Recent Results from Long-Baseline Experiments

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(With Input from Mayly Sanchez)

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3. September. 2018

Invisibles 2018, KIT, Karlsruhe

elusives
neutrinos, dark matter & dark energy physics

Department of Sciences
& Technology
Government of India

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Neutrino Mixing & PMNS Matrix

FLAVOR Eigenstates

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

MASS Eigenstates

Atmospheric | Cross Mixing | Solar | Majorana

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$\nu_\mu \leftrightarrow \nu_\tau$

Atmospheric ν_μ
Long Baseline
L/E ~500 Km/GeV

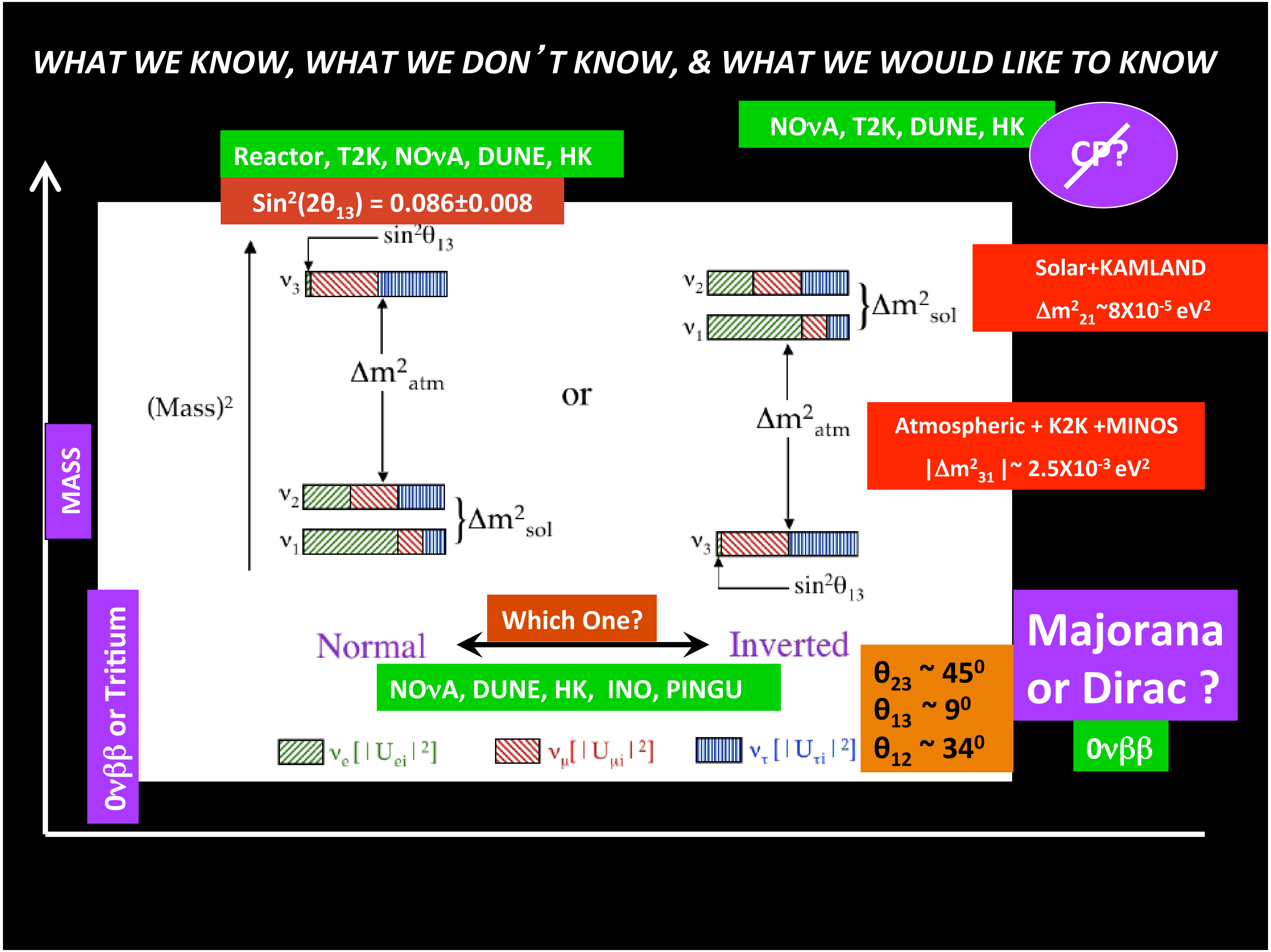
$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

Reactor Short Baseline
ν_μ Long Baseline
L/E ~ 500 Km/GeV

$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

Solar + Reactor Long Baseline
L/E ~ 15,000 Km/GeV

ν oscillations with 3ν's can be described by three(3) angles, one(1) phase, two(2) mass-squared (Δm^2) difference, and two(2) signs of mass squared (Δm^2) differences.


WHAT WE KNOW, WHAT WE DON'T KNOW, & WHAT WE WOULD LIKE TO KNOW
NOνA, T2K, DUNE, HK
CP?
Reactor, T2K, NOνA, DUNE, HK
$Sin^2(2\theta_{13}) = 0.086 \pm 0.008$
$\sin^2\theta_{13}$
ν_3
ν_2
ν_1
Δm^2_{sol}
Solar+KAMLAND
$\Delta m^2_{21} \sim 8X10^{-5}\ eV^2$
Δm^2_{atm}
(Mass)^2
or
Atmospheric + K2K +MINOS
$|\Delta m^2_{31}| \sim 2.5X10^{-3}\ eV^2$
MASS
ν_2
ν_1
Δm^2_{sol}
ν_3
$\sin^2\theta_{13}$
Which One?
Normal
Inverted
NOνA, DUNE, HK, INO, PINGU
$0\nu\beta\beta$ or Tritium
$\nu_e[|U_{ei}|^2]$
$\nu_\mu[|U_{\mu i}|^2]$
$\nu_\tau[|U_{\tau i}|^2]$
$\theta_{23} \sim 45^0$
$\theta_{13} \sim 9^0$
$\theta_{12} \sim 34^0$
Majorana or Dirac ?
$0\nu\beta\beta$

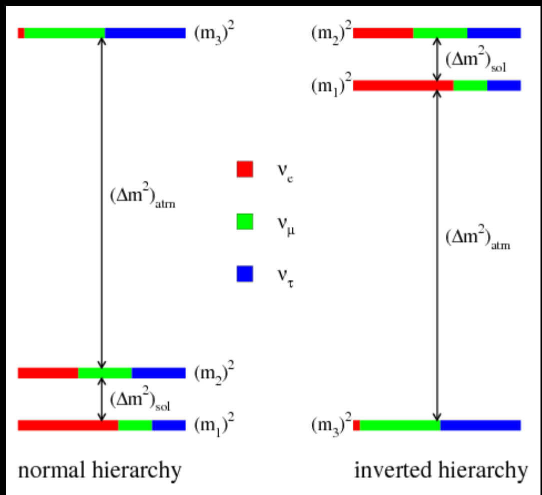
Neutrino Masses and Mixing
What do we not know in 3-flavor paradigm

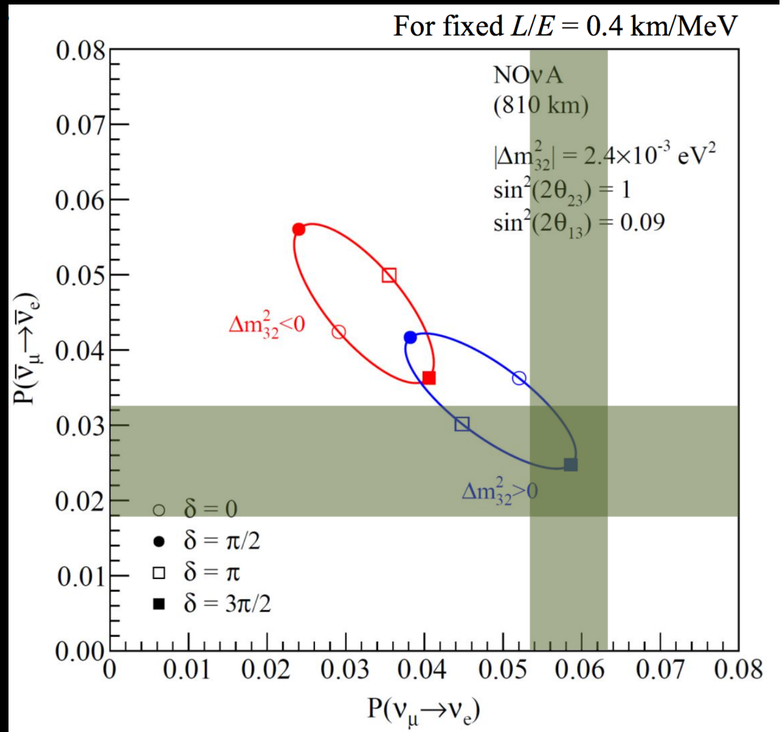
- ❑ ***CP violation in the lepton sector has NOT been measured***
  - ✓ ***May explain matter-antimatter asymmetry through leptogenesis***
  - ✓ ***Precision measurement of δ_{CP} is neded to understand the structure of PMNS matrix and underlying symmetries***
- ❑ ***Mass Hierarchy or ordering is NOT known for the atmospheric neutrinos***
  - ✓ ***Important to be able to understand the reach of experiments that study if neutrinos are Majorana or Dirac***
- ❑ ***Octant of ϑ_{23} is NOT known***
  - ✓ ***In case of non-maximal mixing this uncertainty impacts our knowledge of MH and CPV***
  - ✓ ***Precision measurement of ϑ_{23} is important for testing PMNS unitarity and for model building***

Goals of Long-Baseline Experiments

- Measure the oscillation probabilities of
  a) Appearance channels: $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
  b) Disappearance channels: $\nu_\mu \rightarrow \nu_\mu$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$

- Precision measurements of θ_{13}, Δm^2_{32}, θ_{23}
- Probe the Mass Hierarchy
- Study the CP violation parameter δ

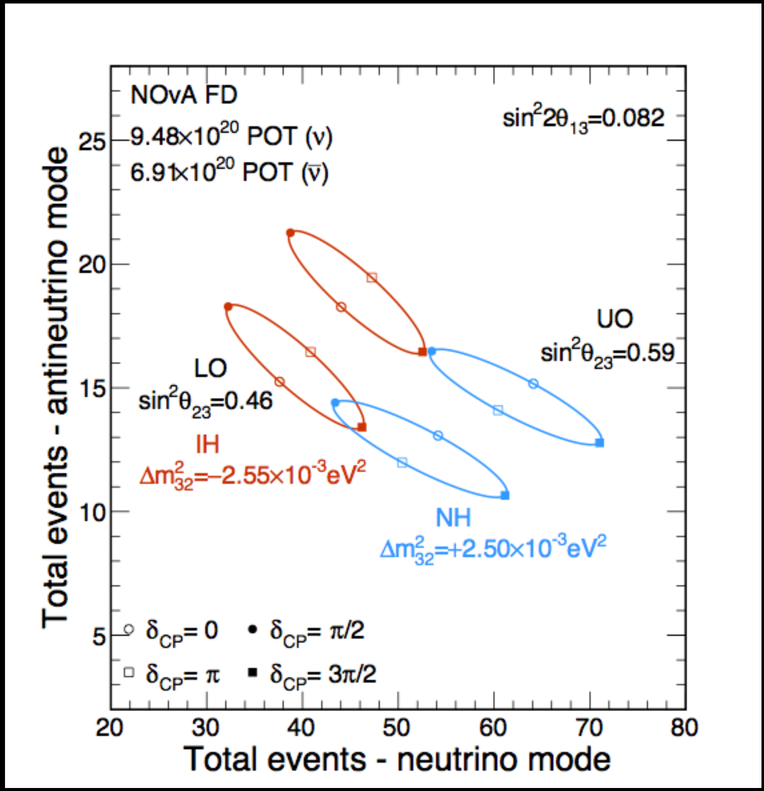




- Additional Physics Goals:
  -Neutrino cross-sections and interaction physics
  -Sterile Neutrinos
  -Supernovae and Exotic Searches

Neutrino Masses and Mixing
Neutrino and Antineutrino Data are Required

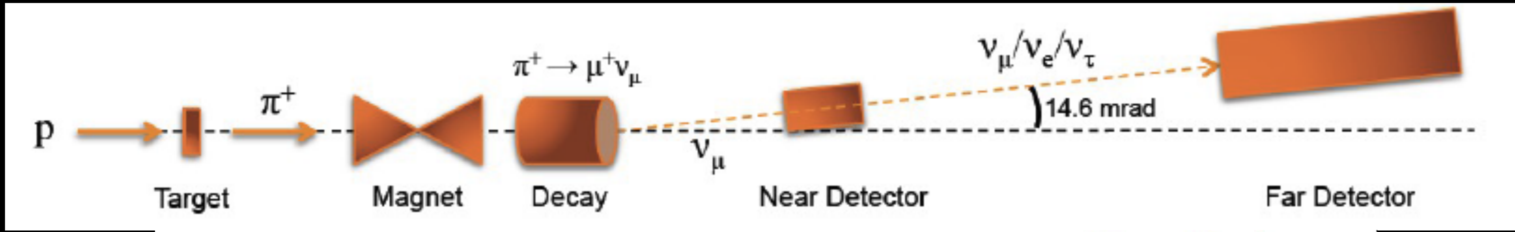
- ✓ ***What is the Mass Hierarchy or Mass Ordering for neutrinos?***
- ✓ ***Is there ν_μ - ν_τ symmetry (is the large mixing angle maximal; if not what is the octant)?***
- ✓ ***Is CP violated in the lepton sector?***
- ✓ ***Are there other neutrinos beyond the three known active flavors?***

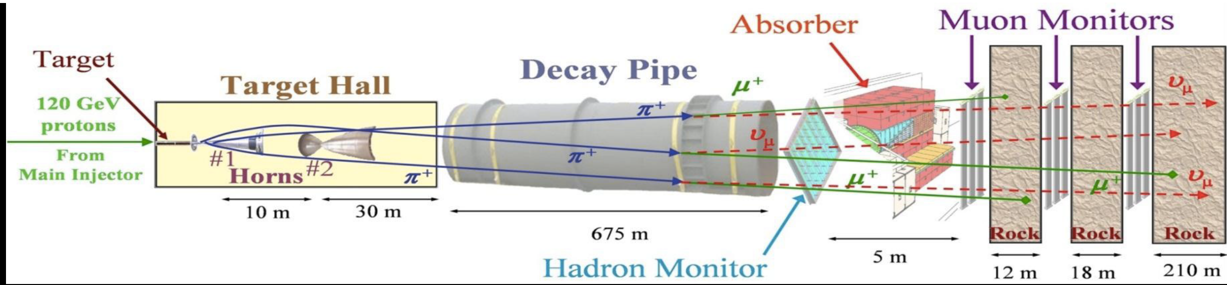


The long-baseline accelerator experiments seek to answer these questions

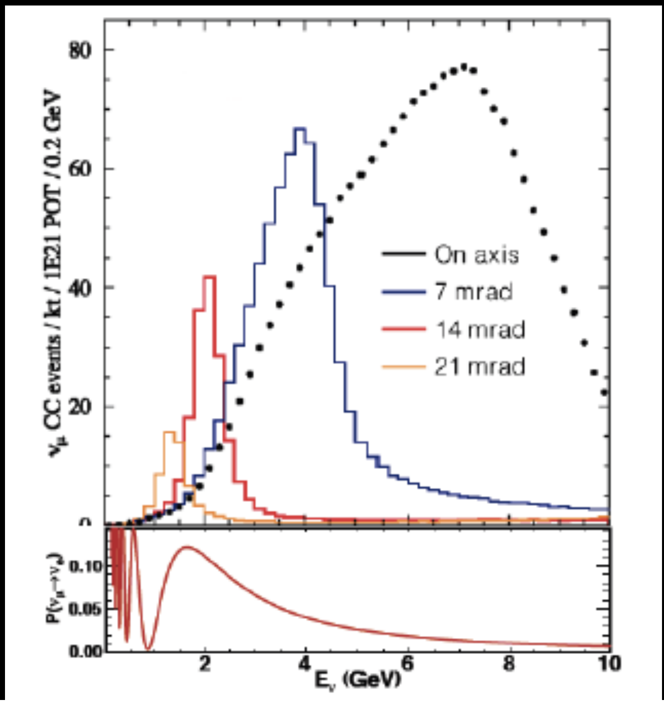
Long-Baseline Experiments/Program

Producing Neutrino Beams @ Fermilab





- ➢ *NuMI beam operated up to 750 kW*
- ➢ *700kW achieved*



Detectors placed at 14.6 mrad off-axis from the beam direction

- ✓ ***This leads to a narrow band beam peaked at ~2GeV energy***
- ✓ ***This happens near the maximum oscillation***
- ✓ ***Leads to reduced high energy Neutral Current (NC) events***

