3. **Mixing:** Is  $\theta_{23}$  exactly  $45^\circ$ ? If not, is it above or below  $45^\circ$ ?



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix} \begin{pmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{i\delta} & 0 & \cos(\theta_{13}) \end{pmatrix} \begin{pmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ -\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- Cross section measurements
- Cosmic Ray physics
- Supernova neutrino detection
- Sterile Neutrino searches
- Magnetic monopole searches
- and more!

# Oscillation Probabilities in vacuum

$\nu_\mu$  disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - [\sin^2(2\theta_{13})\sin^2(\theta_{23}) + \cos^4(\theta_{13})\sin^2(2\theta_{23})]\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

$\nu_e$  appearance

$$P(\nu_\mu \rightarrow \nu_e) = P_{atm} + 2\sqrt{P_{atm}}\sqrt{P_{sol}} (\cos\Delta m_{32}^2 \cos\delta \mp \sin\Delta m_{32}^2 \sin\delta) + P_{sol}$$

**CP dependence**

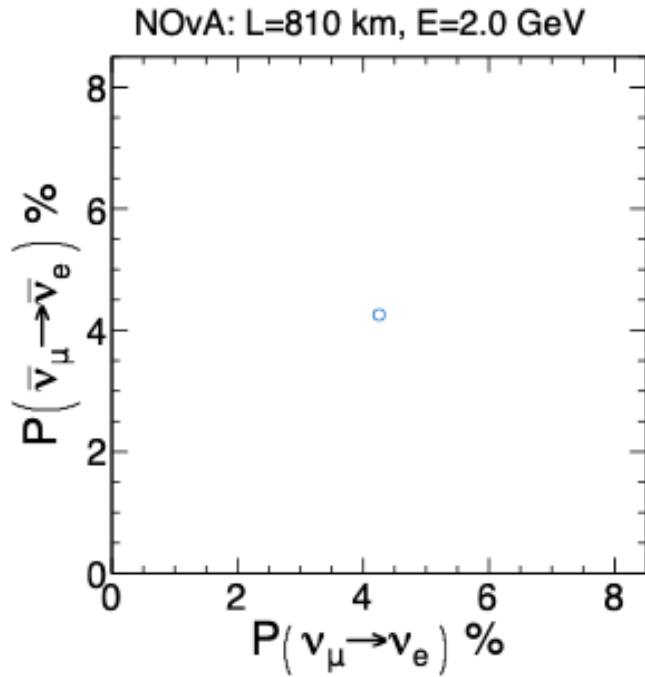
$$\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$m_{atm}^2 = \Delta m_{31}^2 = m_3^2 - m_1^2 = 2.5 \times 10^{-3} eV^2$$

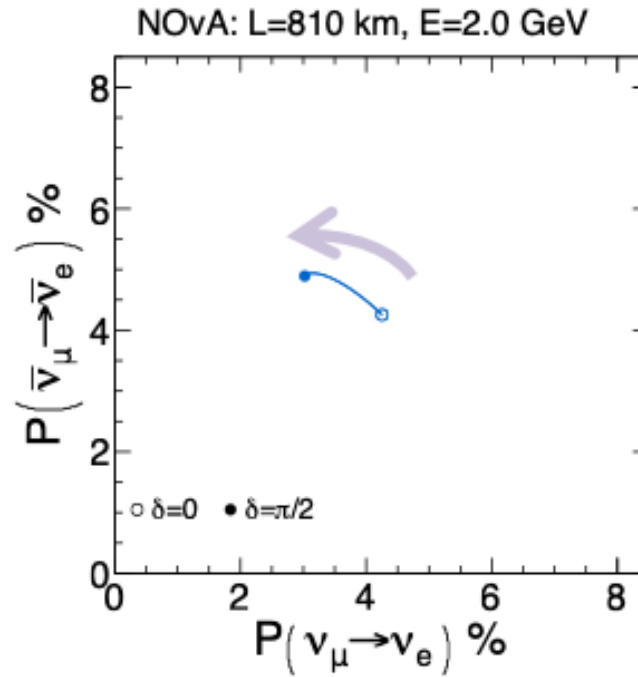
$$\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$m_{sol}^2 = \Delta m_{21}^2 = m_2^2 - m_1^2 = 7.6 \times 10^{-5} eV^2$$