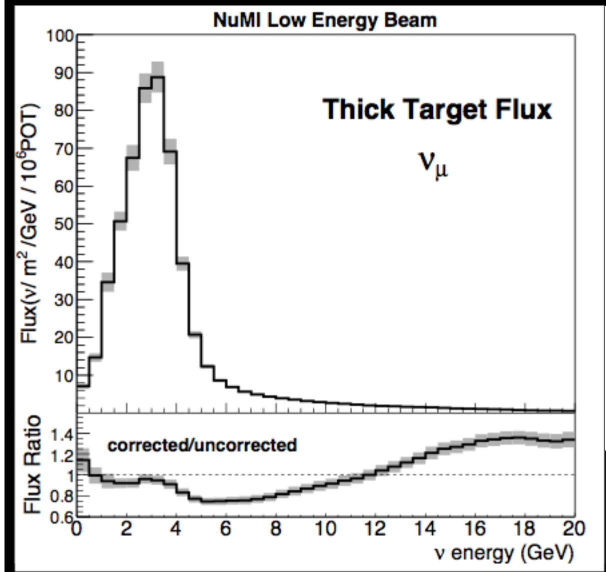
How Long-Baseline Experiments Work

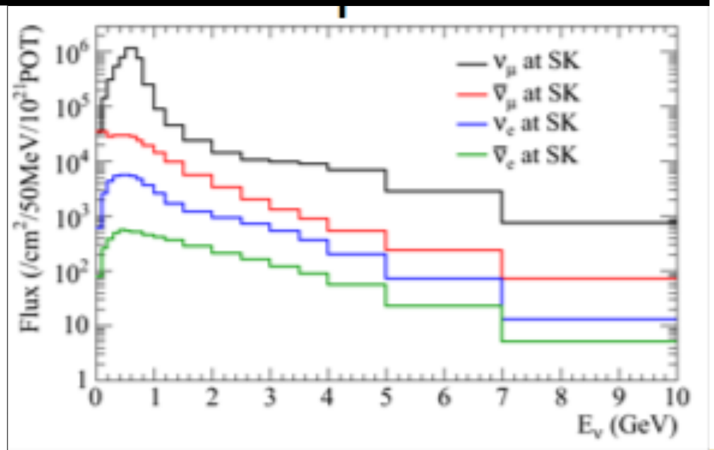
Precision is achieved by placing a Near Detector close to the beam and a Far Detector at or close to the oscillation maximum

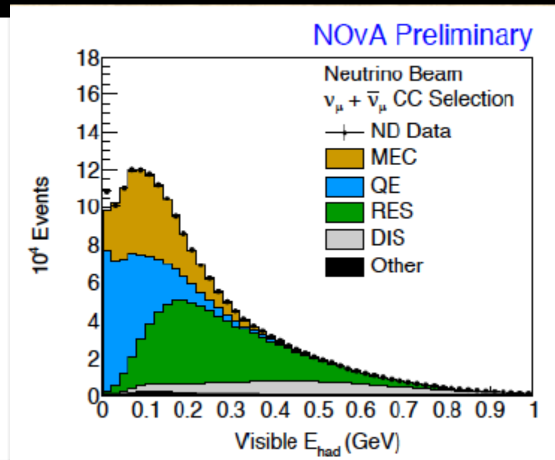
$$ND(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{ND}$$
$$FD(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{FD} \times P_{osc}$$

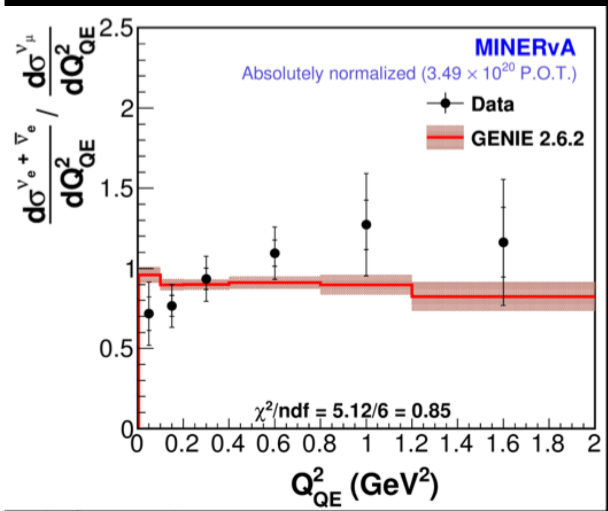
Understanding the Neutrino Flux, Cross Sections & Detector Efficiencies is must for achieveing High Precision Results

Understanding Neutrino Flux and Cross Sections



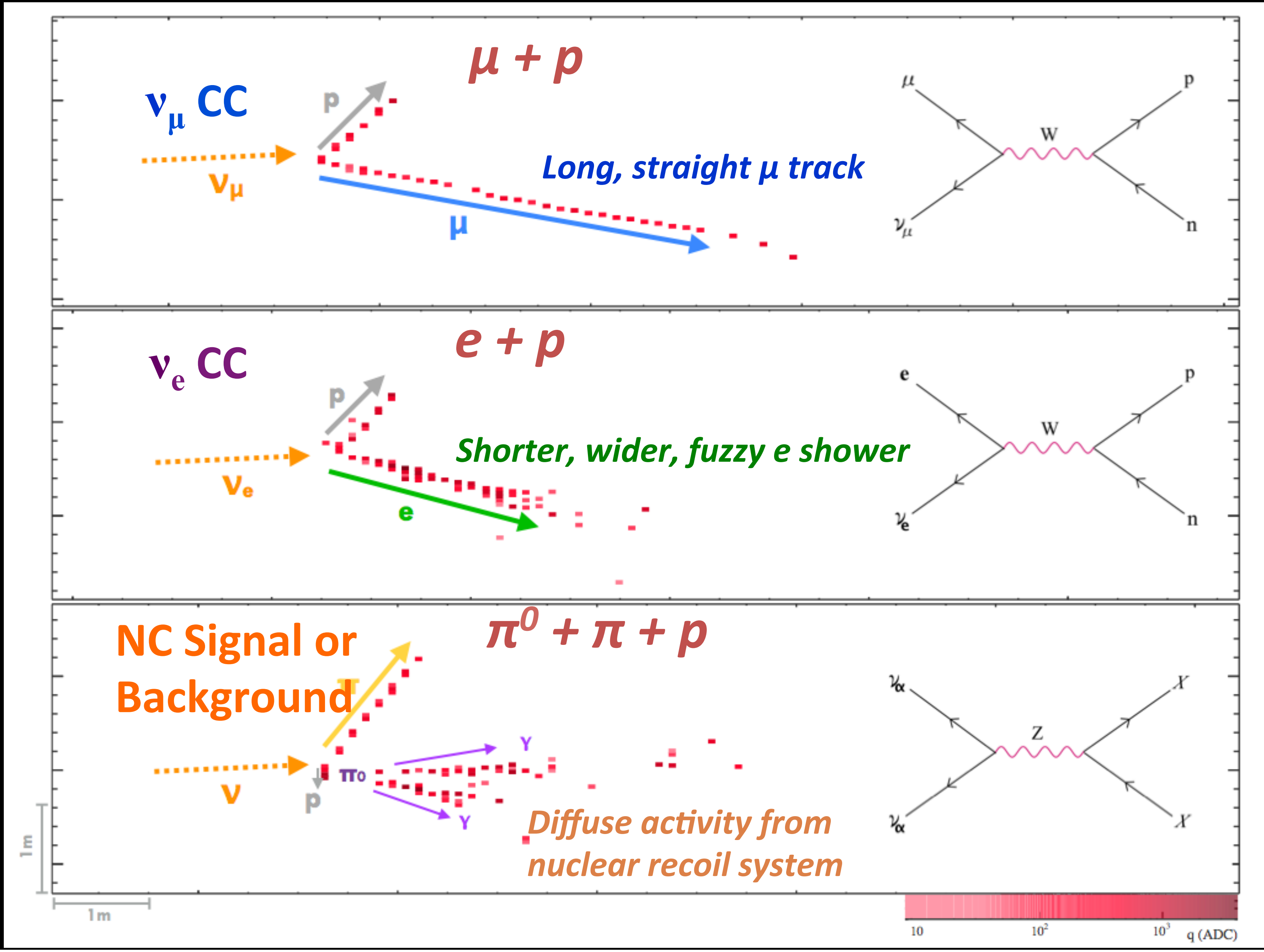






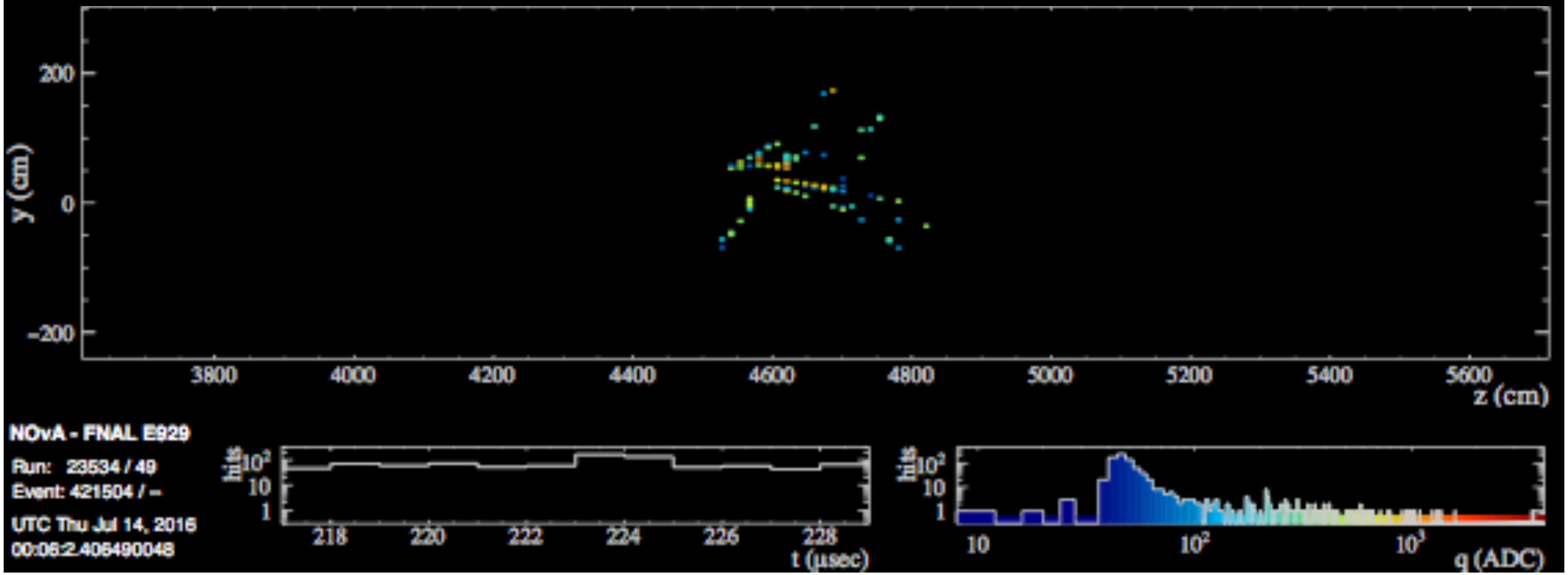
- ✓ ***LBL experiments make special effort to understand the beam flux and neutrino cross-sections.***
- ✓ ***MINERvA at Fermilab is designed to study neutrino interactions. Broad spectrum of result available from them.***
- ✓ ***T2K has pursued this topic aggressively significantly reducing their systematic uncertainties.***
- ✓ ***High statistics sample continues to provide evidence for the need for better modeling/data.***