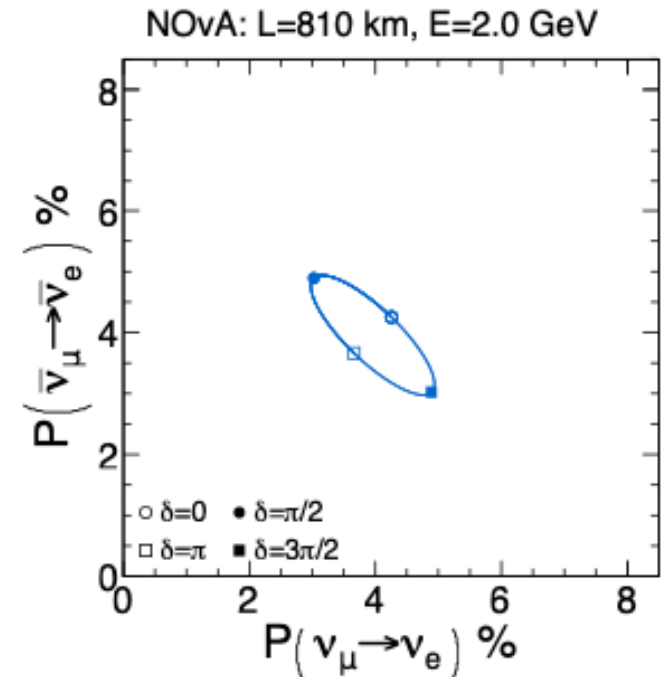
# Untangling $\delta$



$$\delta_{cp} = 0$$



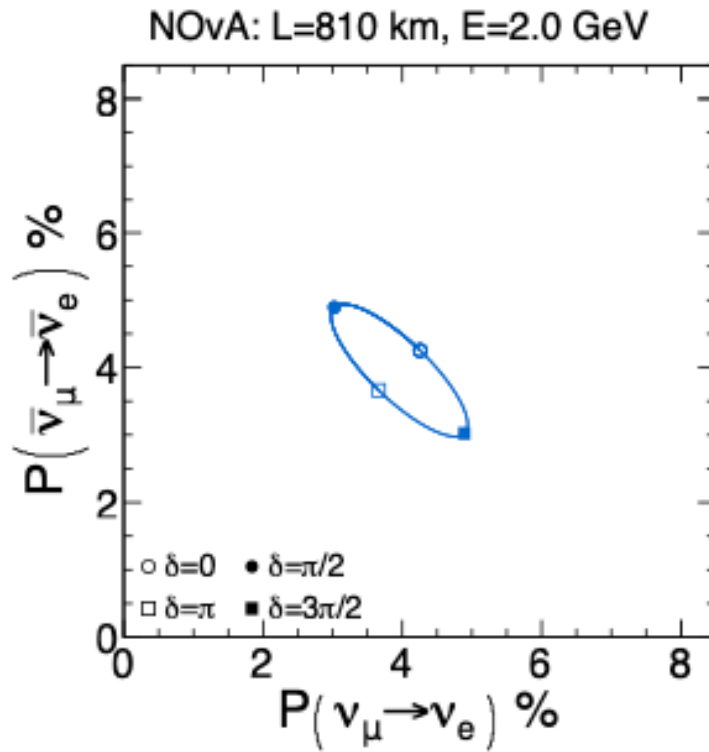
$$\delta_{cp} = \frac{\pi}{2}$$



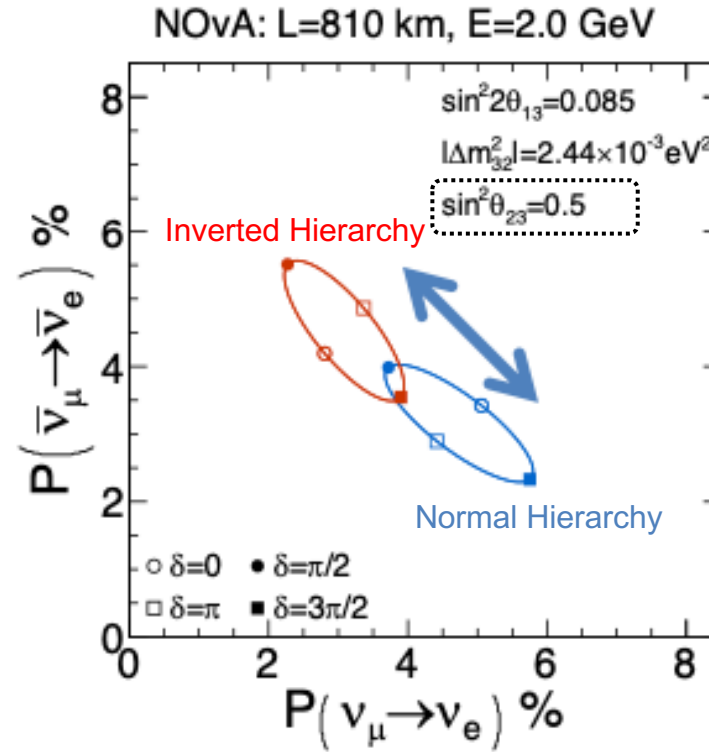
$$\delta_{cp} = 0 \rightarrow 2\pi$$

In Vacuum

# Untangling Mass Hierarchy

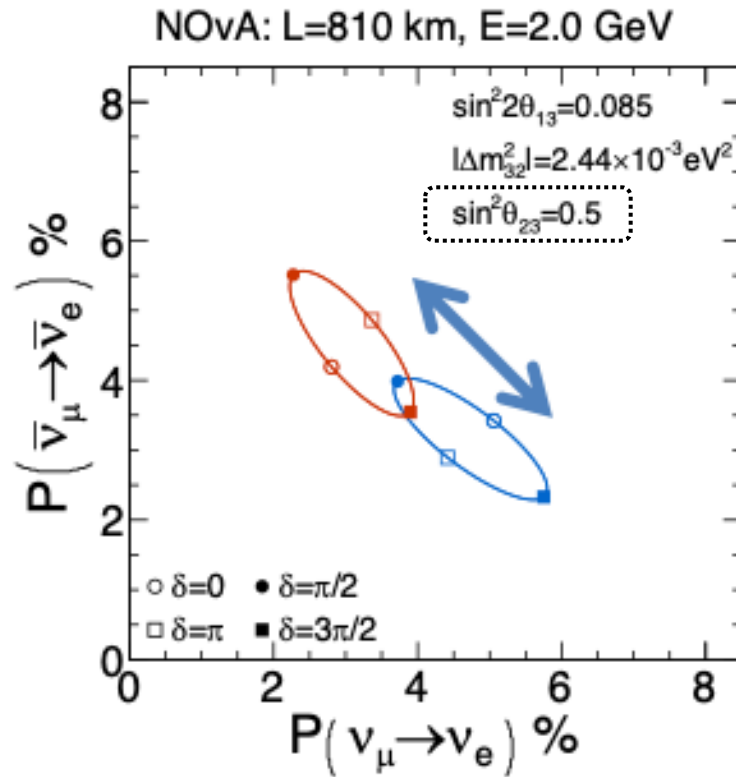


Vacuum Oscillations

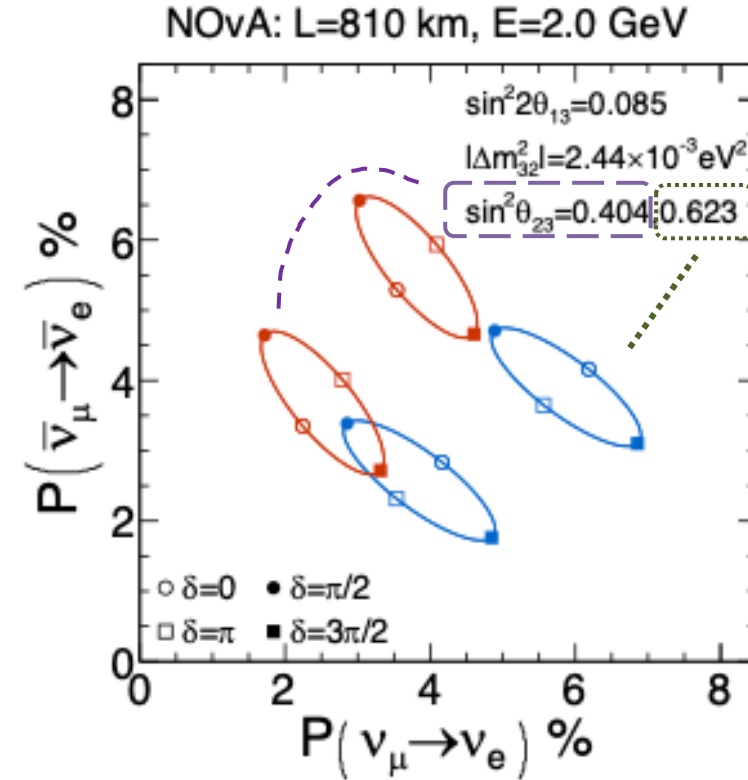


Oscillations including Matter Effects

# Untangling $\theta_{23}$

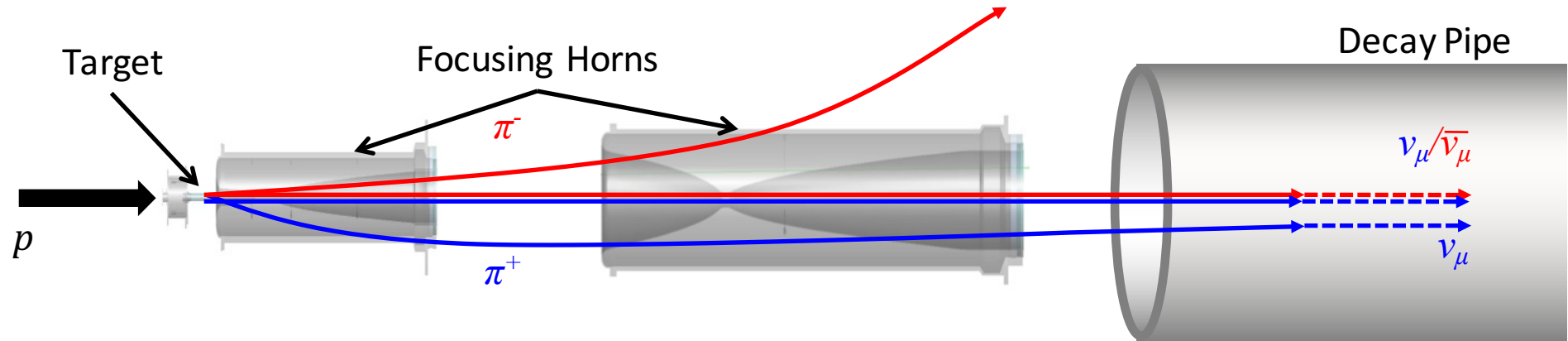


**Maximal Mixing**  
 $\theta_{23} = 45^\circ$

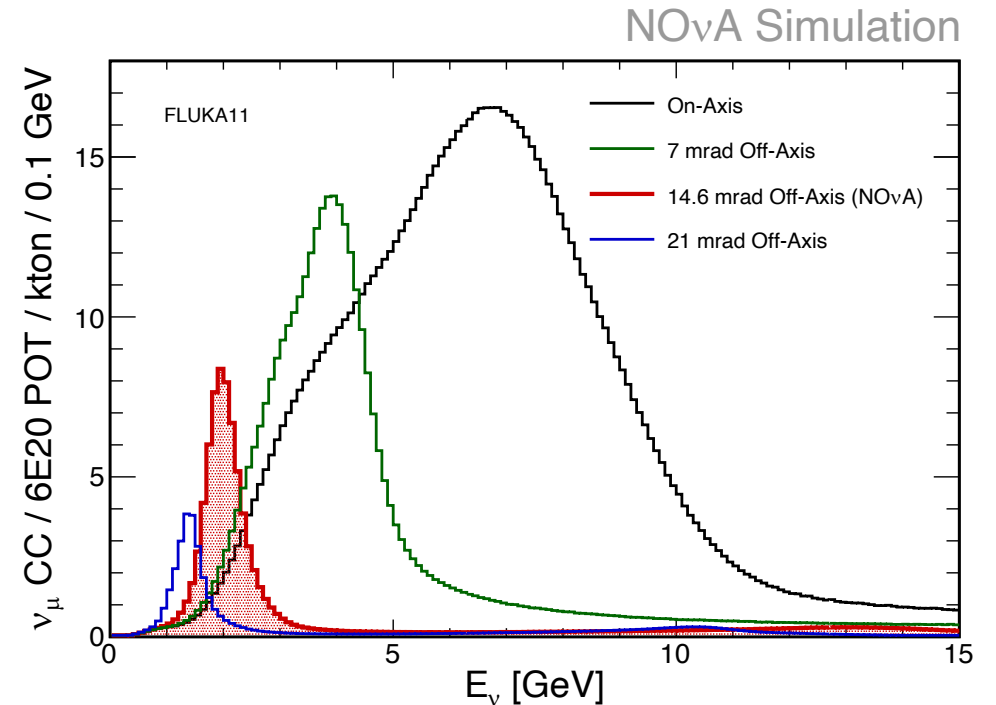


**Upper vs Lower Octant**  
 $\theta_{23} > 45^\circ$      $\theta_{23} < 45^\circ$

# Neutrinos at the Main Injector (NuMI)



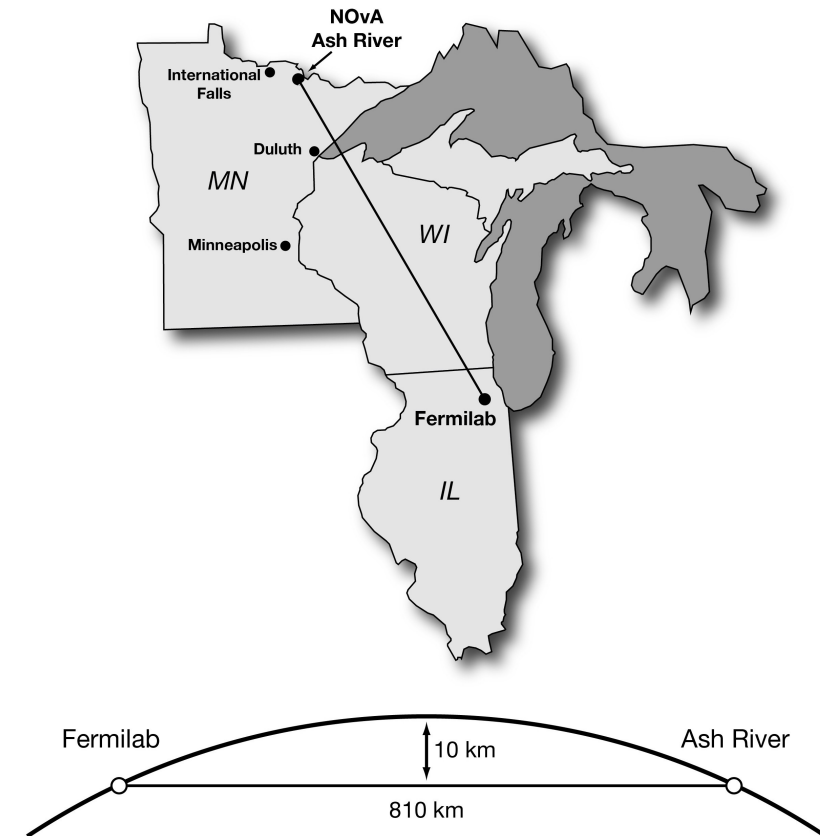
- Focusing horns allow for neutrino and antineutrino configuration
- NOvA is 14.6mrad off-axis to minimize backgrounds
- Neutrino energies peak at  $\sim 2$  GeV
- **NuMI new power record:**