NOνA FD Event Topologies

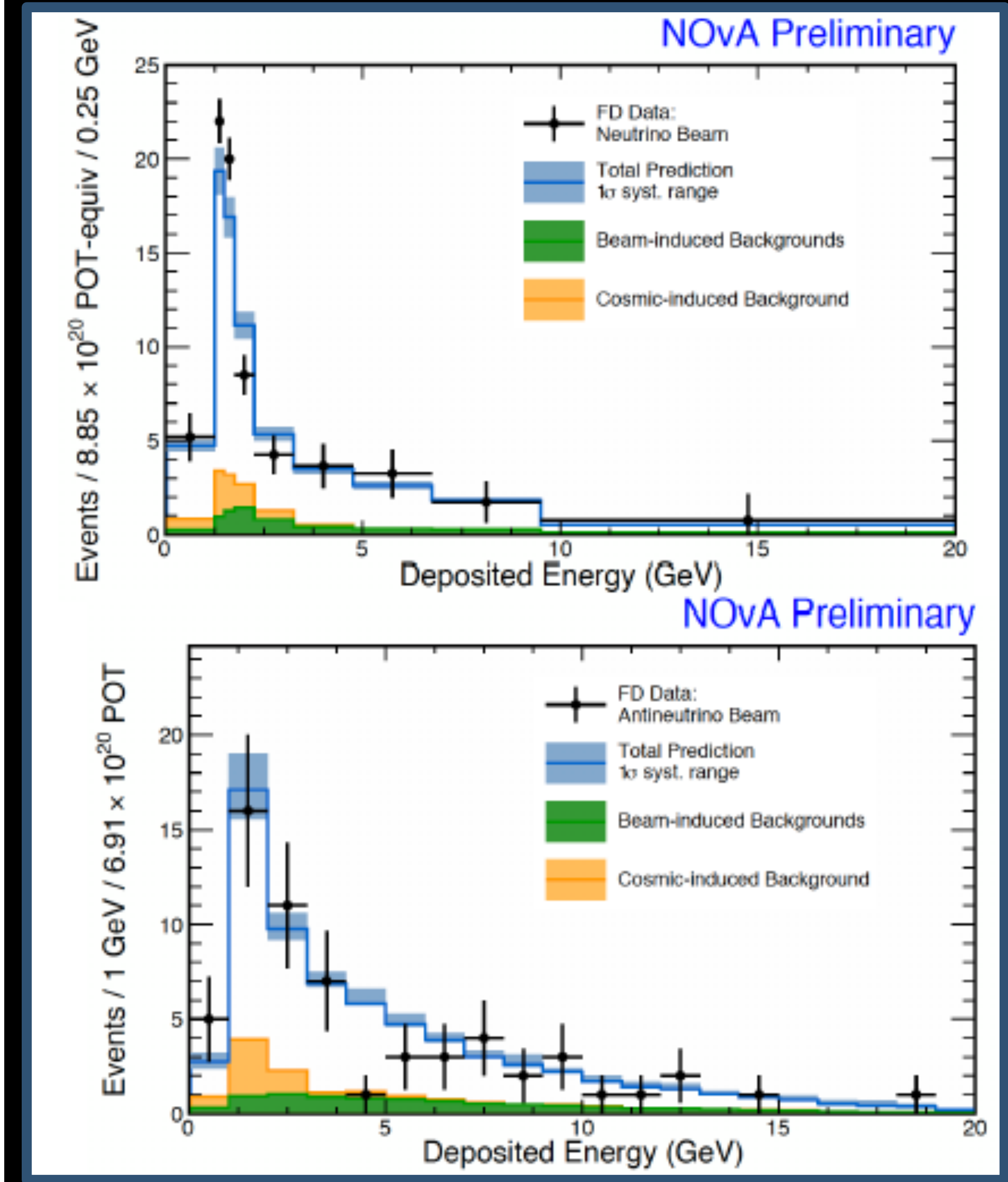


Are there other neutrinos beyond the three known active flavors

Neutrino and Antineutrino Neutral Current Event Disappearance



NOvA NC Spectra in the Far Detector



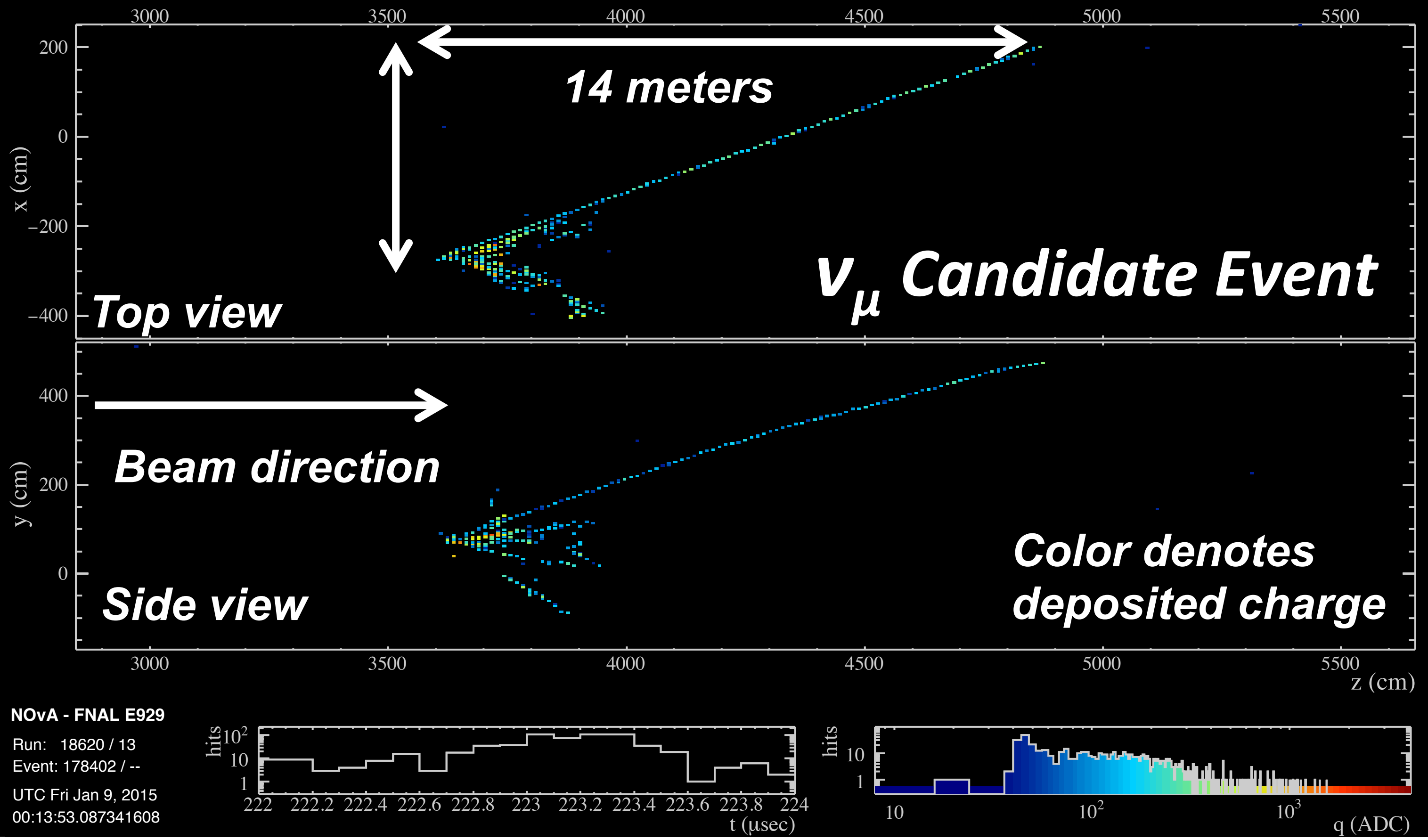
For the neutrino beam:
Observe: 201 events
Predict: 188 ± 13 (syst.) events (38 background)

For anti-neutrino beam:
Observe: 61 events
Predict: 69 ± 8 (syst.) interactions (16 background)

No significant suppression of Neutral Current events observed either for neutrino or anti-neutrino beams.

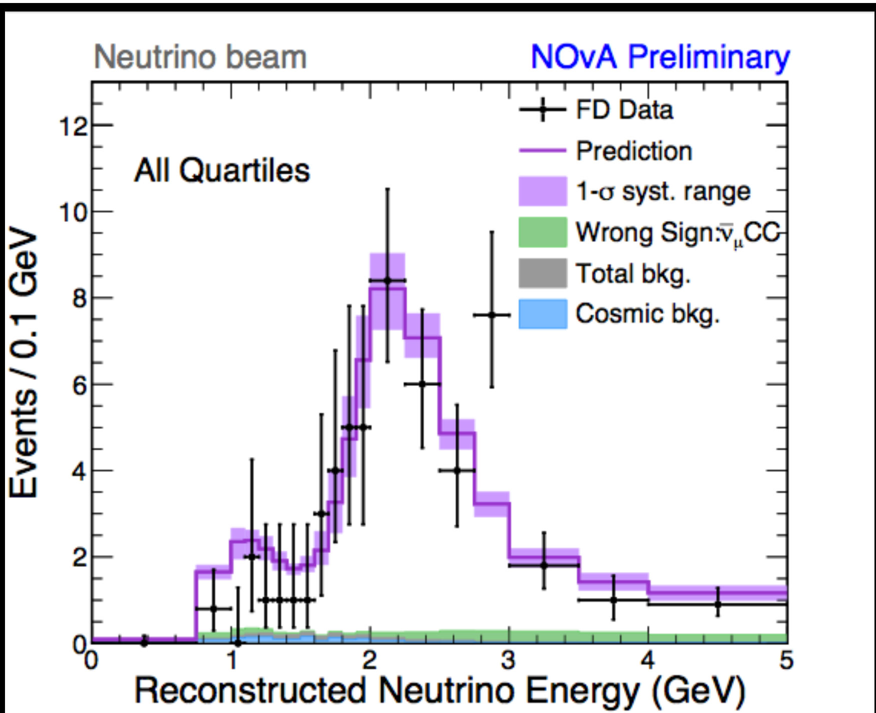
Is there a νμ - ντ symmetry?

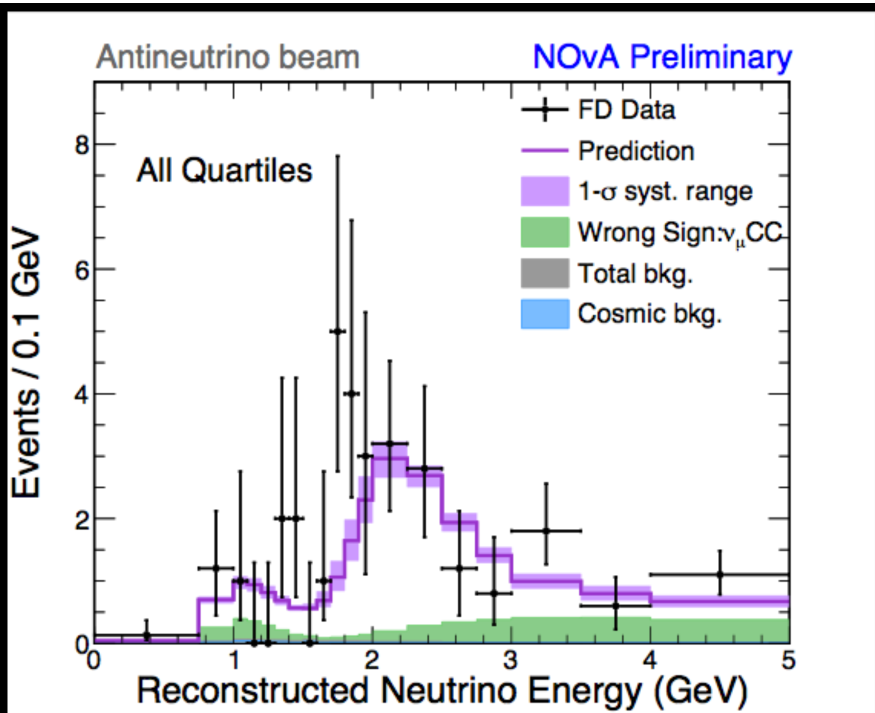
Muon Neutrino and Antineutrino Disappearance



NOvA Disappearance Spectra in the Far Detector

- Muon neutrinos are selected and the true Far/Near ratio is used to obtain a FD prediction from ND data. The dip is a signature of oscillation where the muon neutrino disappears.
- We estimate cosmic background rate from the timing sidebands of the NuMI beam triggers and cosmic trigger data.

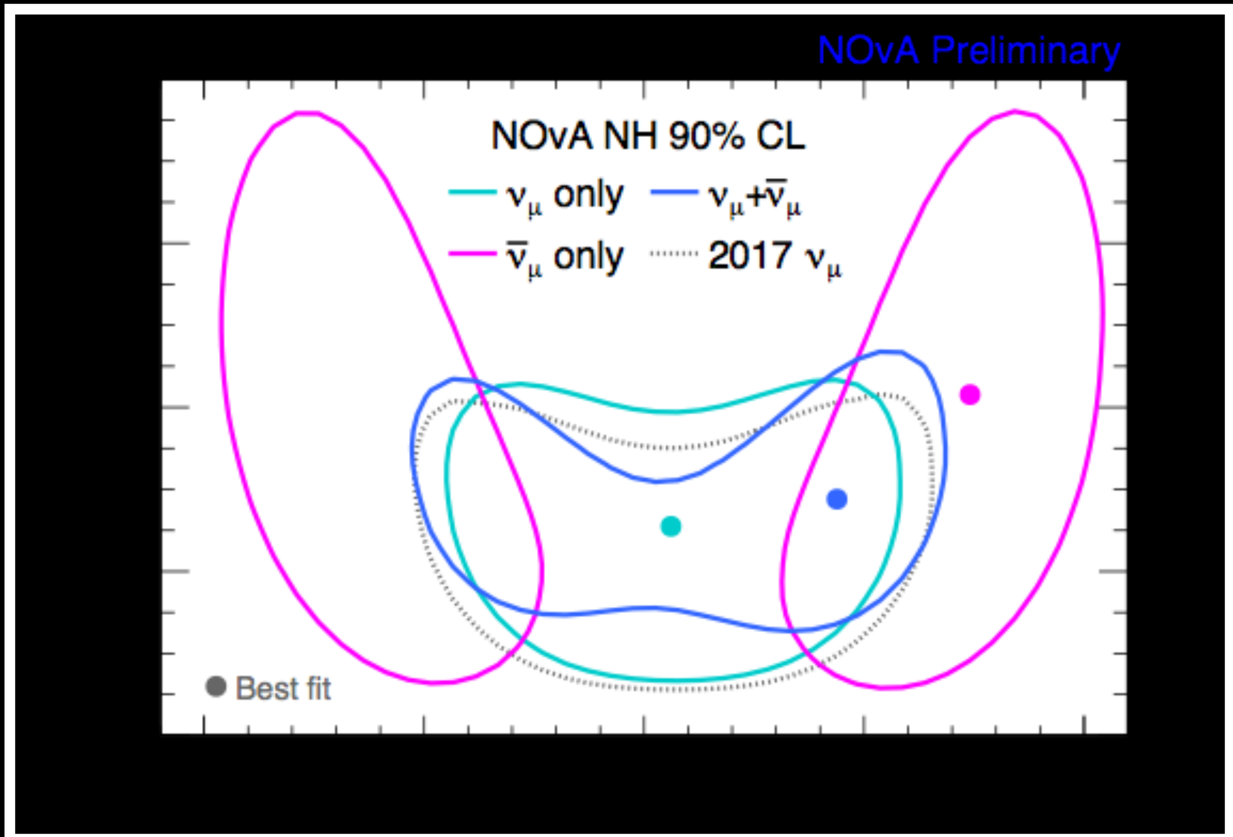




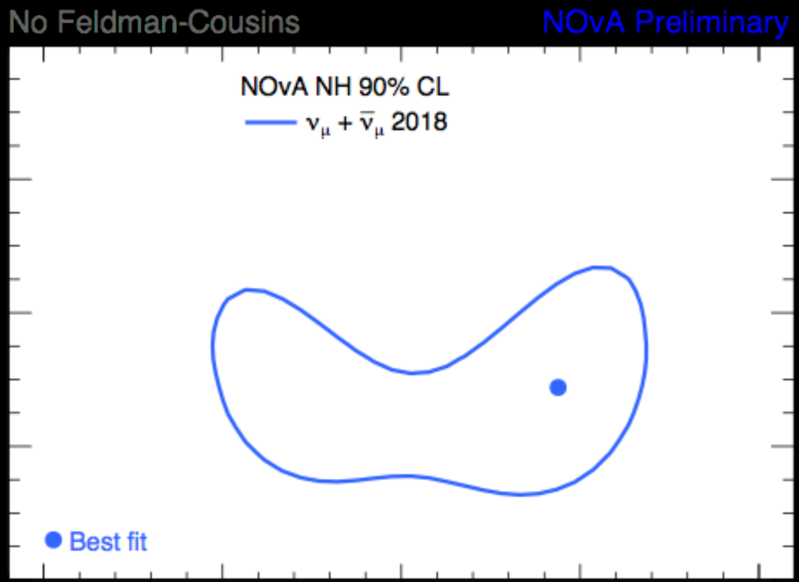
Neutrino Mode: Observe: 113 events; Expect: 730 +38/-49 (syst.) events w/o oscillation
Anti-Neutrino Mode: Observe: 65 events; Expect: 266 +12/-14 (syst.) events w/o oscillation

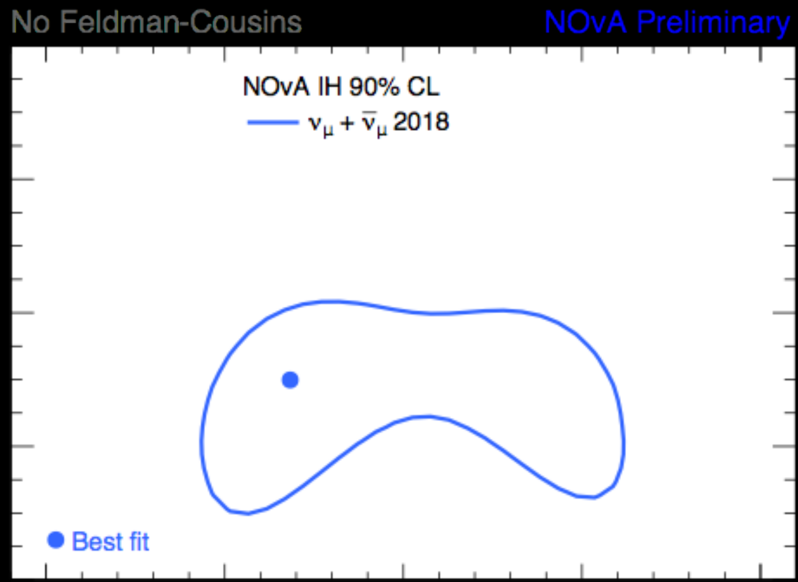
NOvA ν_μ & vbar$_\mu$ Disappearance Results

- ✓ *The combined data of neutrino & antineutrino beams are fit assuming CPT invariance*
- ✓ *Neutrino beam mode: Observe: 113 events, Best fit expectation:126 events*
- ✓ *Anti-neutrino beam mode, Observe: 65 events, Best fit expectation: 52 events*
- ✓ *If fit separately, the anti-neutrino beam mode prefers a more non-maximal solution.*
- ✓ *Consistency with the combined fit oscillation parameters for the neutrino and antineutrino datasets is better than 4% (32% for neutrino-only compatibility and 14% for antineutrino-only). Combined data is consistent with the previous results.*



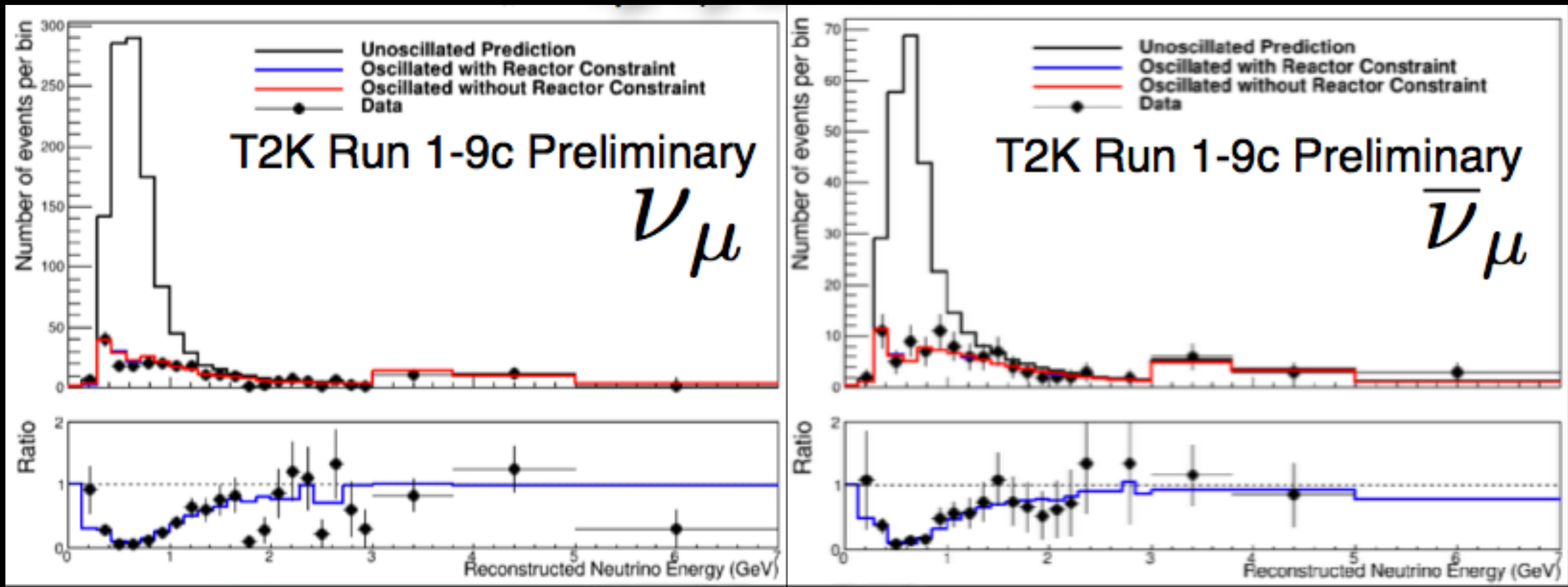
NOvA ν_μ & vbar$_\mu$ Disappearance Results