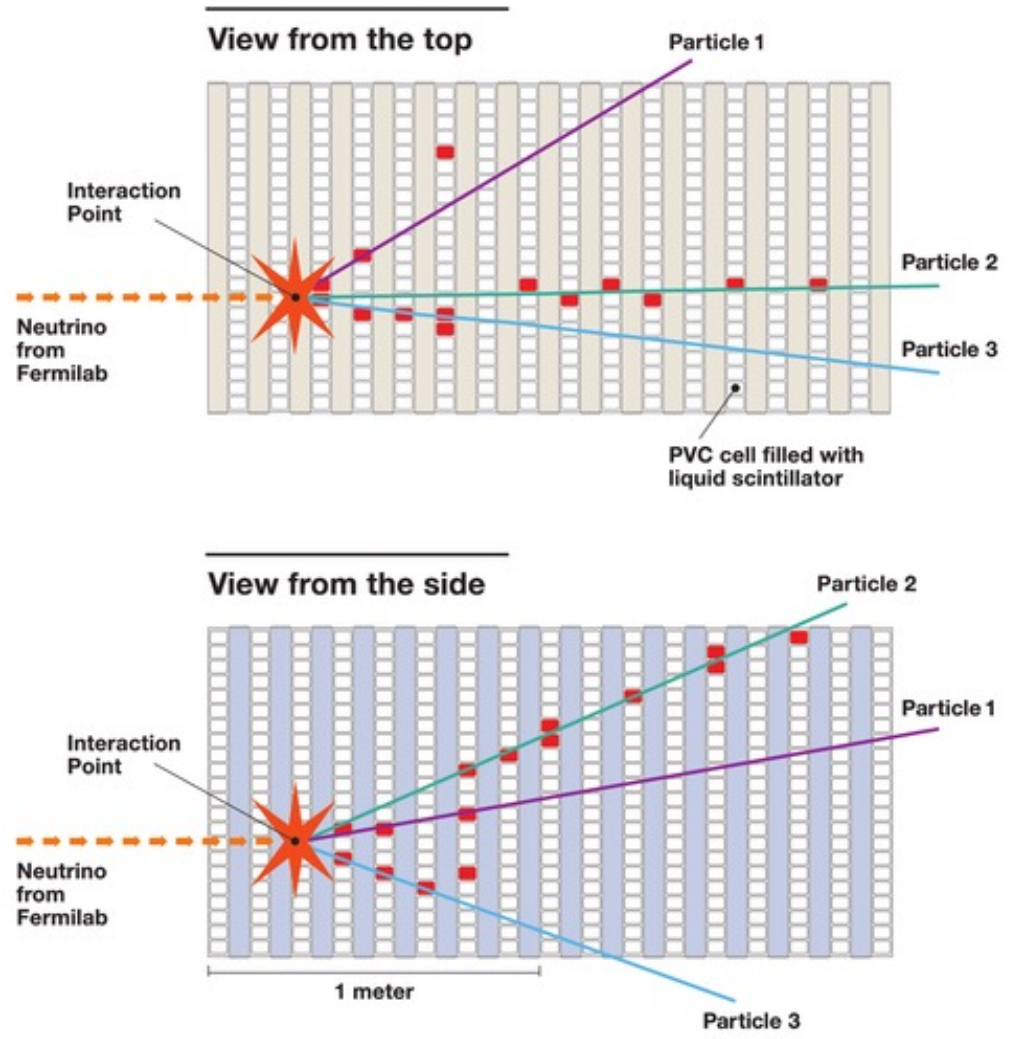
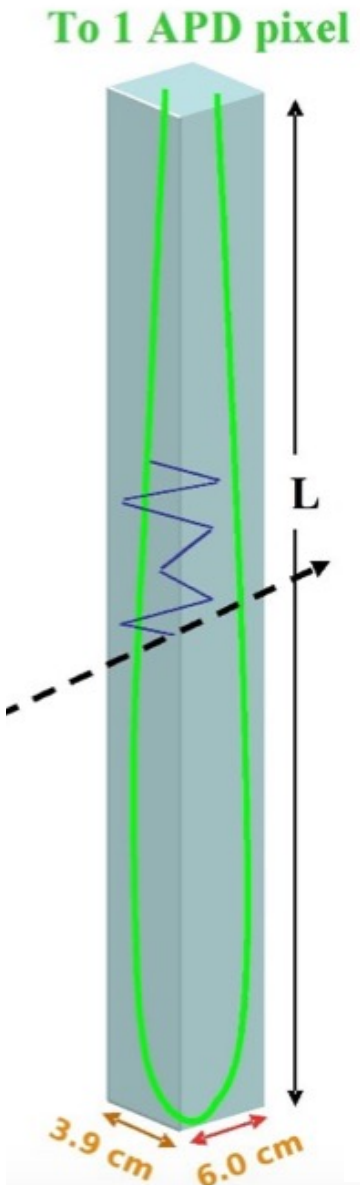
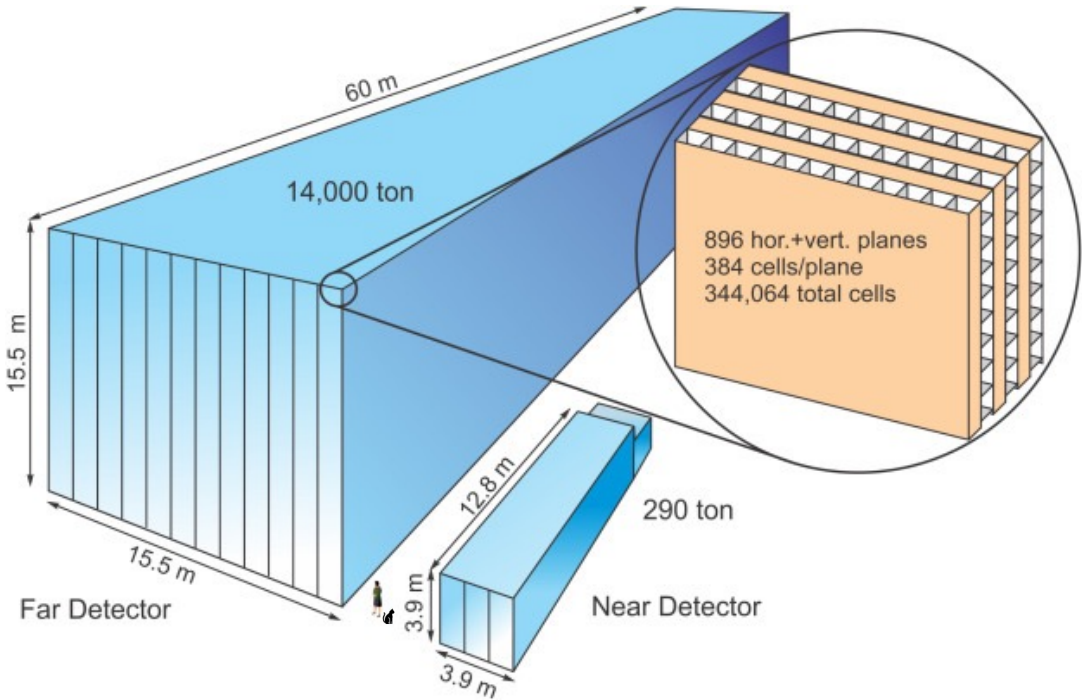


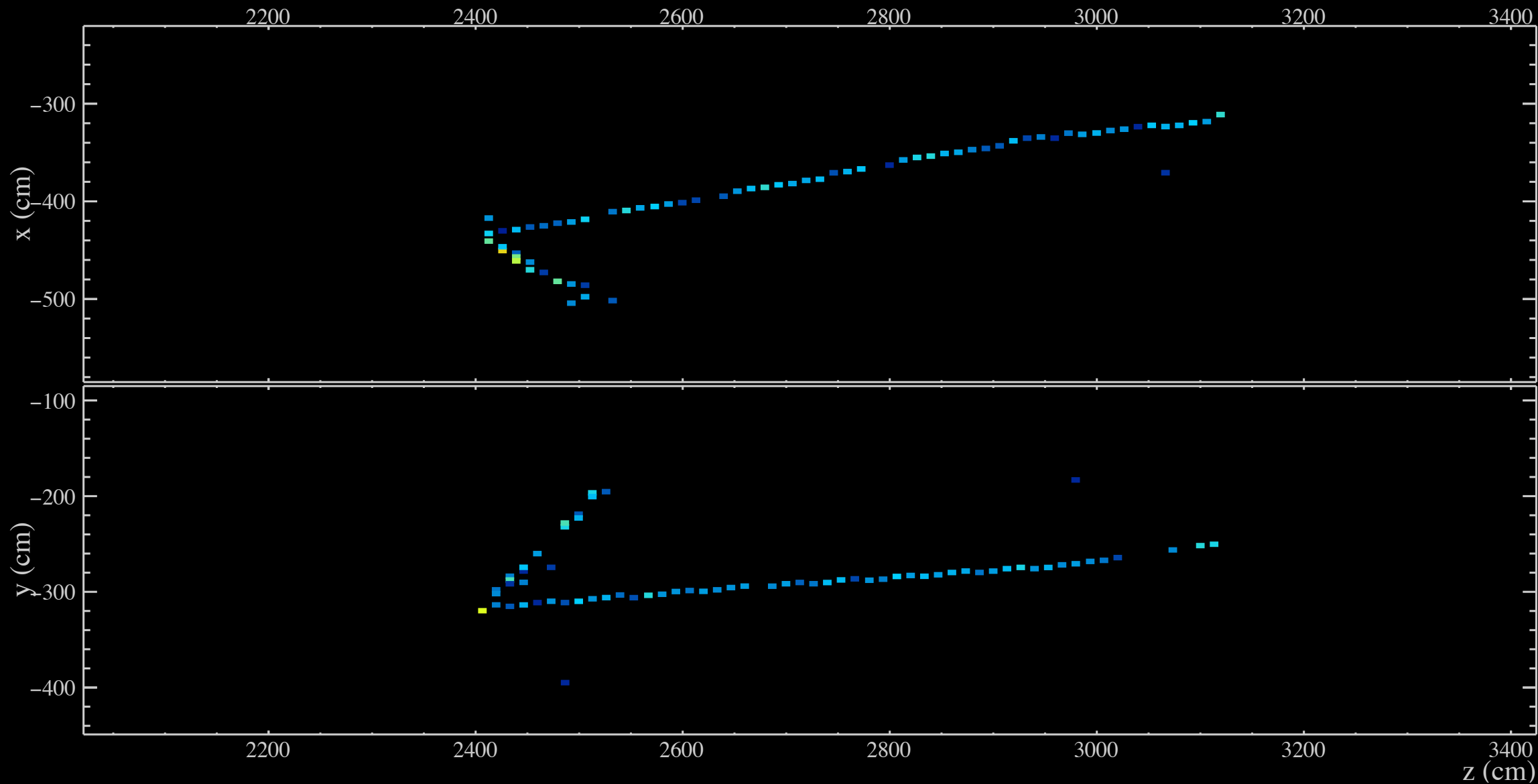
# The NuMi Off-axis $\nu_e$ Appearance Experiment