- ✓ *Matter effect introduces a small asymmetry in the maximal disappearance point between neutrinos and anti-neutrinos*
- ✓ *Tension between the muon neutrino and antineutrino dataset (at the 1σ level) favors upper octant for normal hierarchy and lower octant for the inverted hierarchy*

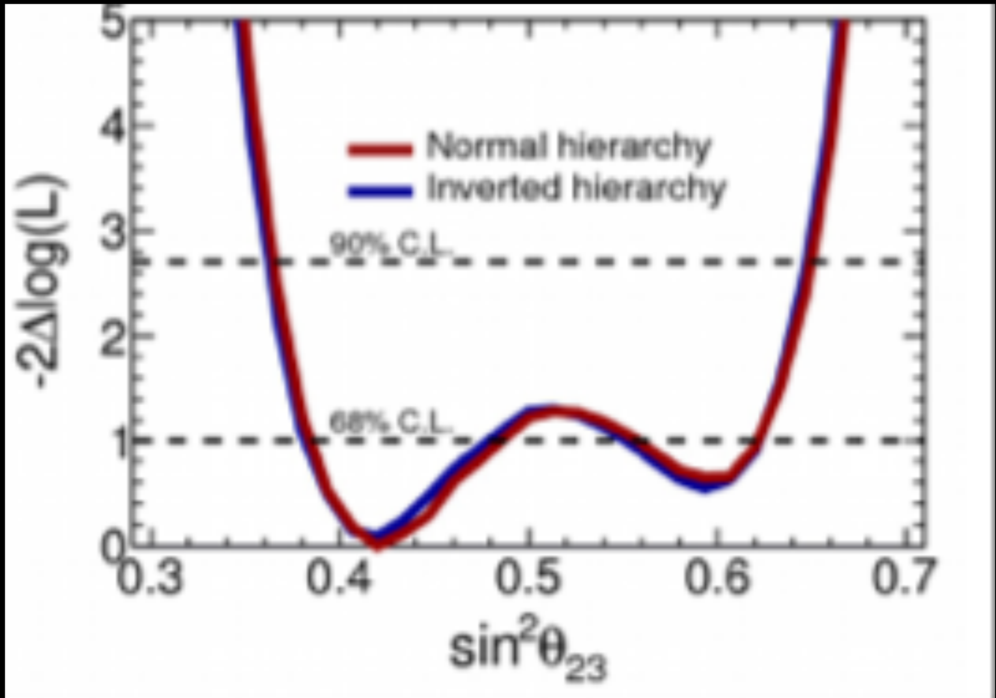
T2K ν_μ & vbar$_\mu$ Disappearance Results



- *T2K uses an off-axis beam (2.5º) with large water Cherenkov detector – SuperK at a baseline of 295 km. Collected data in both neutrino and antineutrino modes.*
- *They observe: 243 neutrino events with ~269 expected after oscillations and 102 antineutrino events with ~96 expected after oscillations.*

MINOS+: Disappearance Results

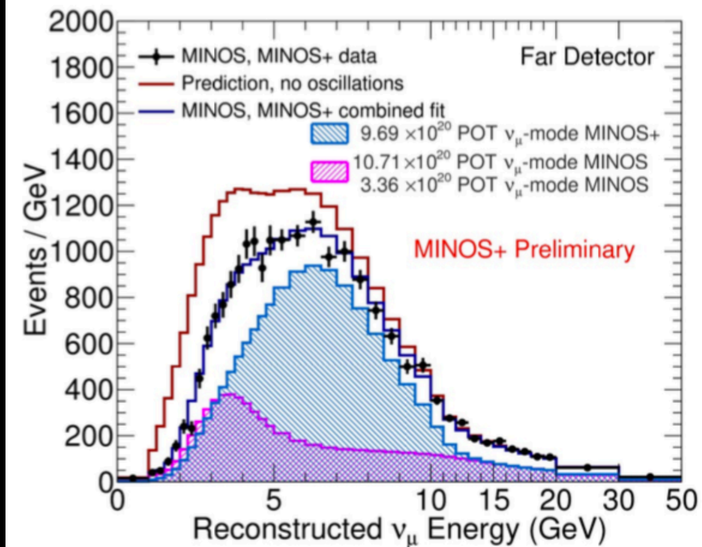
MINOS+ uses the NuMI beam at on axis as configured for NOvA

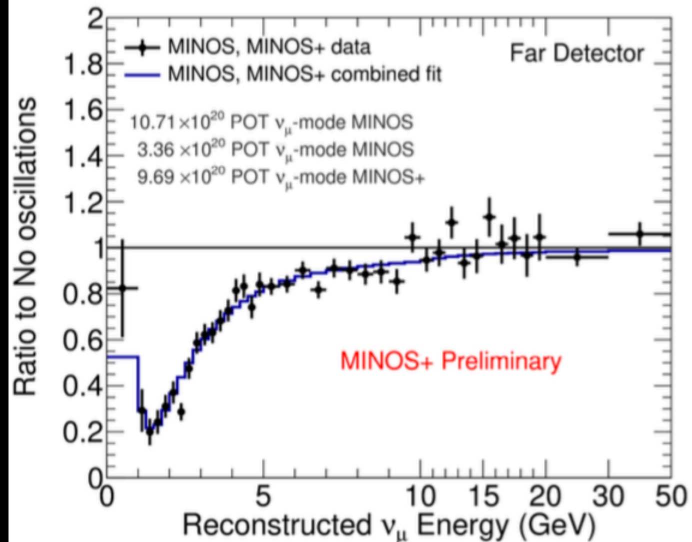


Best fit
$\Delta m^2_{32} = 2.42\text{x}10^{-3}\ \text{eV}^2$
$\sin^2\theta_{23} = 0.42$

Exclusion of maximal mixing:	1.1σ
Preference for lower octant:	0.8σ
Preference for normal hierarchy:	0.2σ

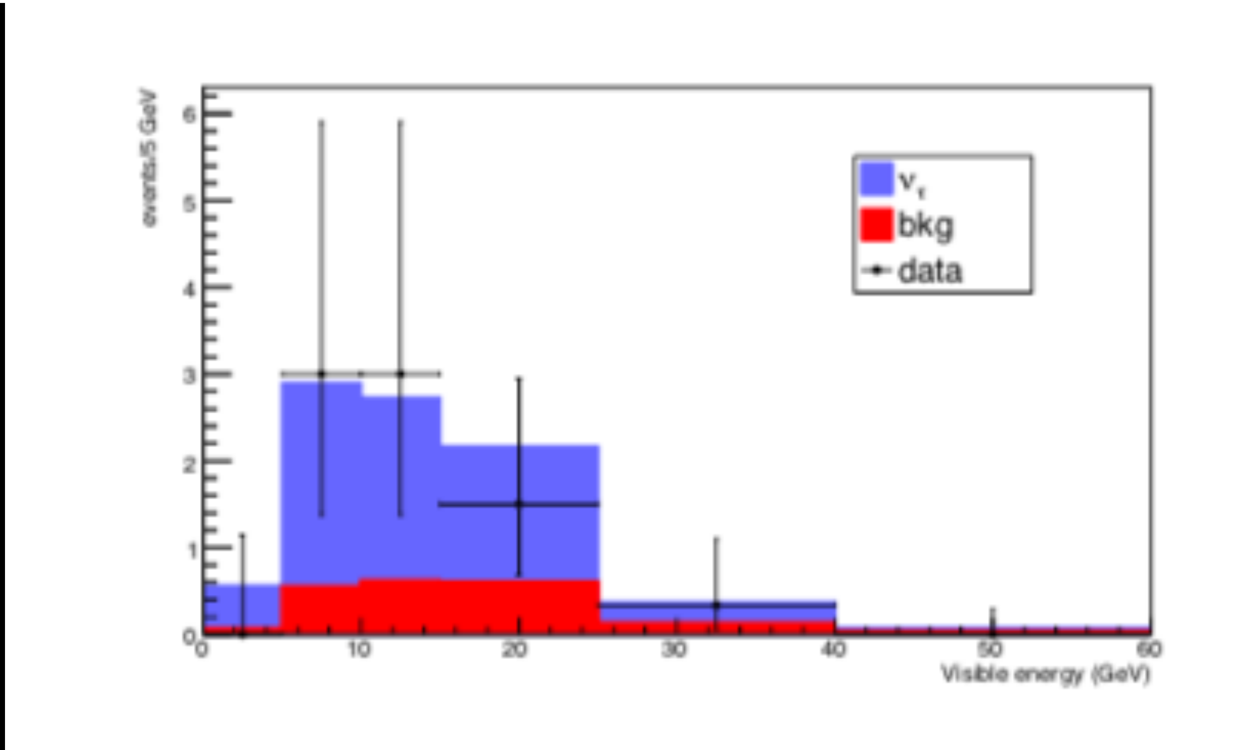
A. Aurisano Neutrino 2018





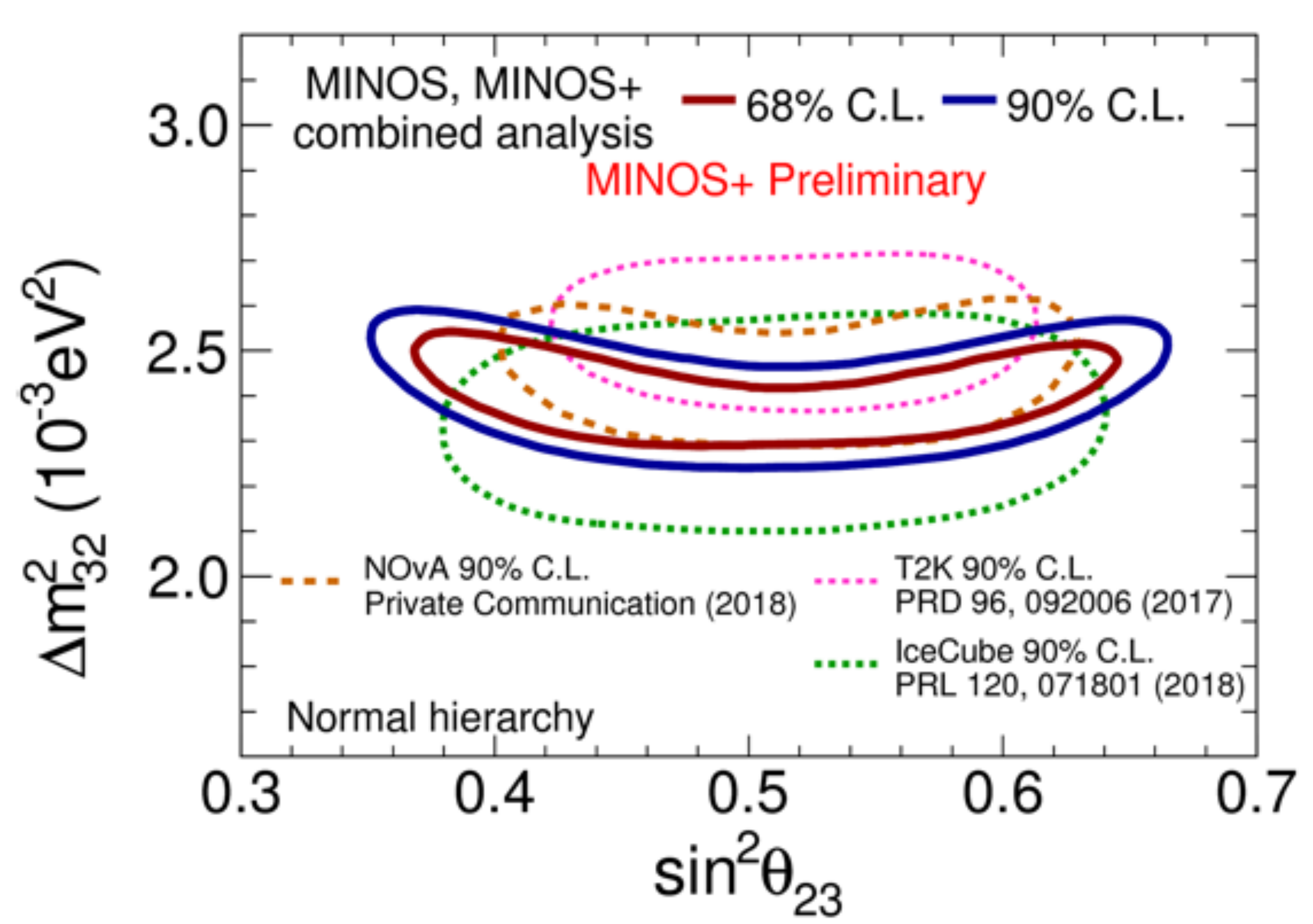
OPERA: CERN to LNGS: On-Axis Beam

OPERA has released their final results for the dominant mode of muon neutrino oscillation to tau neutrinos



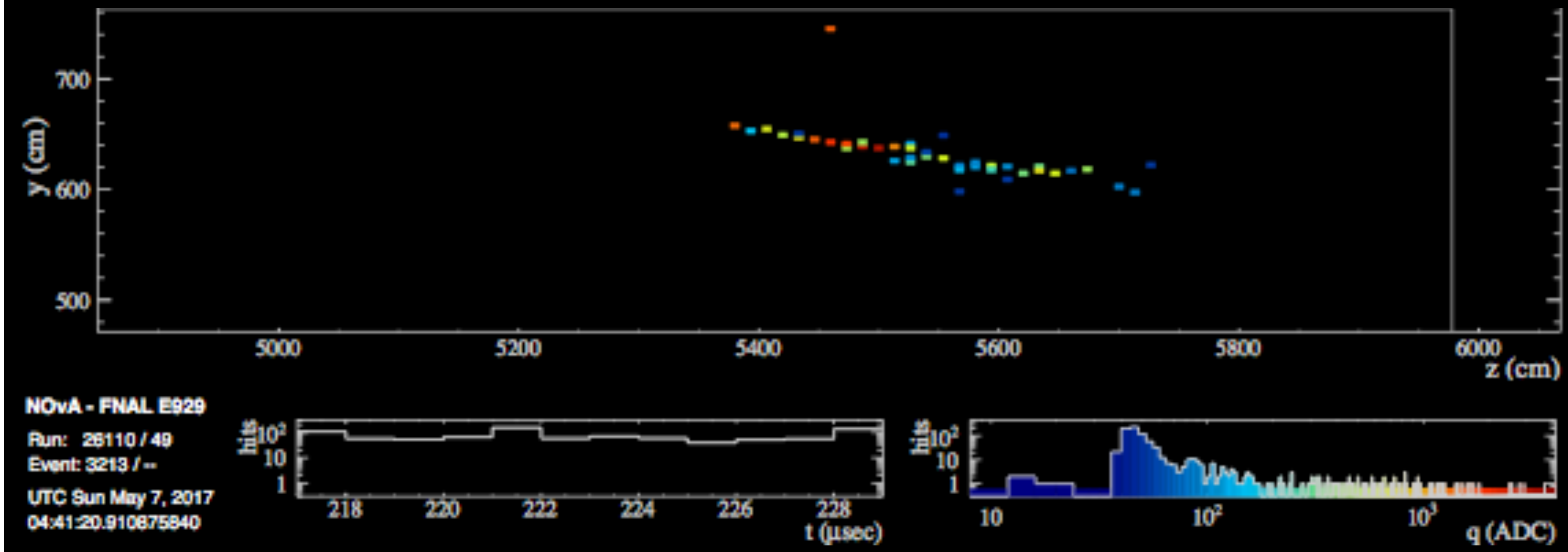
- ✓ ***10 tau neutrino candidates***
- ✓ ***6.1σ evidence of appearance***

Comparison of Various Experiments



What is the Mass Hierarchy or Ordering?
Is CP violated in the lepton sector?

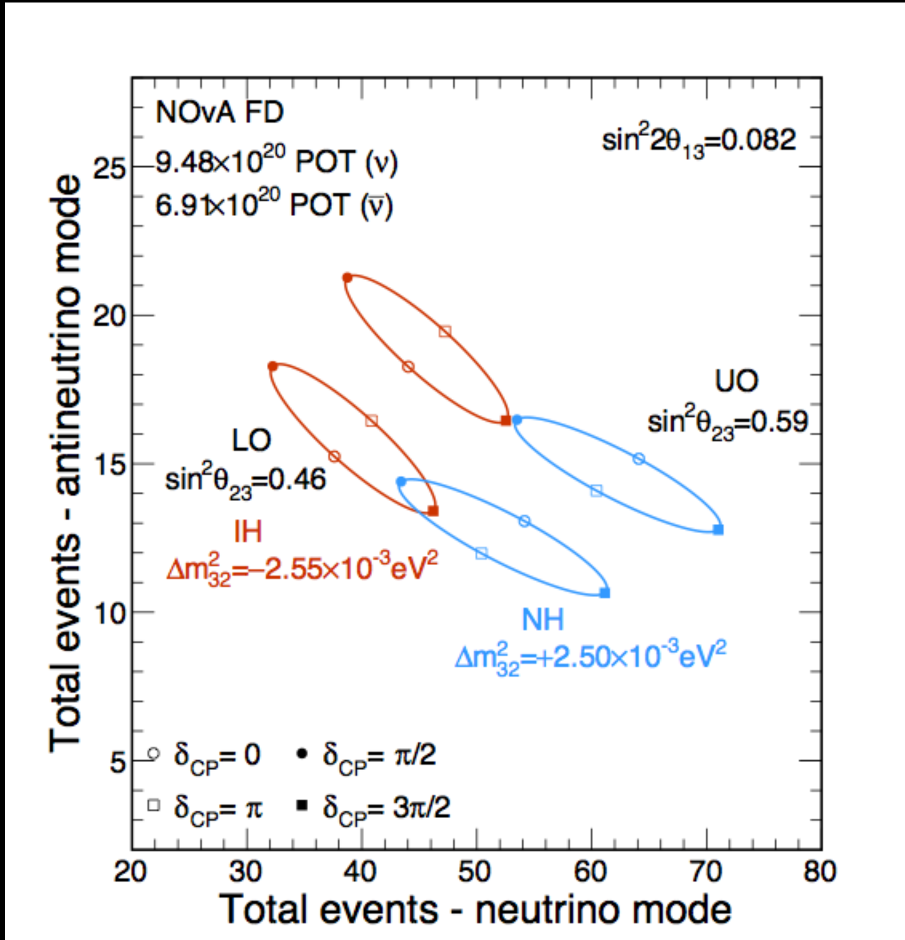
Electron Neutrino and Antineutrino Appearance



Electron Neutrino Appearance Expectation

- ✓ *Event counts in neutrino and antineutrino mode vary according to the oscillation parameters.*

- ✓ *Ellipses as a function of CP are drawn for normal and inverted hierarchy (NH and IH) as well as upper and lower octant (UO and LO).*

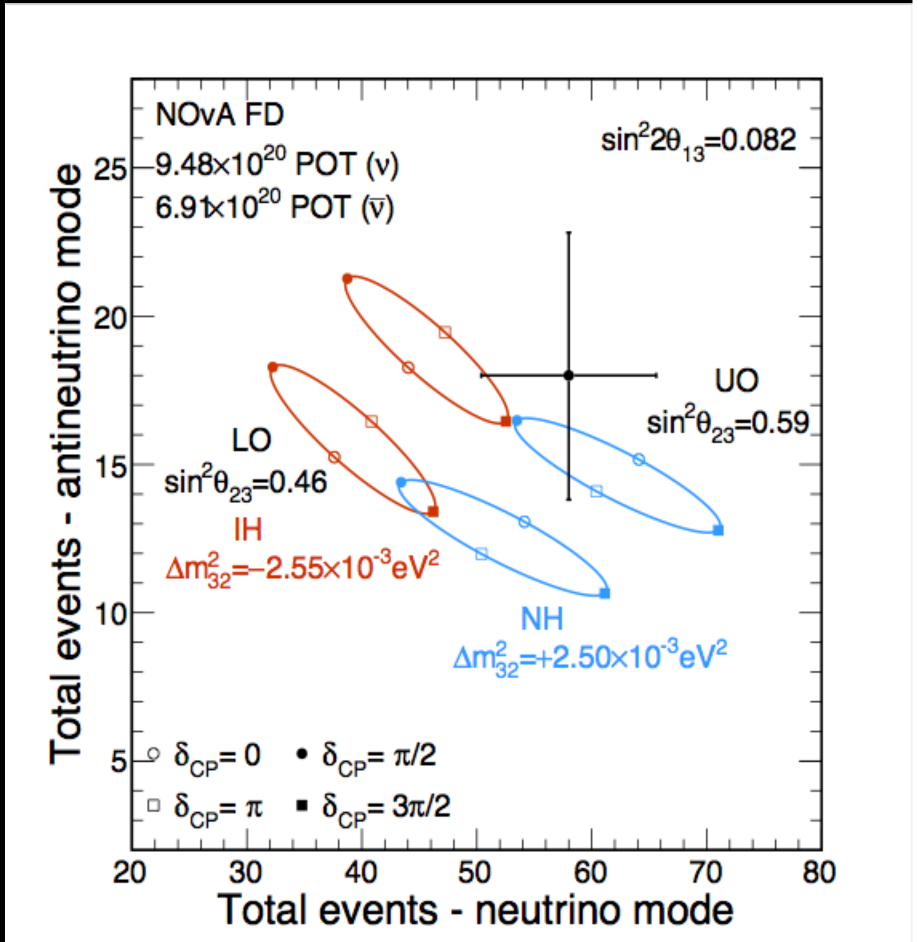


Expect 30 – 75 events for Neutrino Mode and 10 -22 for Antineutrino mode

Electron Neutrino Appearance Expectation

- ✓ ***Event counts in neutrino and antineutrino mode vary according to the oscillation parameters.***

- ✓ ***Ellipses as a function of CP are drawn for normal and inverted hierarchy (NH and IH) as well as upper and lower octant (UO and LO).***

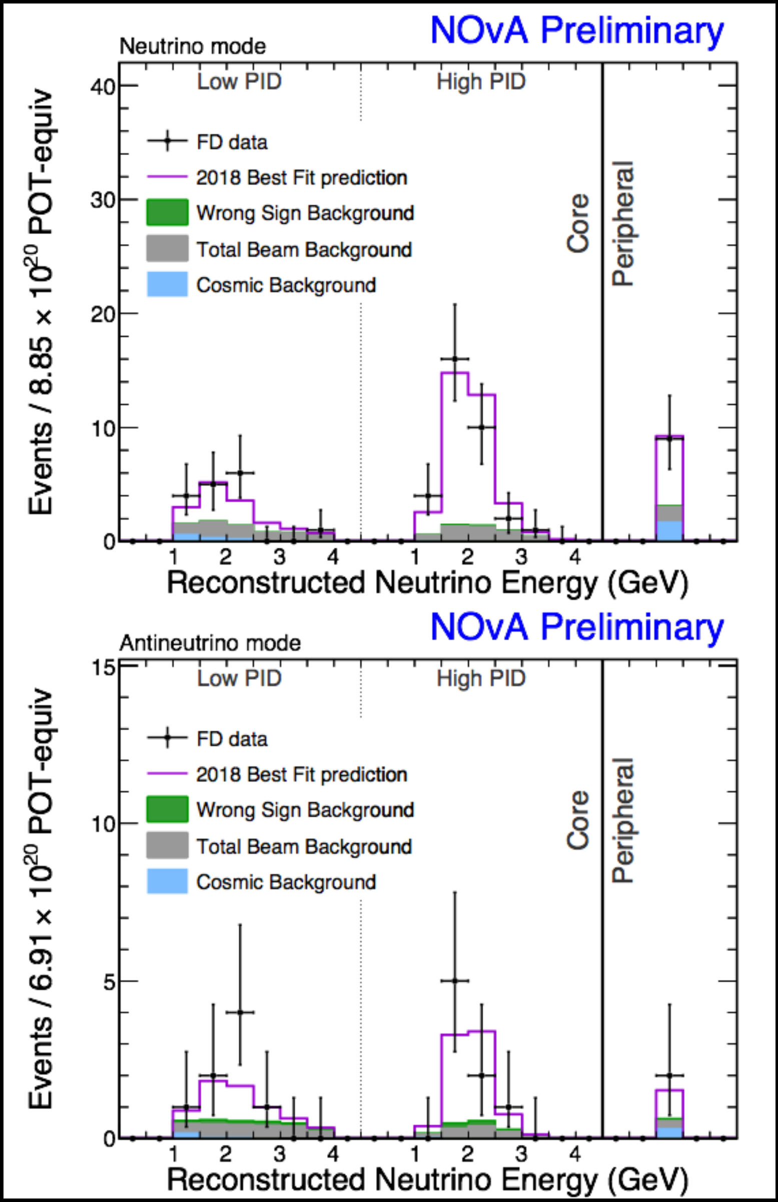


NOvA observes 58 events in Neutrino, 18 events in Antineutrino Mode

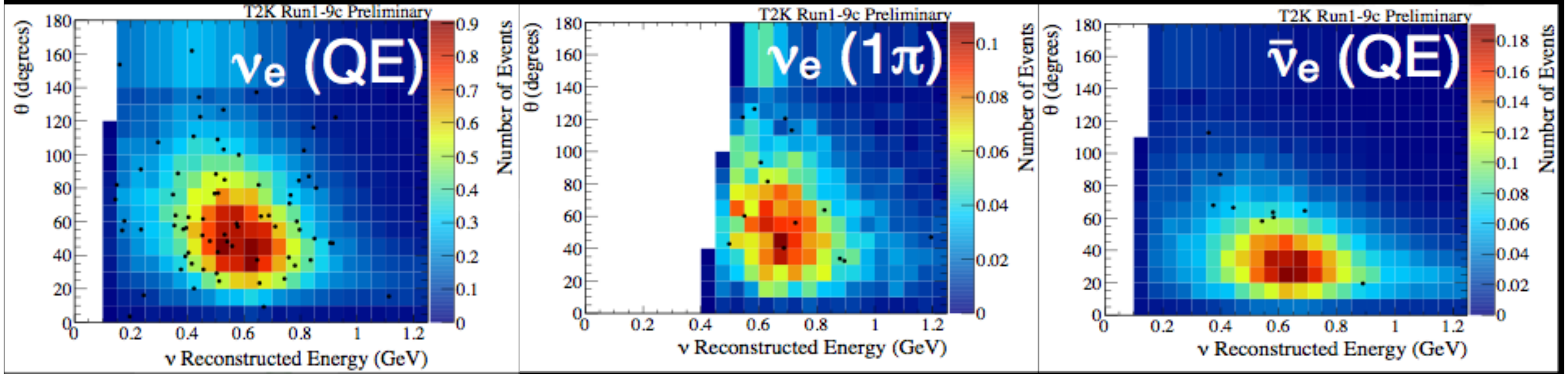
NOvA ν_e and ν_{ebar} Appearance

- ✓ *In the neutrino beam we observe 58 events and expect 15 background events*
  - ➢ *11 from beam*
  - ➢ *3 cosmic background, &*
  - ➢ *< 1 wrong sign one*
- ✓ *For the antineutrino beam we observe 18 events and expect 5.3 background evnts*
  - ➢ *3.5 beam background*
  - ➢ *< 1 cosmic, &*
  - ➢ *1 wrong sign event*

> 4σ evidence of electron anti-neutrino appearance



T2K ν_e and vbar$_e$ Appearance

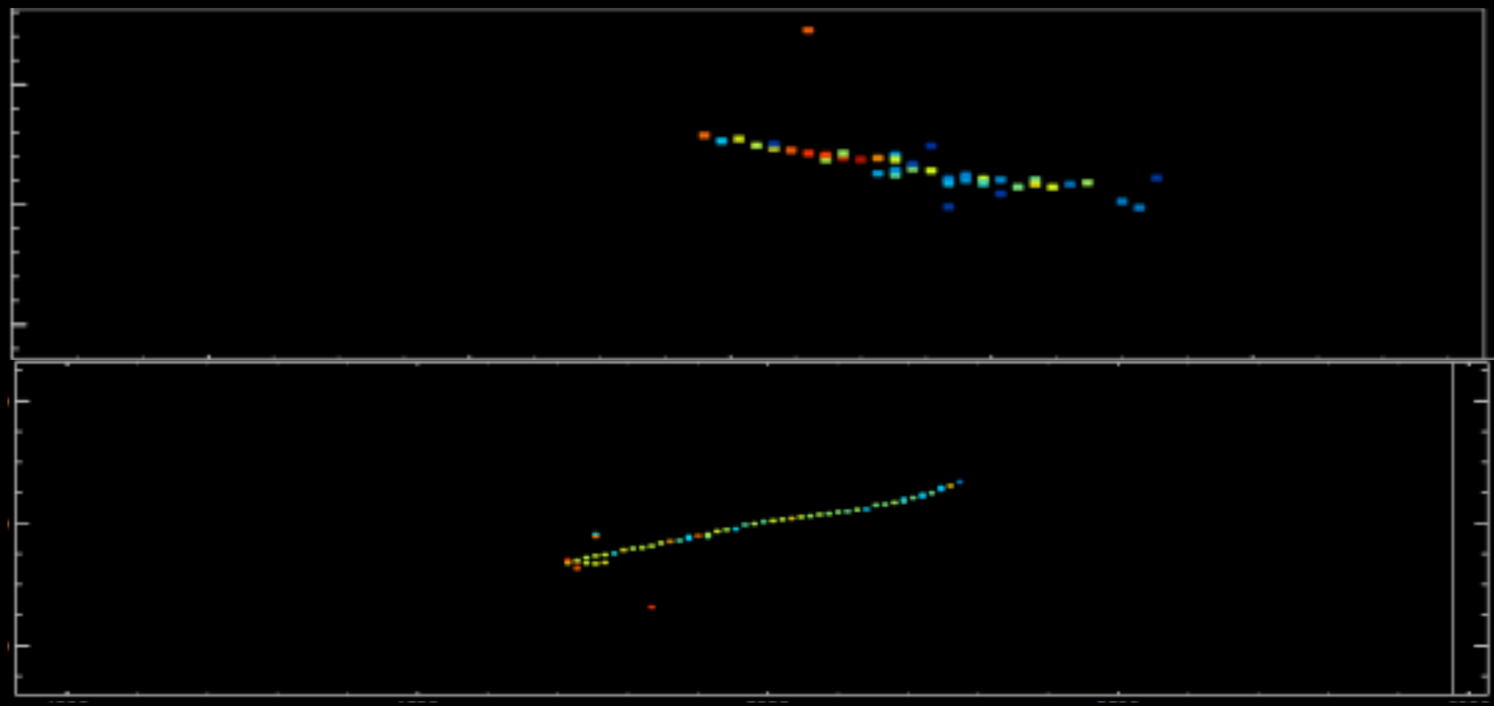


- ✓ *T2K has observed 75 (and 15 CC1pi nue) neutrinos and 9 antineutrinos. There are 74 (6.9 CC1pi nue) and 12 expected at NH, $\delta_{CP} = -\pi/2$ (or $3\pi/2$) which is the largest asymmetry.*