- Predominantly muon (anti)neutrino beam
- 14.6 mrad off-axis
- **Two functionally equivalent liquid scintillator detectors**
  - Far Detector 14 kt
  - Near Detector 300 t
- Detectors are separated by **809 km**
- Physics goals:
  - Mass Ordering, CP phase,  $\theta_{23}$



# Detector Overview





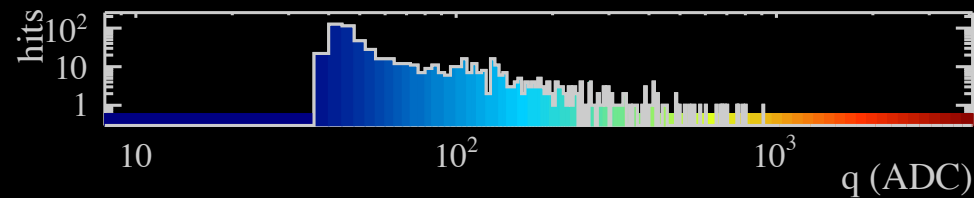
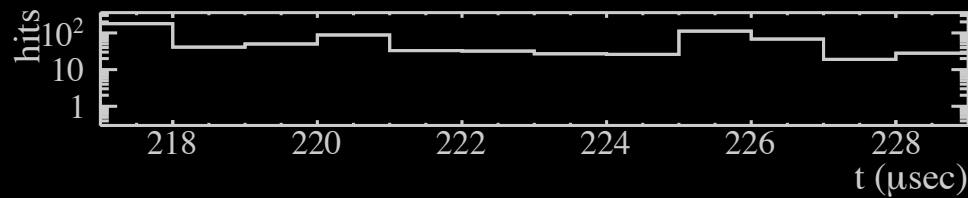
**NOvA - FNAL E929**

Run: 14828 / 38

Event: 192569 / --

UTC Tue Apr 22, 2014

21:41:51.422846016



# NOvA 2020 Results

Best Fit :

**Normal hierarchy**

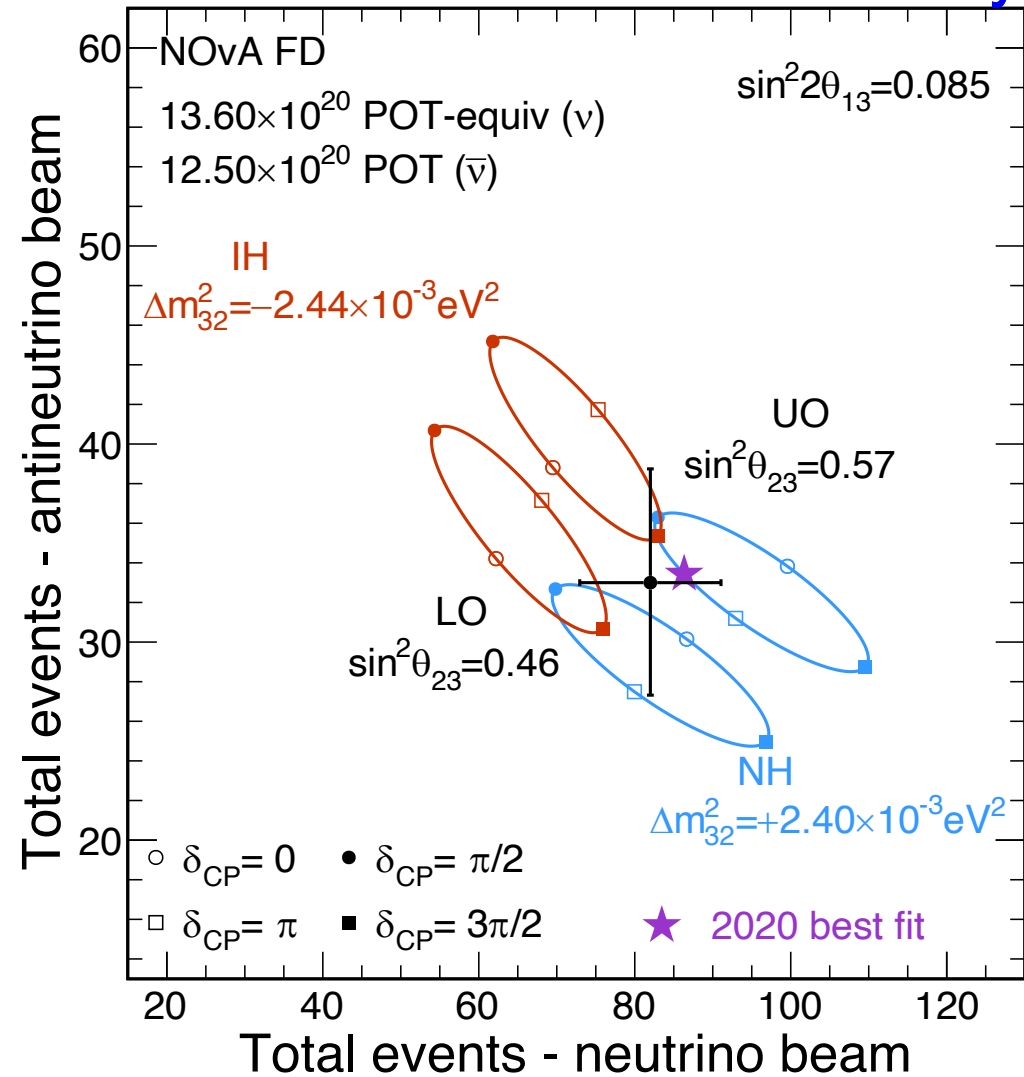
$$\Delta m_{23}^2 = (2.41 \pm 0.07) \times 10^{-3} \text{ eV}^2$$

**Upper Octant**

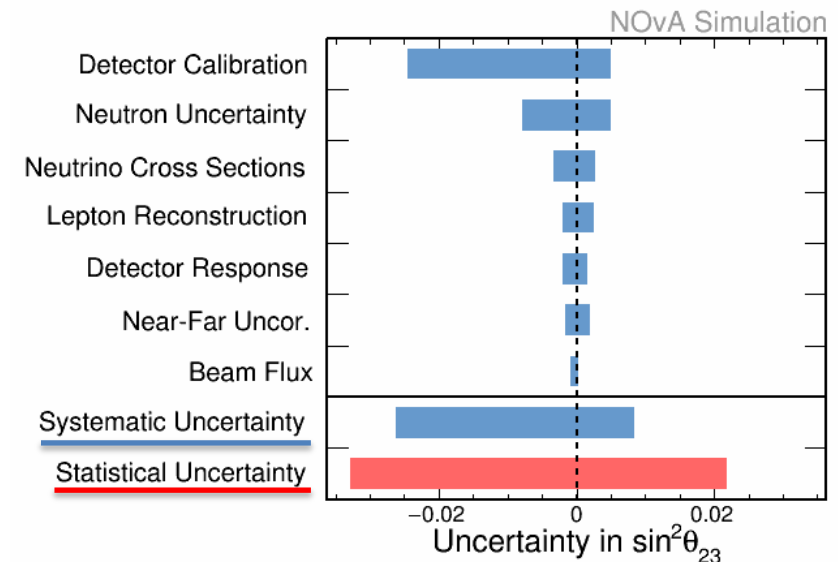
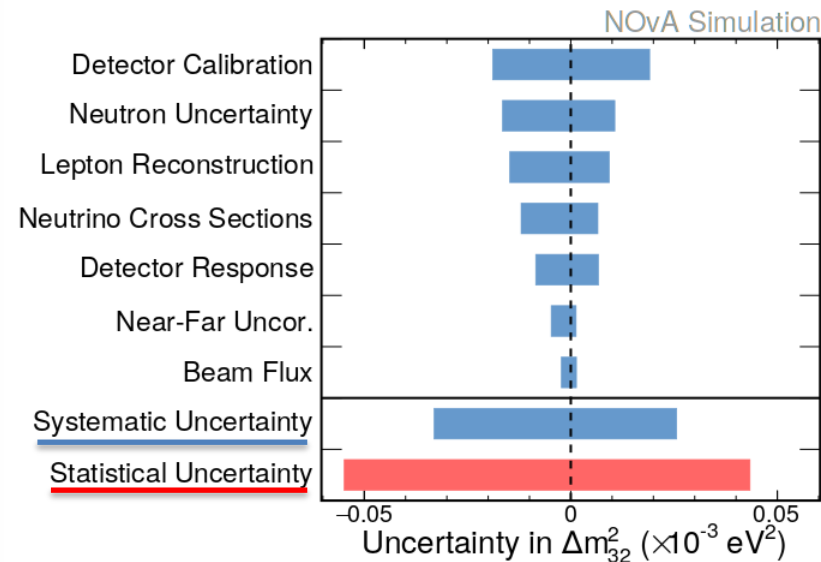
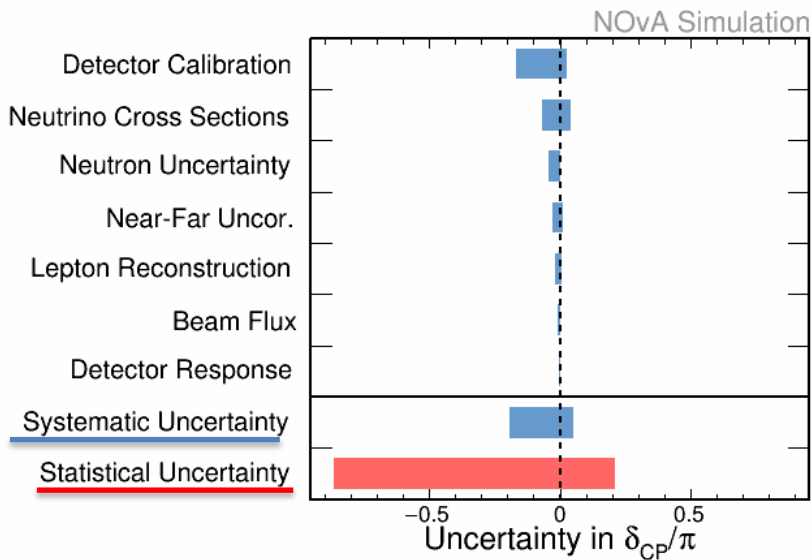
$$\sin^2 \theta_{23} = 0.57^{+0.04}_{-0.03}$$

$$\delta = 0.82\pi$$

NOvA Preliminary



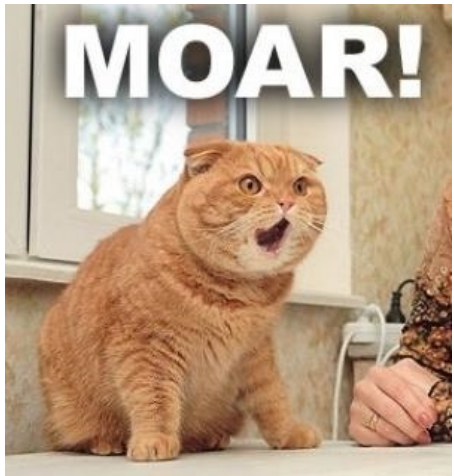
# NOvA Uncertainties



Statistics are currently the largest uncertainty in our measurements

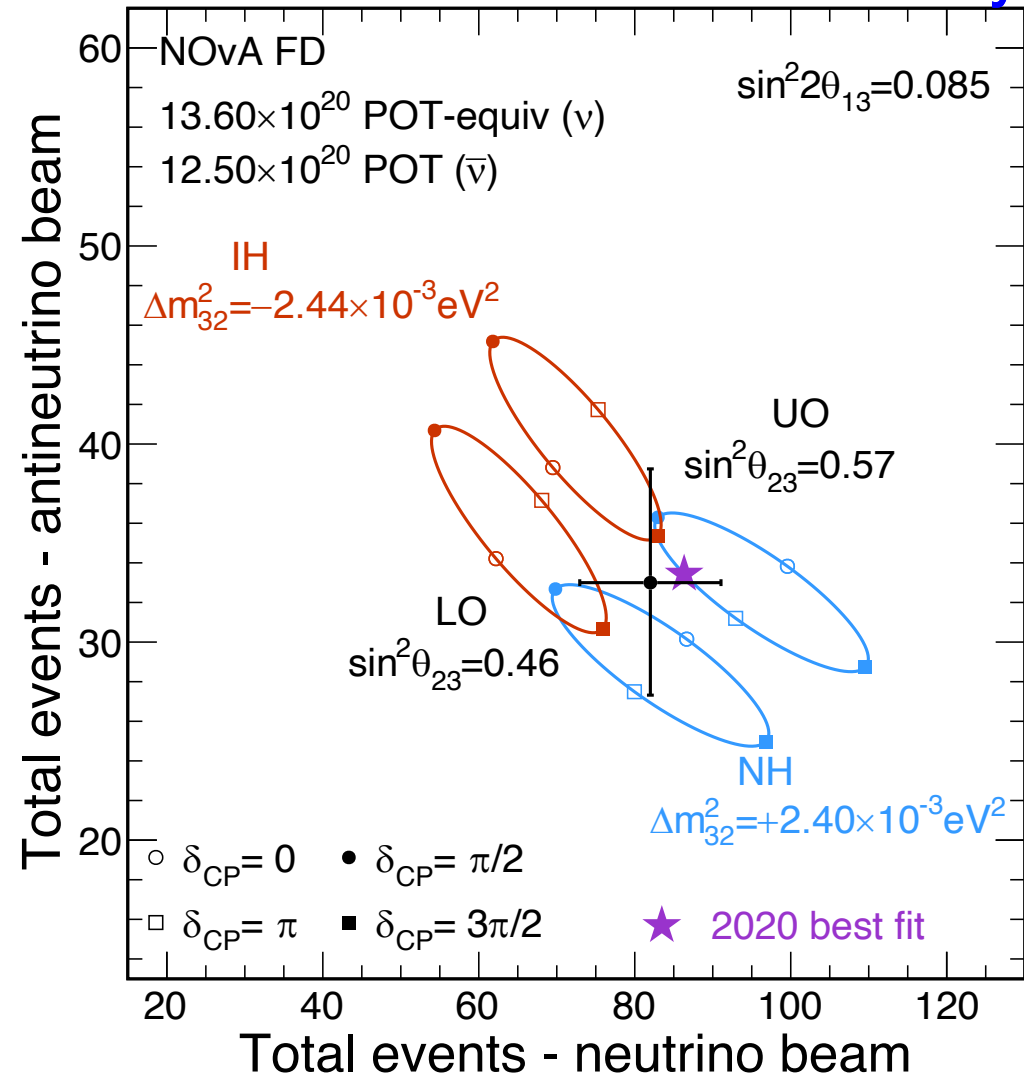
# Summary

- NOvA is a long baseline neutrino oscillation experiment trying to better understand Mass Ordering, CP phase, and  $\theta_{23}$ .
- Joint fit with T2K coming later this year!



**We are taking some time to work on our side quests and increase the size of our oscillation dataset to come back better than ever!**

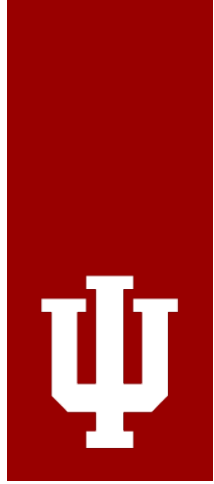
## NOvA Preliminary





April 2022



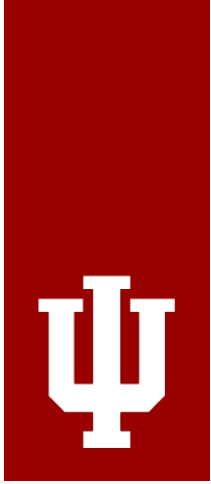


Thank you!  
Gracias!



<http://novaexperiment.fnal.gov>





# Backup slides

# Oscillations in Matter

$\nu_e$  appearance

$$P(\nu_\mu \rightarrow \nu_e) = P_{atm} + 2\sqrt{P_{atm}}\sqrt{P_{sol}} (\cos\Delta_{32} \cos\delta \mp \sin\Delta_{32} \sin\delta) + P_{sol}$$

$$\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL} \left( \frac{\Delta m_{31}^2 L}{4E} \right)$$

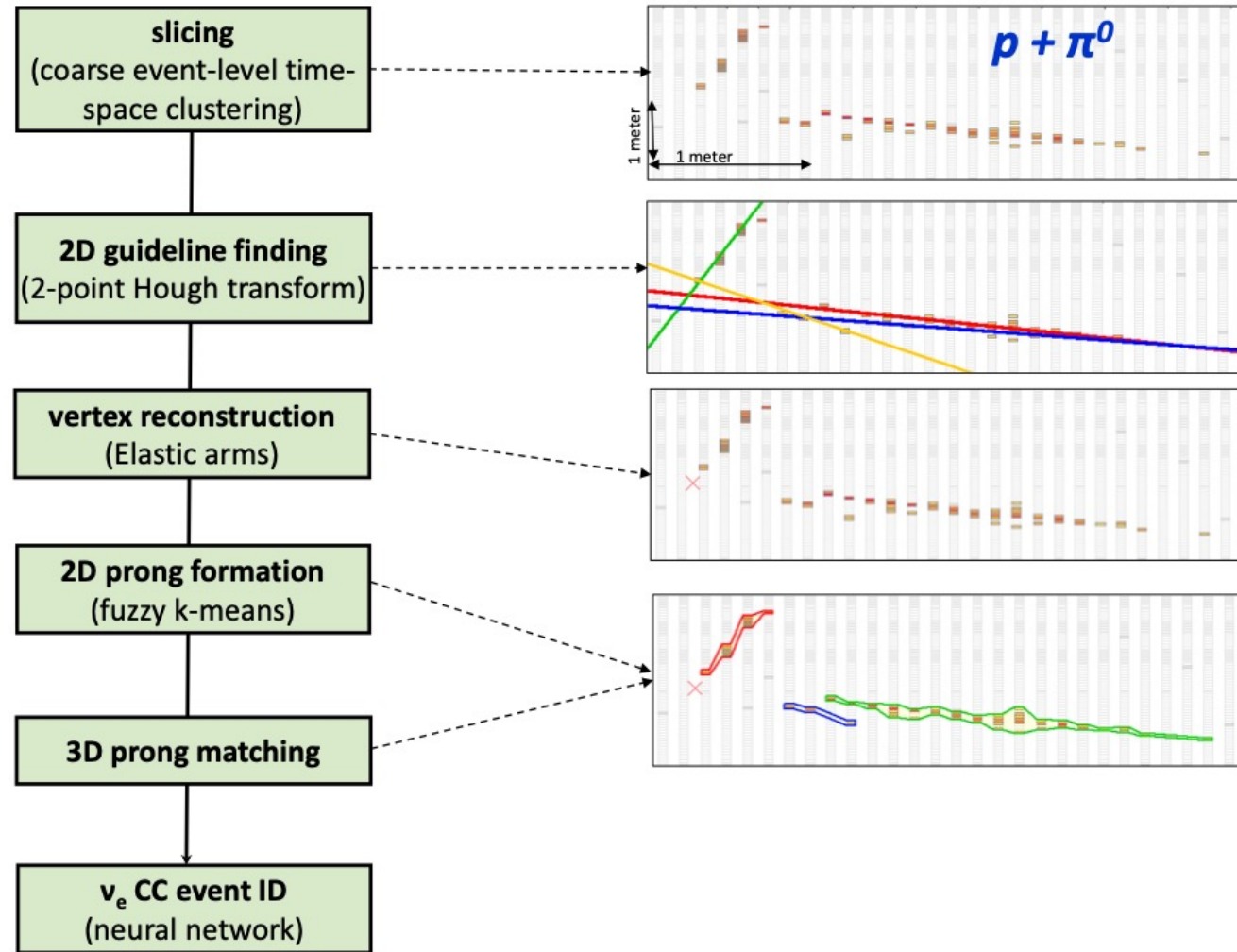
$$\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{aL} \left( \frac{\Delta m_{31}^2 L}{4E} \right)$$