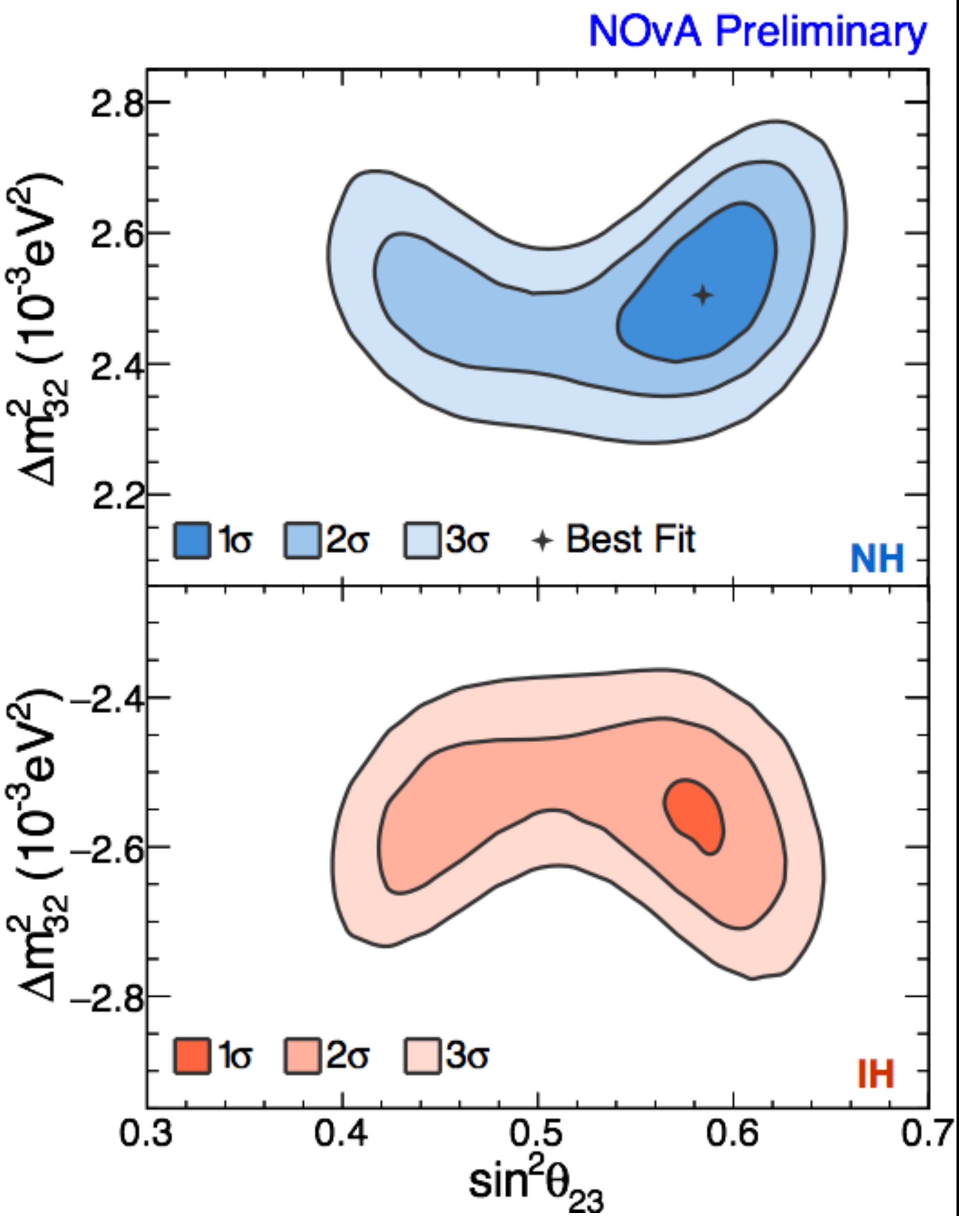
- ✓ *Slightly fewer vbar$_e$ candidates than predicted.*

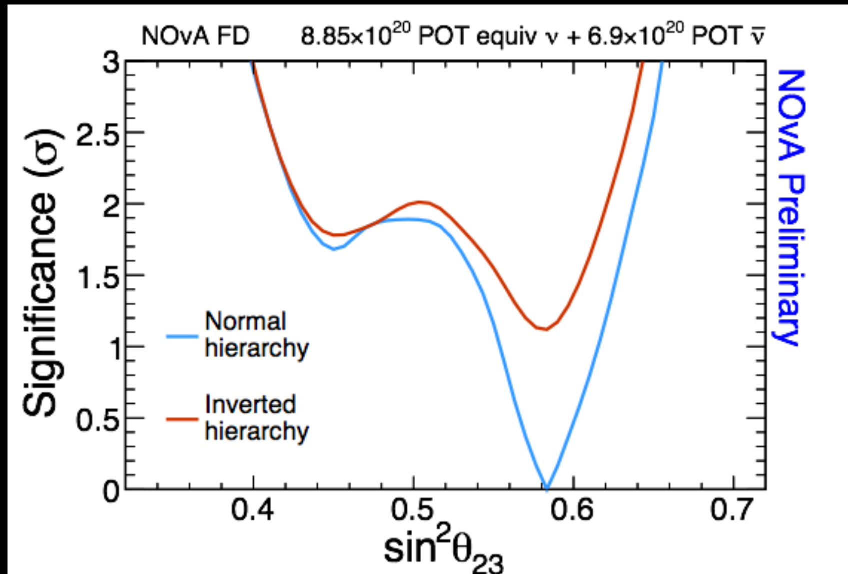
What is the Mass Hierarchy or Ordering?
Is CP violated in the lepton sector?

Joint Appearance & Disappearance



NOvA Allowed Oscillation Parameters





Best Fit:

Normal Ordering

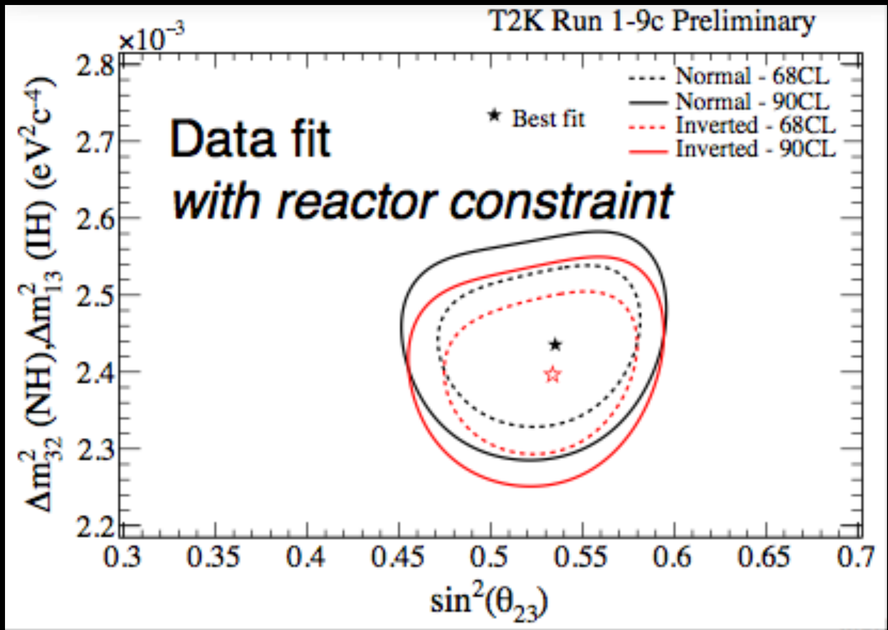
$Sin^2\vartheta_{23}$ = 0.58 ± 0.03 (UO)

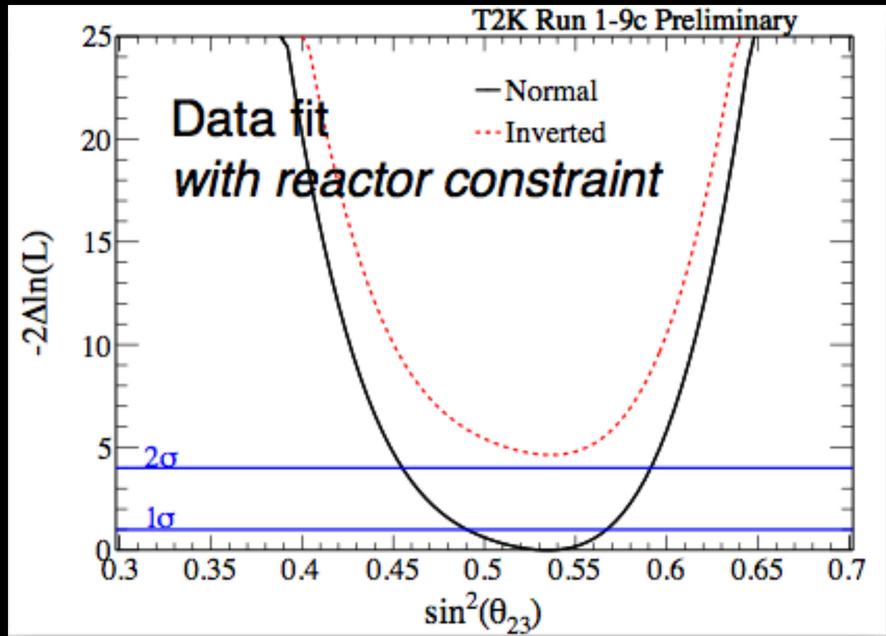
$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3}\ eV^2$

Prefer nan-maximal ϑ_{23} at 1.8σ.

Exclude LO at a similar value.

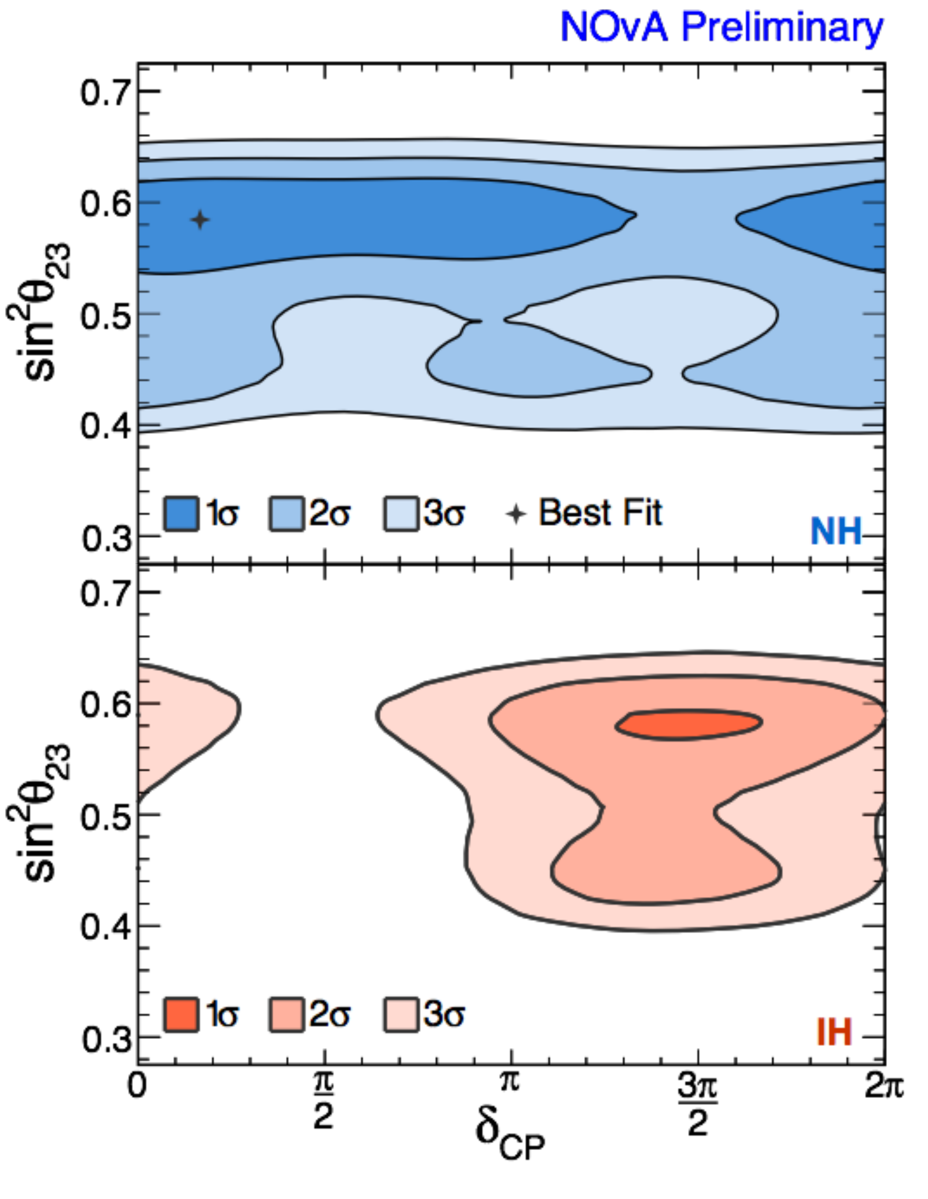
T2K Allowed Oscillation Parameters

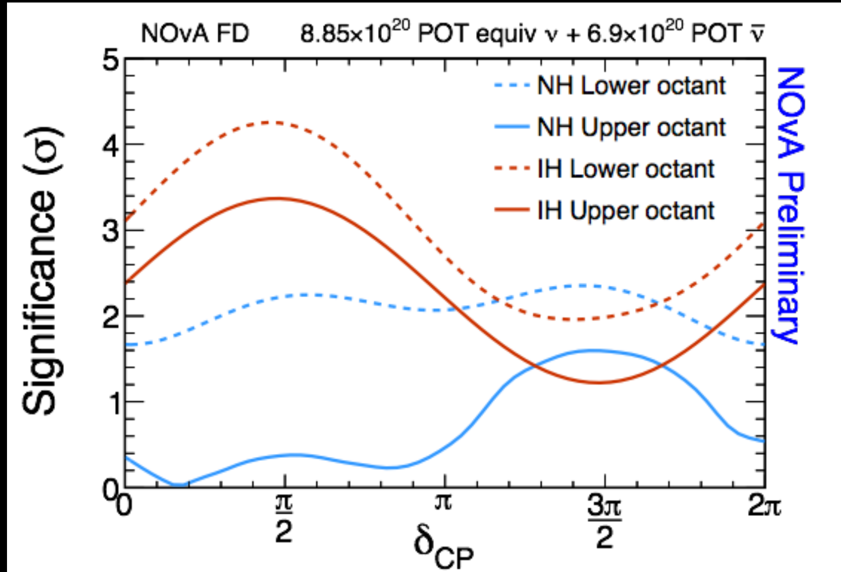




	NH	IH
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$\|\Delta m^2\|$	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$

NOvA Allowed Oscillation Parameters





Best Fit:

$\delta_{CP} = 0.17\pi$

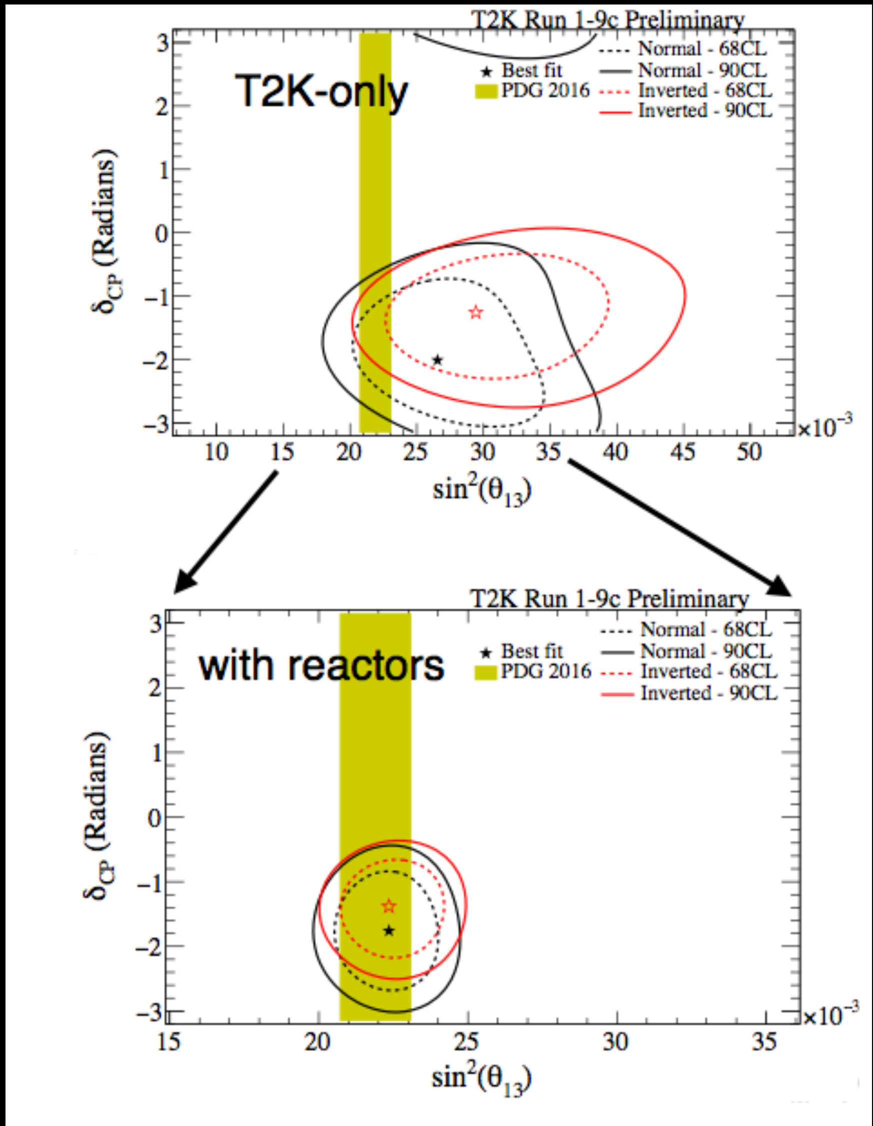
$Sin^2\vartheta_{23} = 0.58 \pm 0.03$ (UO)