$$\Delta_{jk} \equiv \frac{\Delta m_{jk}^2 L}{4E}$$

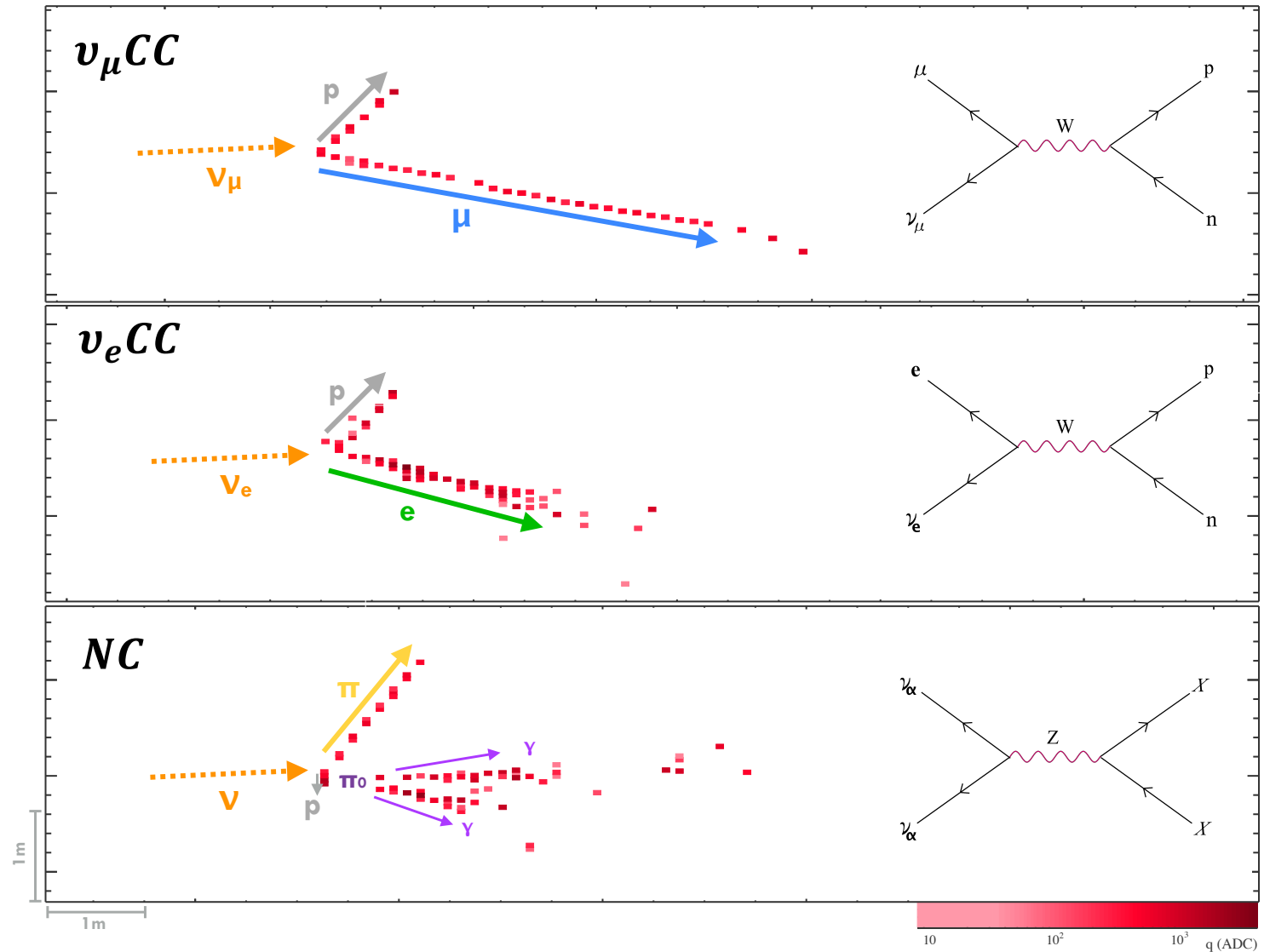
$$a = \frac{G_F N_e}{\sqrt{2}}$$

$$\Delta m_{jk}^2 = m_j^2 - m_k^2$$

# NOvA Reconstruction Chain

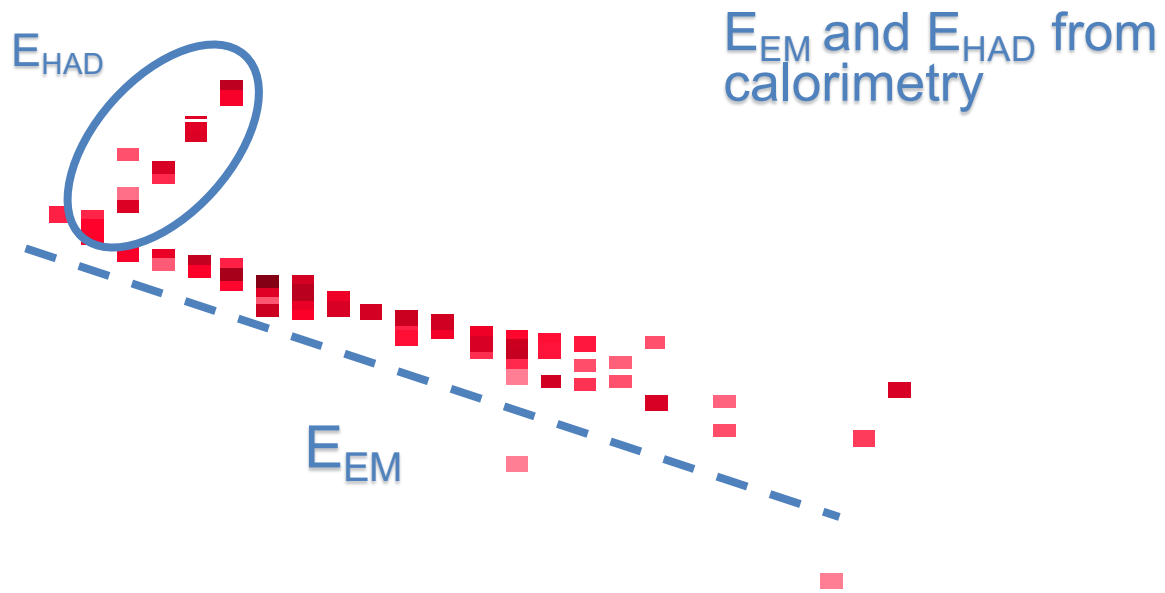


# Event classification

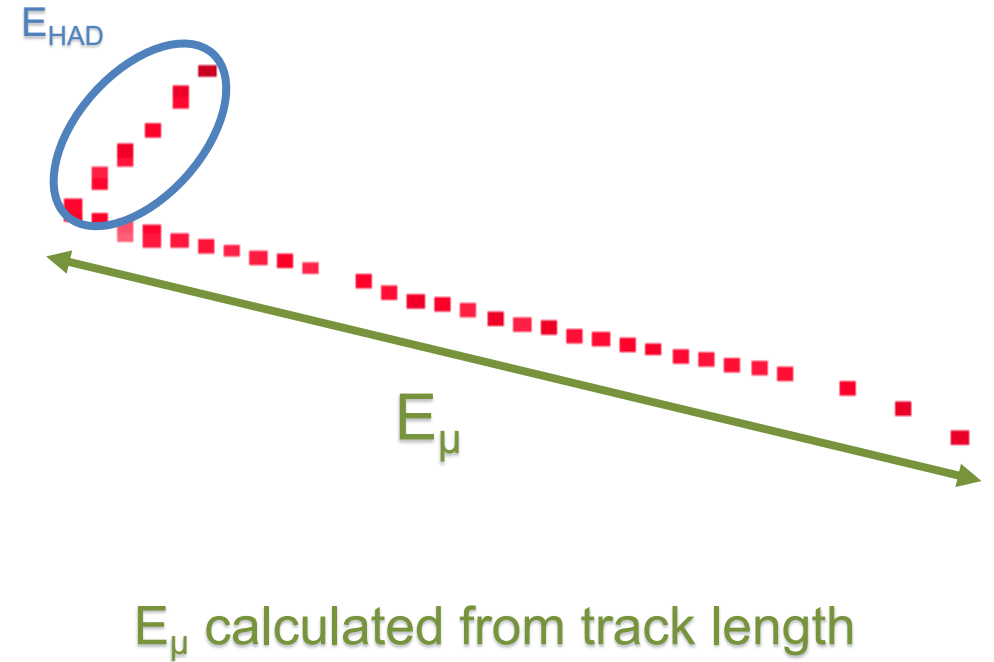


# NOvA Energy Reconstruction for CC

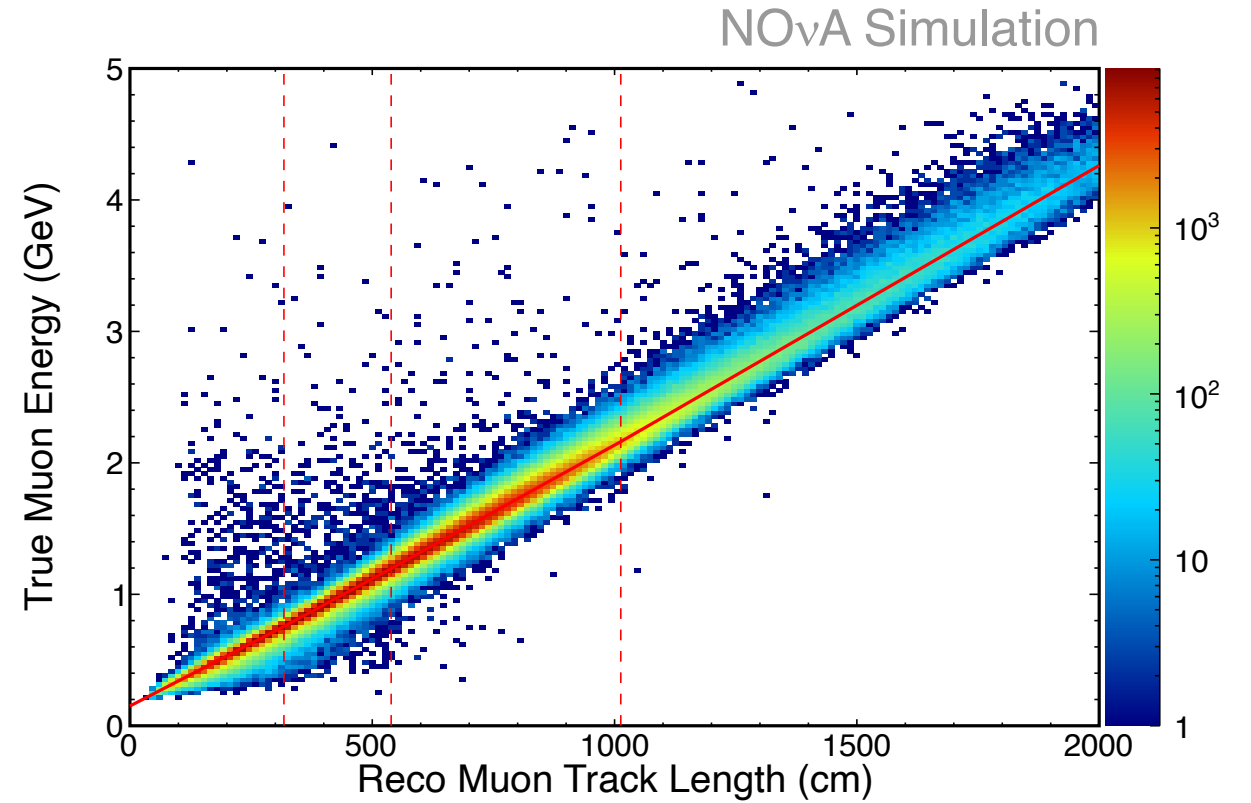
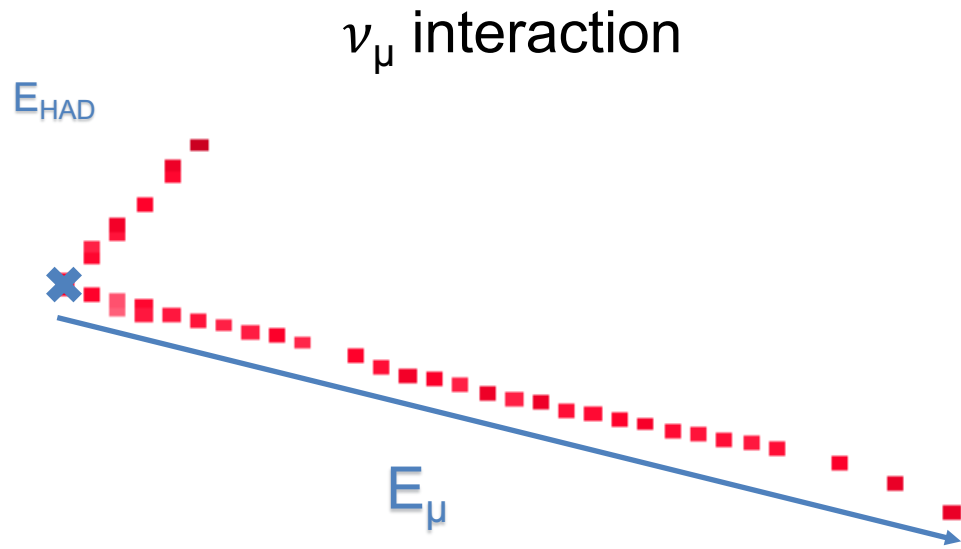
$\nu_e$  interaction



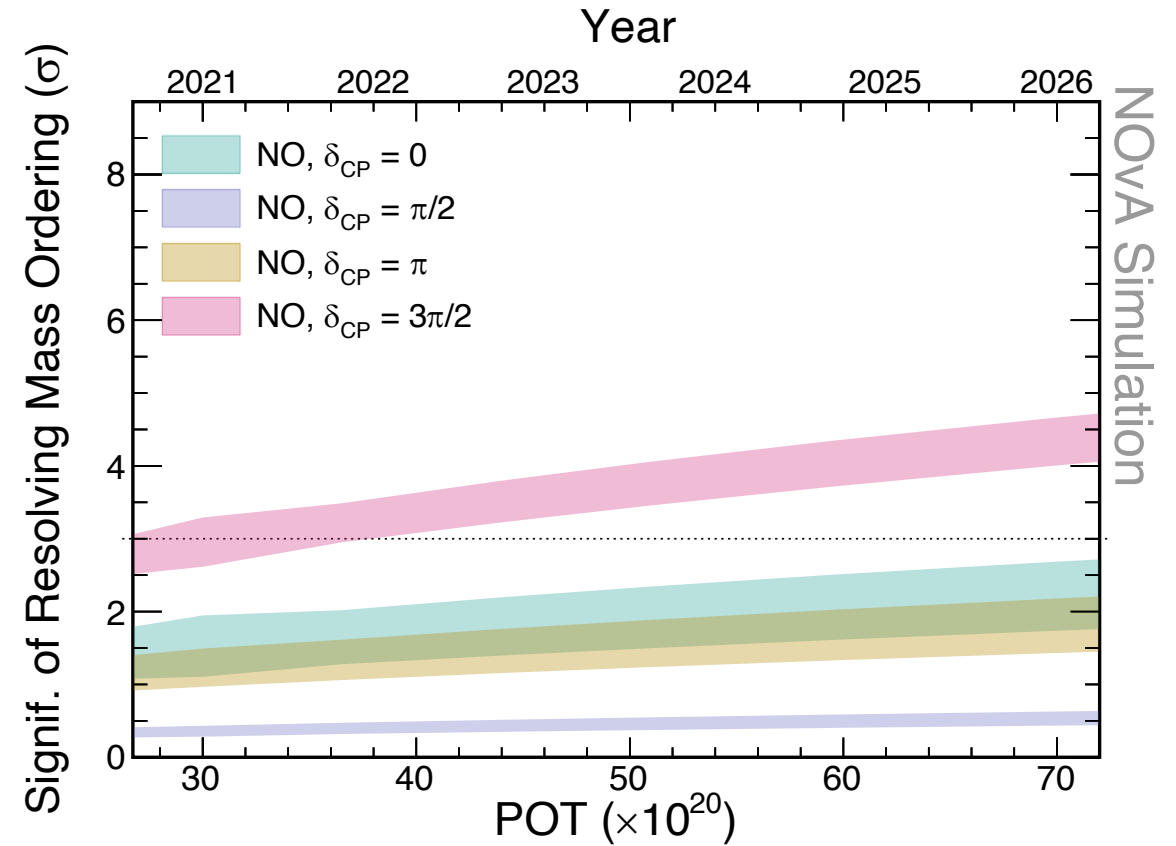
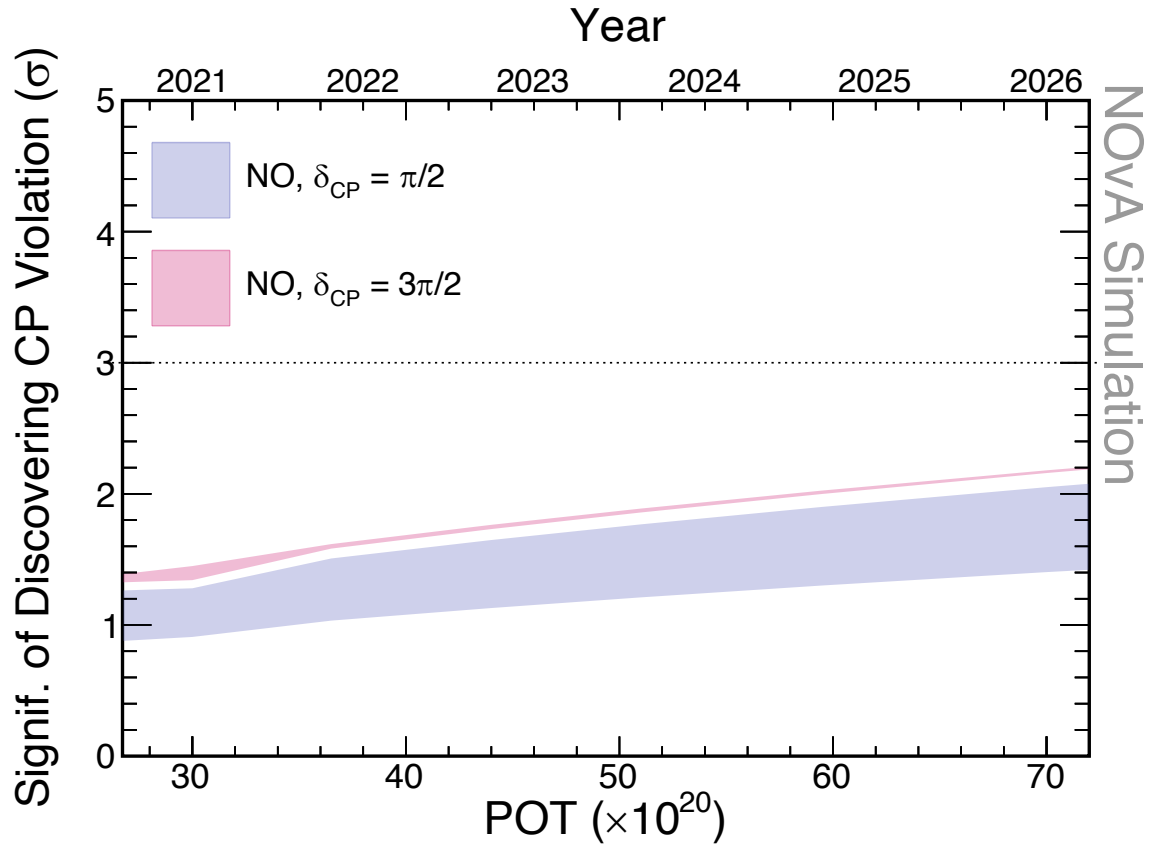
$\nu_\mu$  interaction