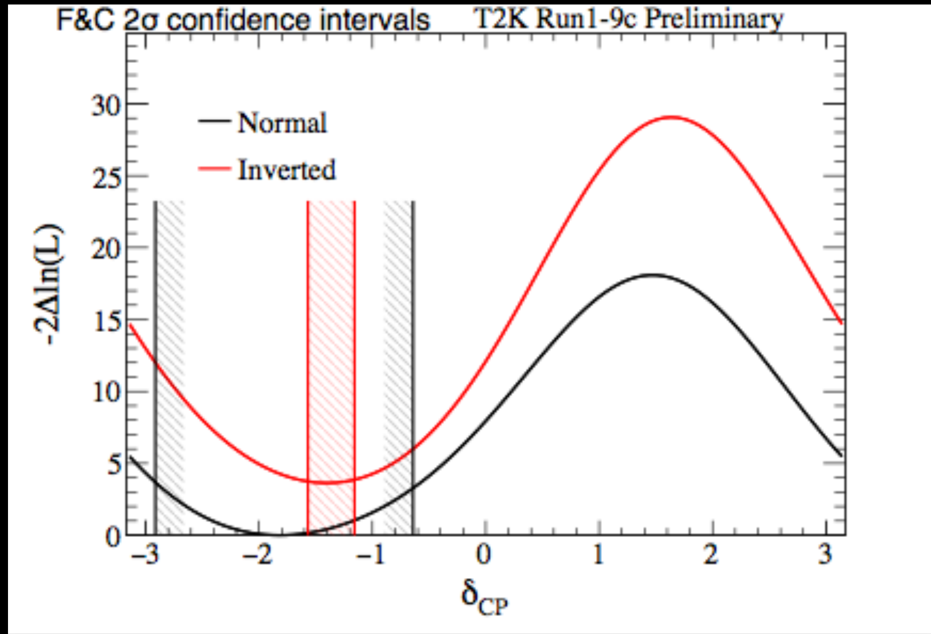
$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3}\ eV^2$

Prefer NH by 1.8σ.

Excludes $\delta_{CP} = \pi/2$ in the IH at > 3σ

T2K Allowed Oscillation Parameters





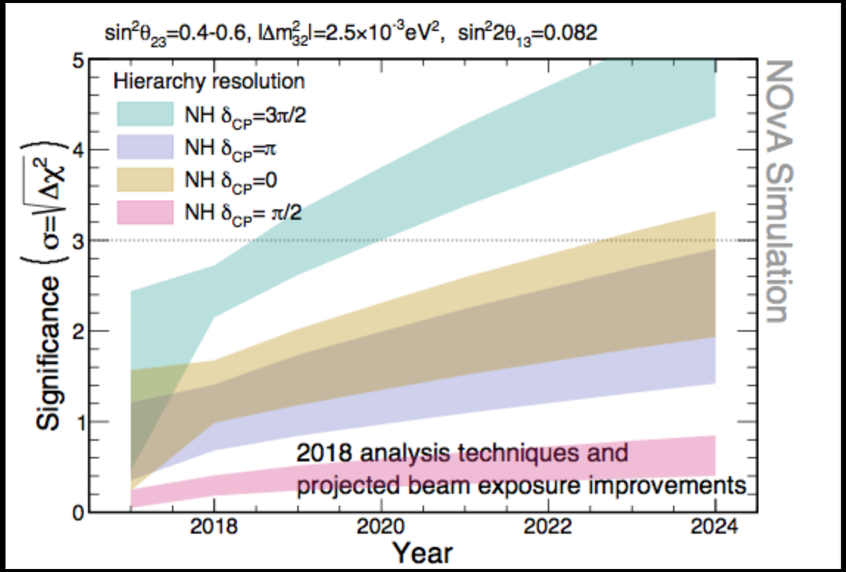
δ_{CP}	Hierarchy	90%	2σ
0	NH	0.421	0.288
π	NH	0.388	0.248
0	IH	0.768	0.660
π	IH	0.783	0.685

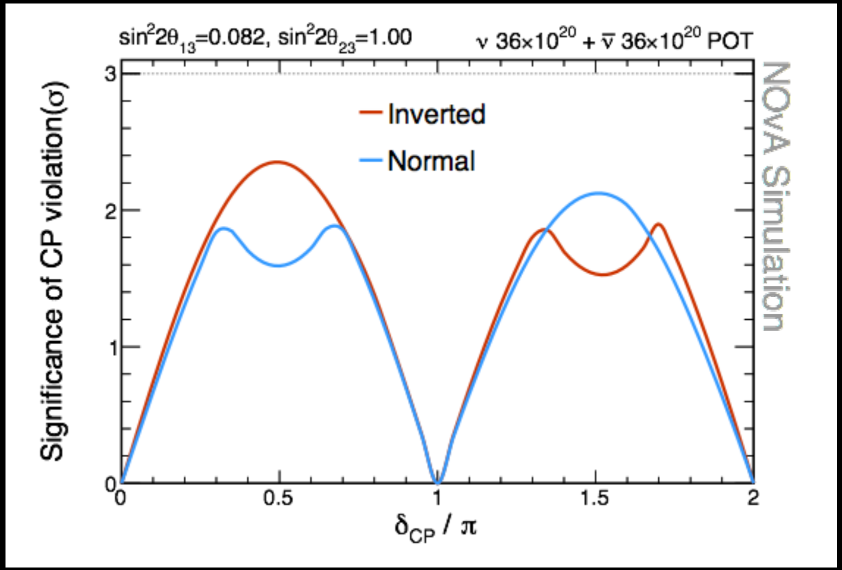
CP conserving values outside 2σ region for both hierarchies

FUTURE

NOvA Prospects

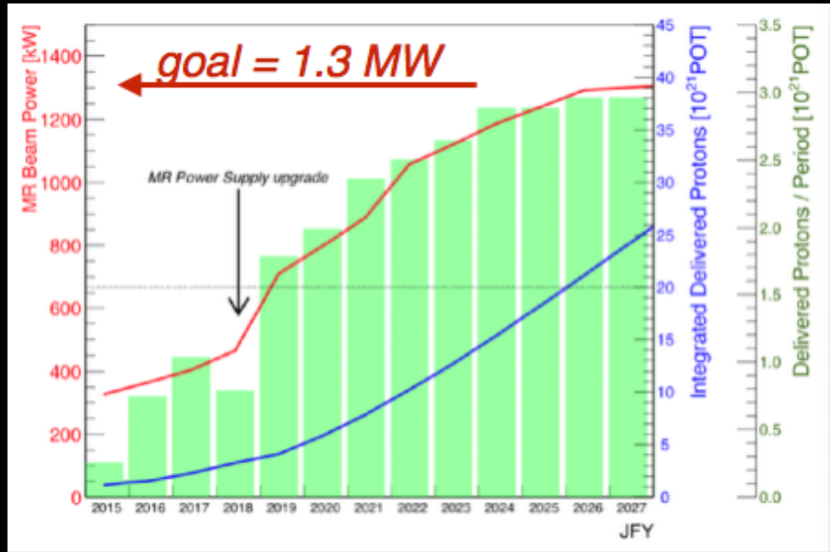
- ✓ *Currently data collection with anti-neutrino beam. After 2018, run 50% with neutrino & 50% with anti-neutrino beam.*
- ✓ *Extended running through 2024, proposed accelerator improvement projects & test beam program will enhance NOvA's ultimate reach.*
- ✓ *3σ sensitivity to hierarchy (if NH and δ_{CP} = 3π/2) for allowed range of ϑ_{23} by 2020. 3σ sensitivity for 30-50% (depending on octant) of δ_{CP} range by 2024.*
- ✓ *>2σ+ sensitivity for CP phase in both hierarchies at δ_{CP}= 3π/2 or δ_{CP} = π/2 (assuming unknown hierarchy) by 2024.*

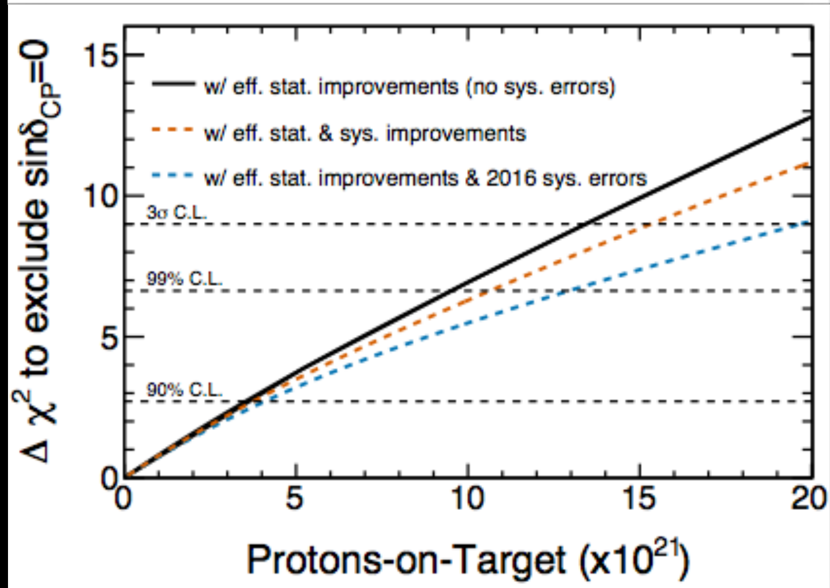




T2K Prospects

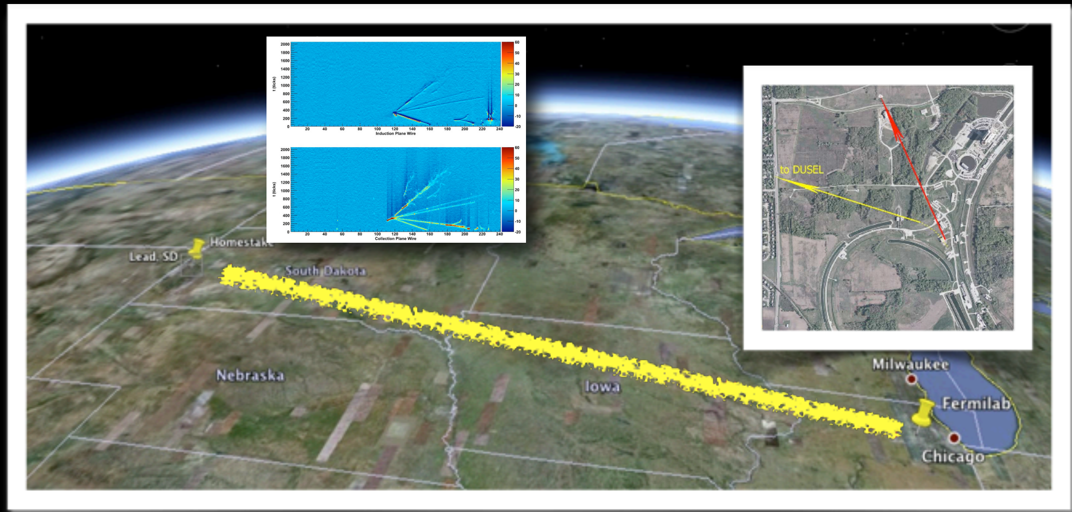
- ✓ *T2K's long term goal is to the pursue CPV in the neutrino sector.*
- ✓ *Proposal to collect 20X10^{21} POT by ~2026 (arXiv:1609.04111 [hep-ex].*
- ✓ *With 20X10^{21} POT, T2K has up to 3σ (median) CPV sensitivity*
- ✓ *Sensitivity improves beyond 3σ with reduced systematic errors*
- ✓ *T2K initiated ND upgrade project in January 2016*





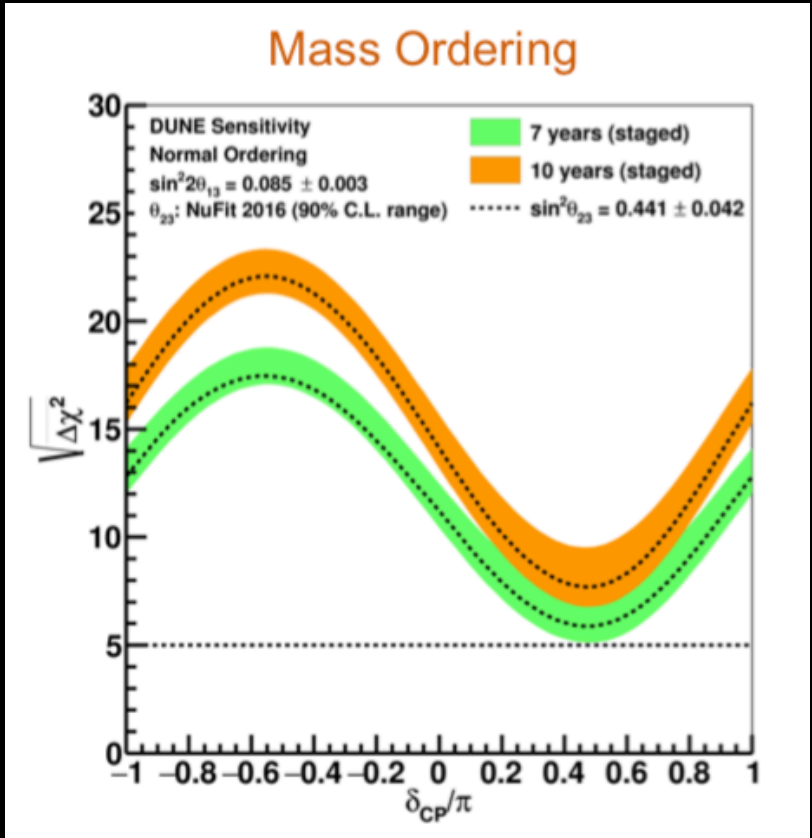
Next Generation Experiments

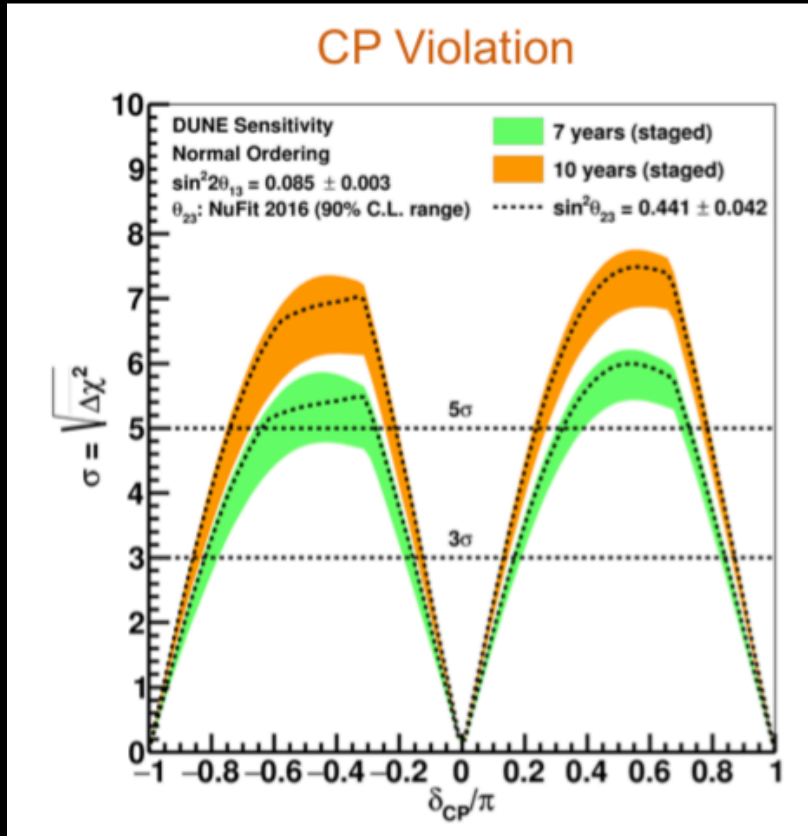
- ✓ *Higher intensity beam can provide more neutrinos and allow for a longer baseline*
- ✓ *Similarly larger mass can allow to collect more events*
- ✓ *Finally better detector resolution can allow for better background rejection*



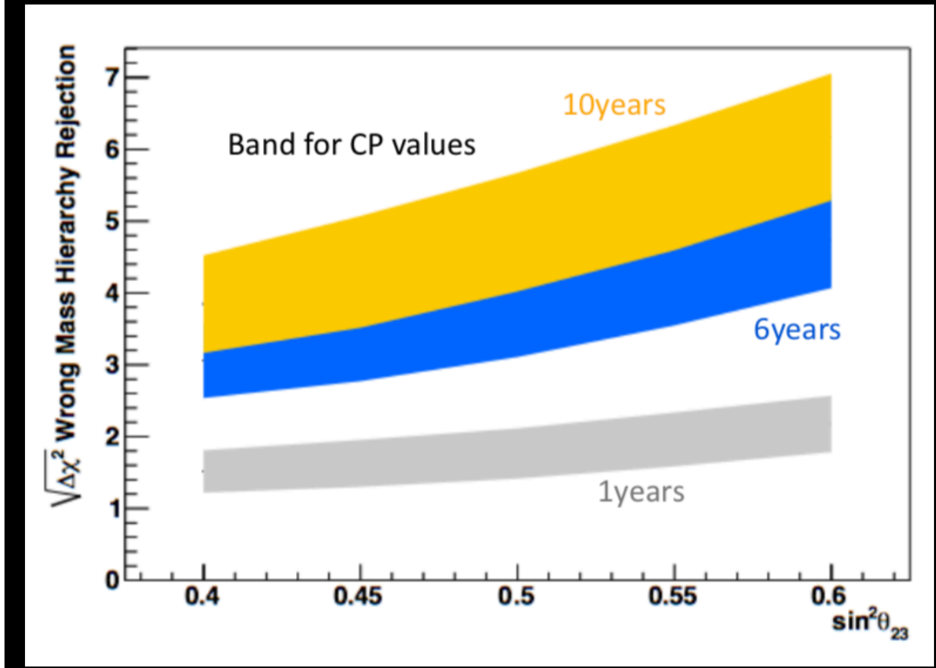
- ➢ *In USA, a new experiment (DUNE) is being planned with a baseline of 1300Km, a new beam to reach 2.3 MW and high resolution LAr detectors*
- ➢ *In Japan, beam upgrade planned to 1.3MW and a new 258 Kton scale detector system is also being planned as part of the T2HK program*

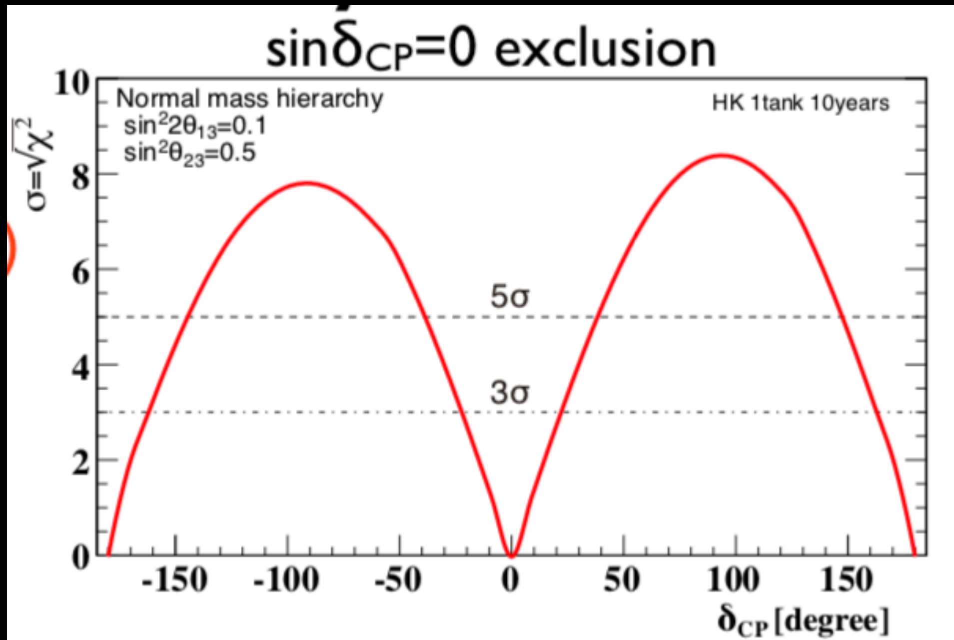
The Future: DUNE in USA





The Future: T2HK in Japan





Summary and Outlook

- ✓ Many new results have been released from the accelerator experiments this summer:
  - ✓ NOvA has strong evidence (> 4σ) of electron-antineutrino appearance
  - ✓ T2K favors non-CP conserving values of δ_{CP} at 2σ.
  - ✓ NOvA excludes δ=π/2 in the IH at > 3σ.
- ✓ The next generation of long-baseline experiments with more mass, longer baseline and better detector resolution is being planned.
- ✓ Better precision will allow us to test the 3-flavor neutrino oscillation framework.
- ✓ Outside of the 3-flavor framework, tests in long-baseline accelerator experiments find no evidence so far for sterile neutrinos beyond LSND and MiniBooNE. A new program using short baseline and decay at rest techniques to study these neutrinos is in progress.

This talk was to be originally given by Mayly Sanchez of Iowa State University. But for some personal reasons she was unable to attend the workshop. I was asked to fill in on Friday evening. I have received considerable help from her in preparing this talk. She deserves all the credit for this talk.

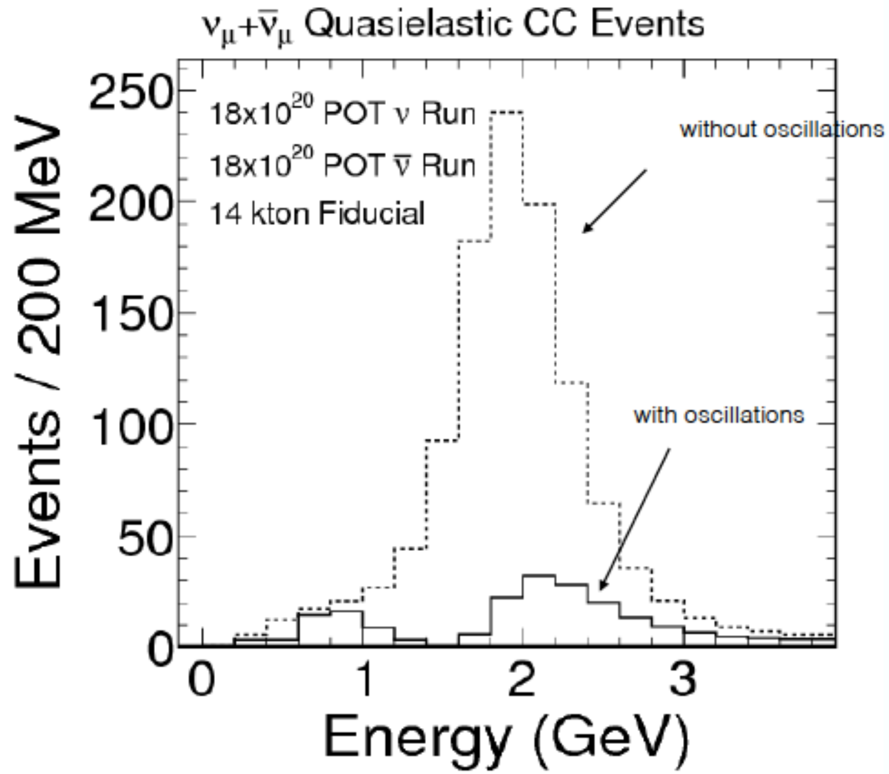
Thank you.

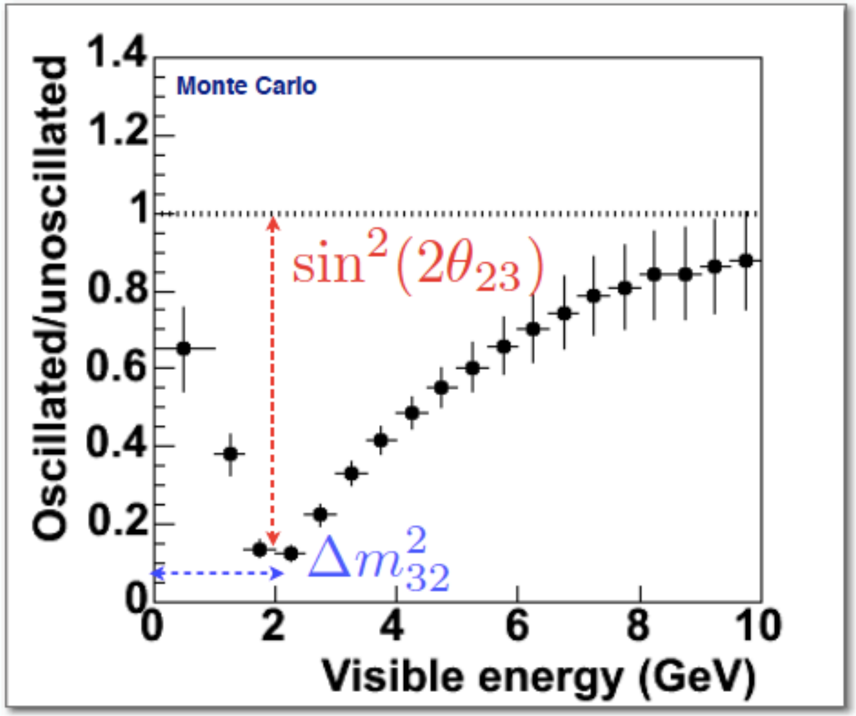
Vielen Dank

Goals of NOvA Experiment

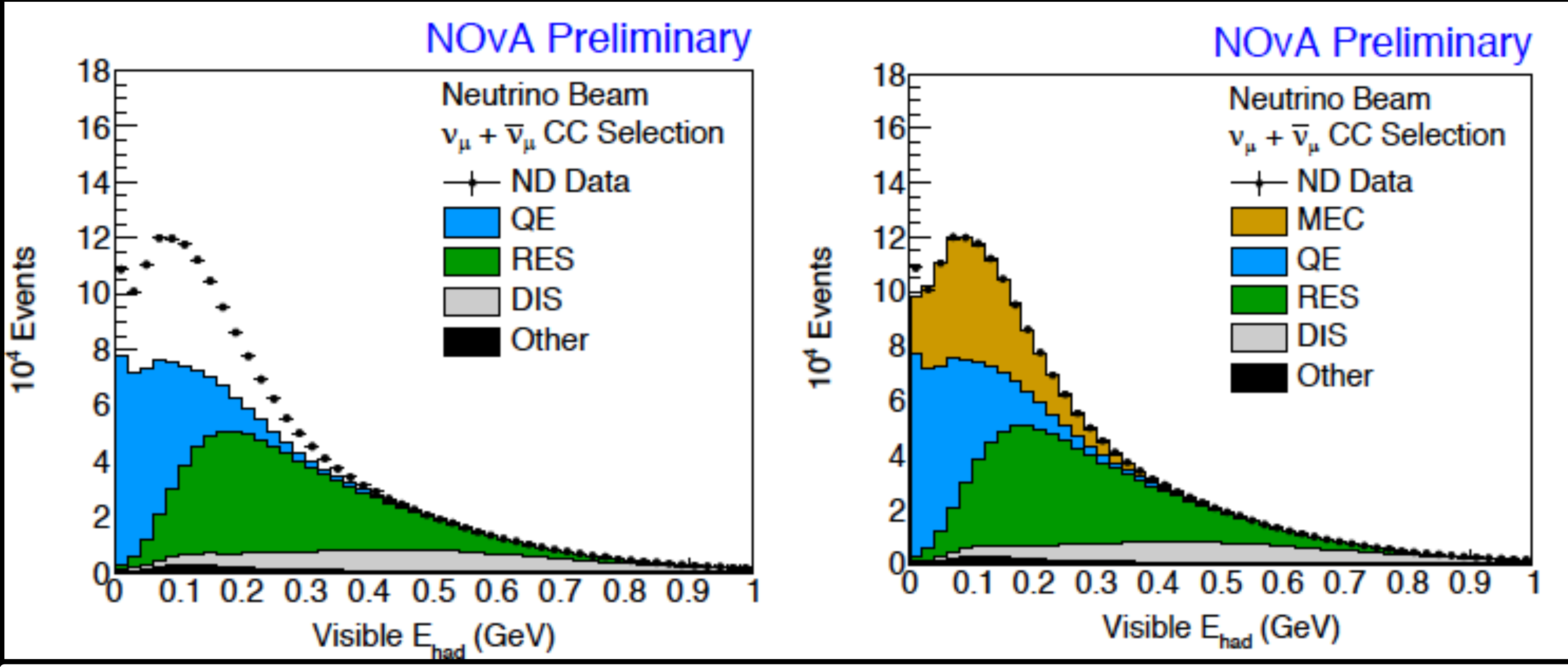
ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{atm} L}{E}\right)$$



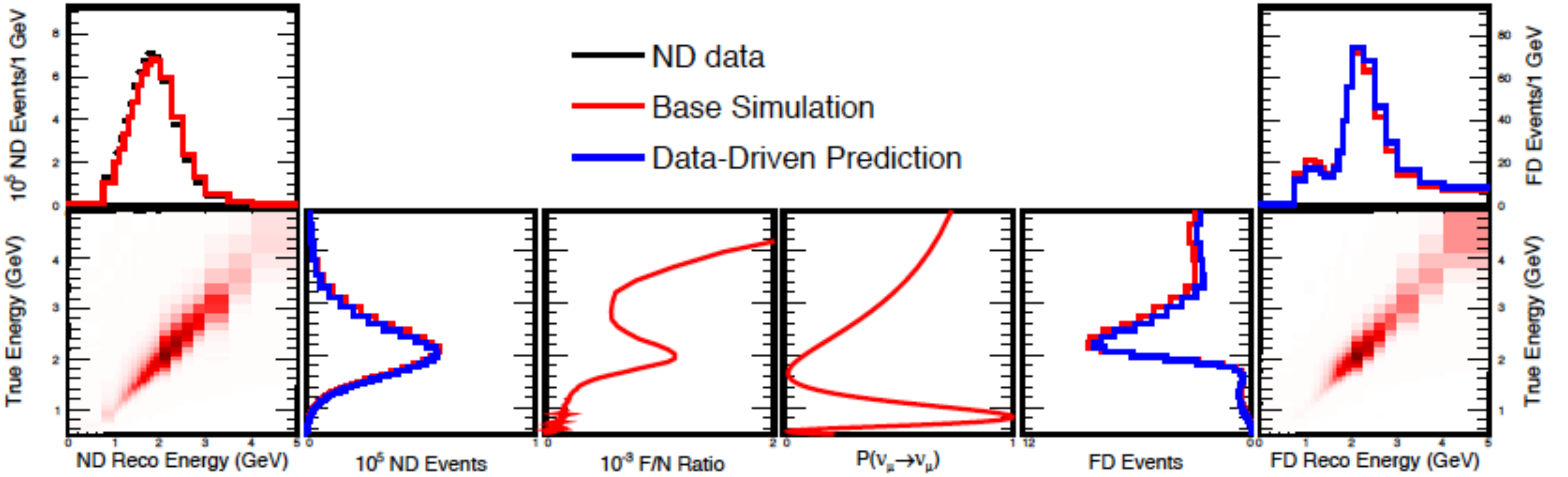


Neutrino Interaction Tuning



- ✓ *The default GENIE prediction is insufficient to describe the NOvA ND data, i.e, the hadronic energy in ν_μ CC interactions show disagreement with the default simulation*
- ✓ *QE, RES tunes to consider long-range nuclear correlations using Valenia model via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]*
- ✓ *DIS at high invariant mass (W>1.7 GeV/c^2) weighted upto 10% based on NOvA data*
- ✓ *Empirical MEC (Meson Exchange Current) model for multi-nucleon ejection (2p2h) amount tuned in 2D 3-momentum and energy transfers space to match ND data [T. katori, AIP Conf. Proc. 1663, 030001 (2015)]*

Near Detector to Far Detector Extrapolation



- *The neutrino spectrum is measured at the ND (before oscillation). This is a combination of neutrino flux times cross-section times efficiency.*
- *Use the measured ND spectrum to predict the FD spectrum*
    - *Translate ND data/MC observation to true energy*
    - *Oscillate ratio to the FD*
    - *Smear back into reconstructed energy*
- *Reduces systematic uncertainties due to largely cancellation of flux combined with cross-section uncertainties*