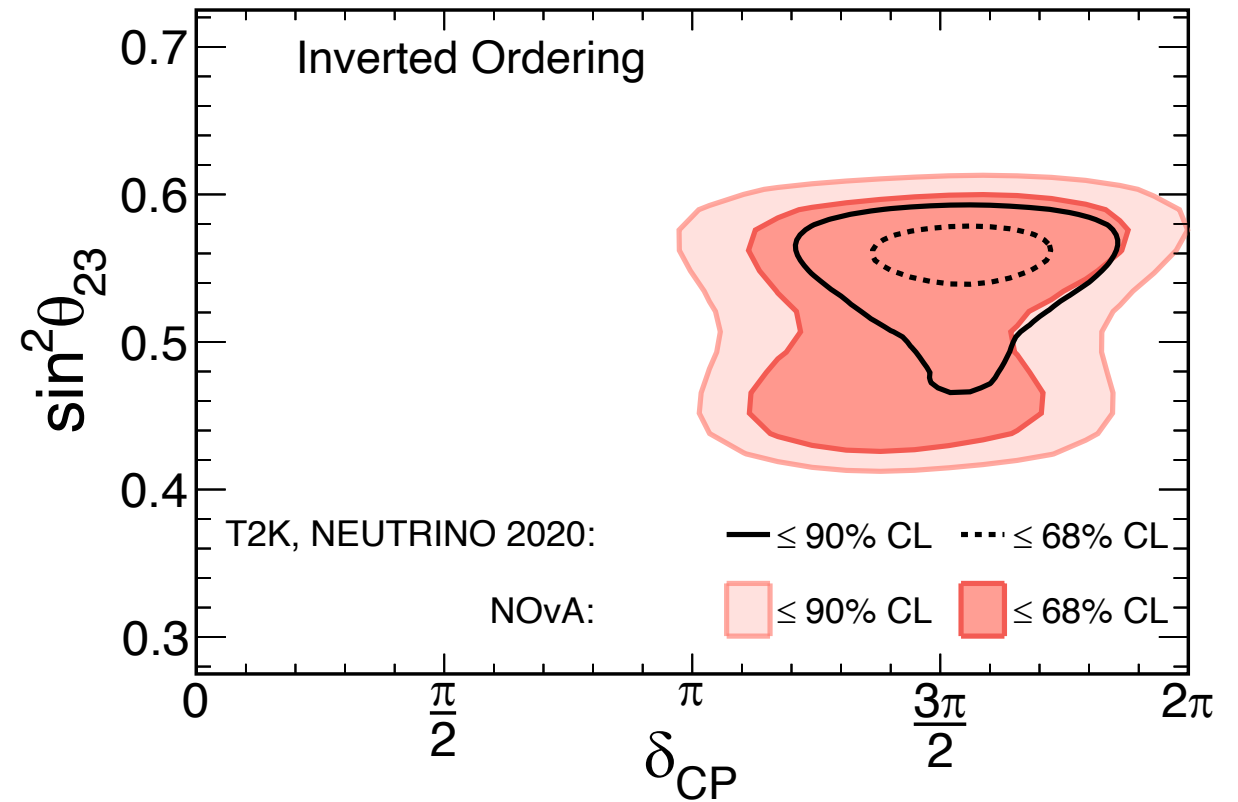
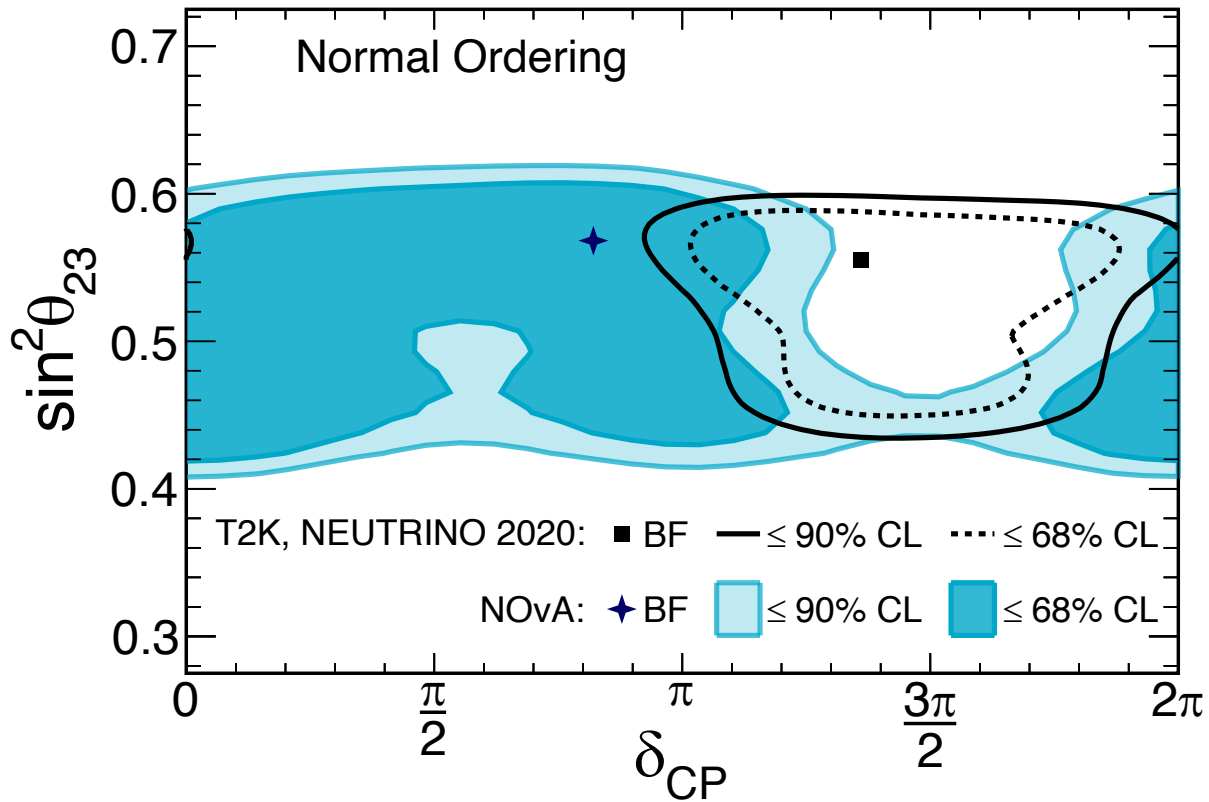
# Looking at $\nu_\mu$ CC



# Projected Sensitivities

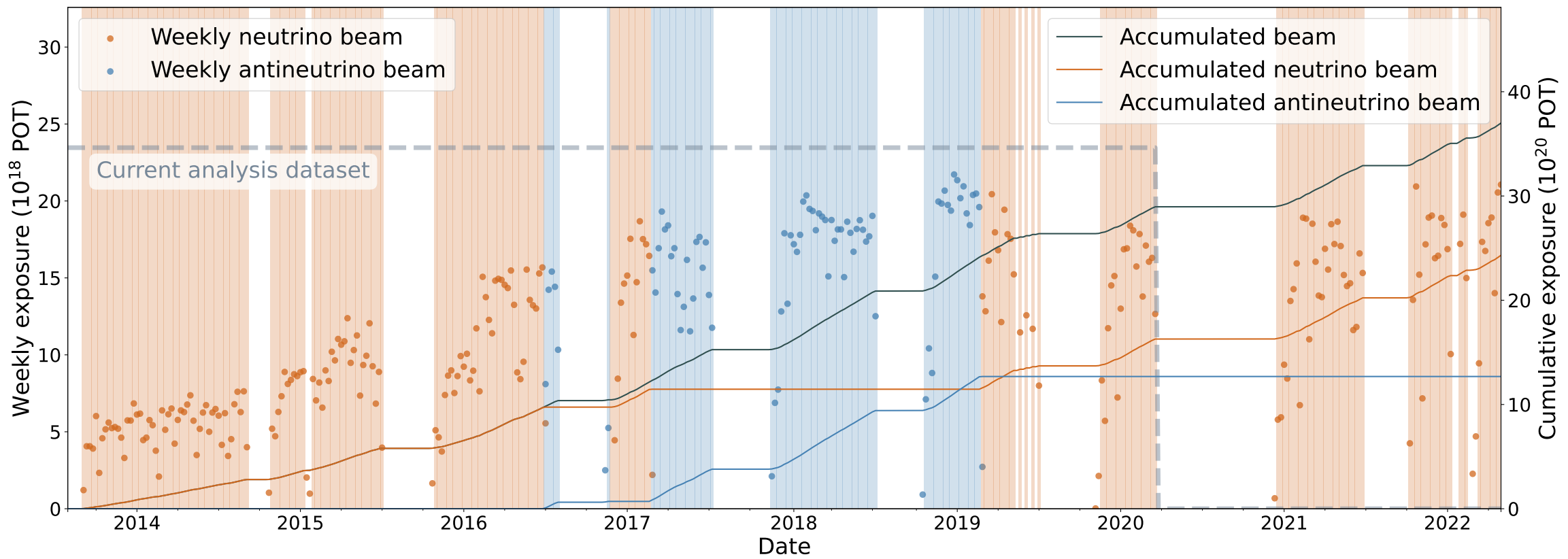


# NOvA vs T2K





# NOvA Exposure



# NOvA with friends

