Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Potential Impact of Reduced Running on NOvA

Peter Shanahan

Pre-PAC Meeting

29 July 2017

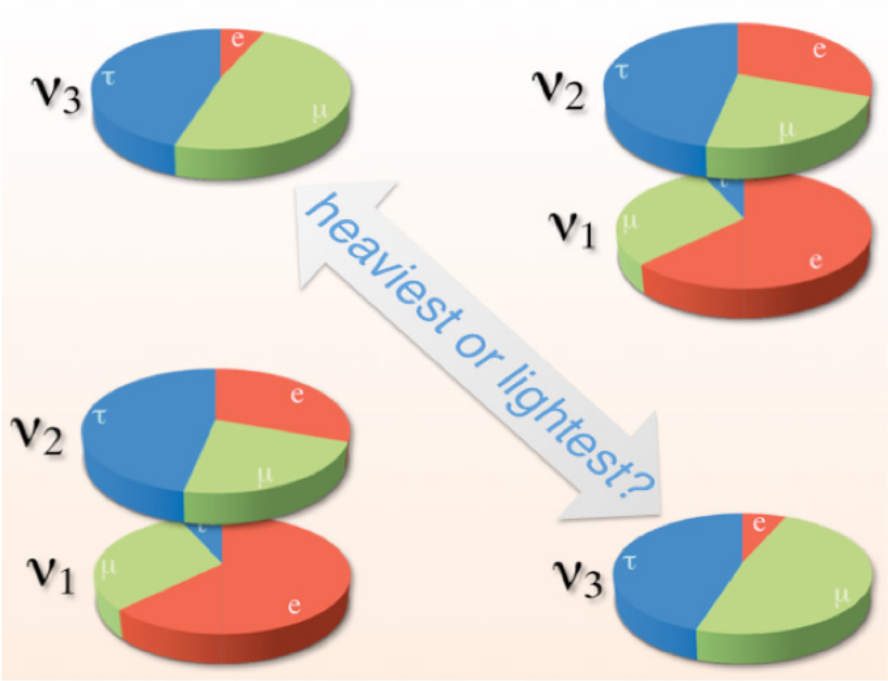
In partnership with:

NOvA

NOvA and the Physics of Long Baseline Neutrino Oscillations

- The discovery of neutrino oscillations opened up an entire new sector of investigation related the structure of neutrino masses and mixing

- Many of the most compelling questions related to the P5 Science Driver *Investigation of the Physics of Neutrino Mass* are accessible in long-baseline oscillation measurements
  - Neutrino Mass Hierarchy?
  - Do Neutrinos Violate CP Symmetry?
  - What is the Pattern of Mixings?
  - Is there more to the story than a 3x3 PMNS Mixing Matrix?



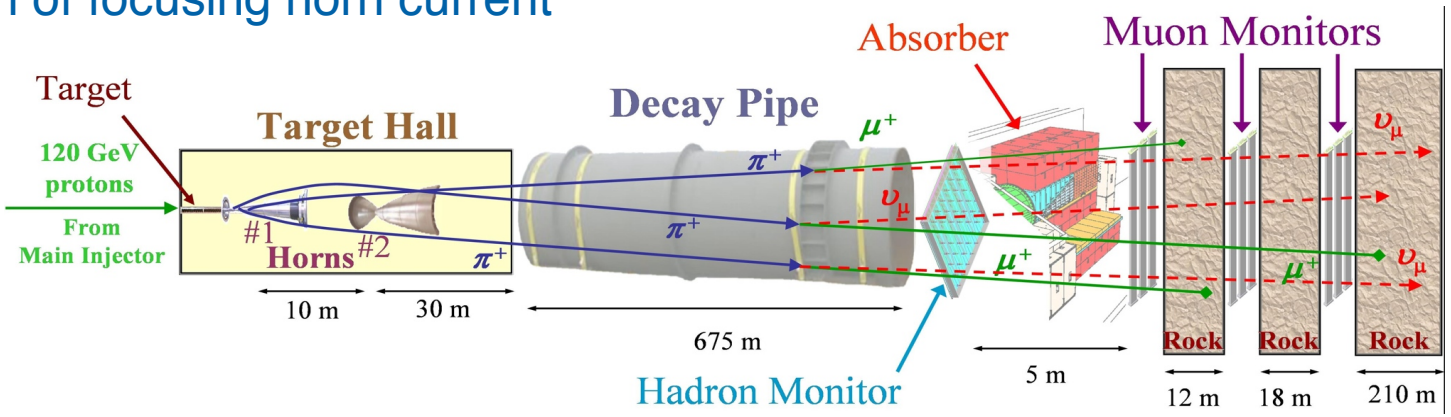
- NOvA addresses these using
  - Two detectors separated by 810 km
  - High-purity ν_μ and $\bar{\nu}_\mu$ beams
  - ν_μ disappearance, ν_e appearance, and flavor-independent (neutral current) disappearance

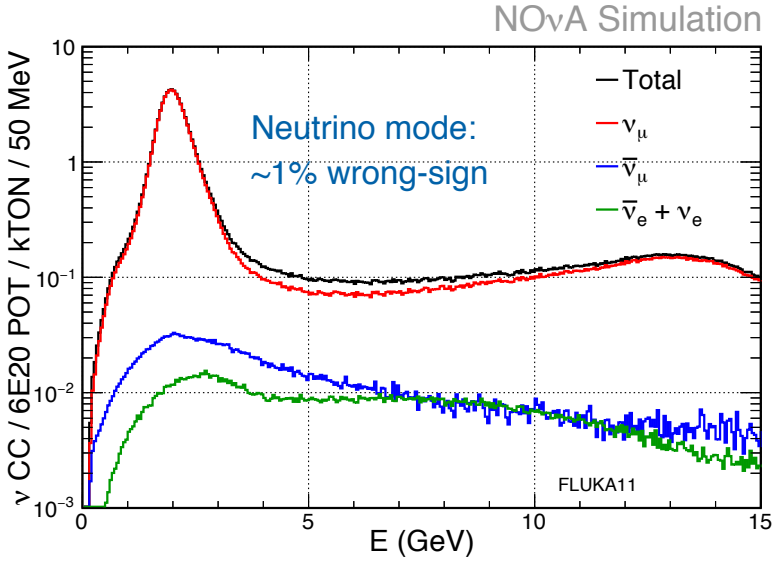
NOvA Collaboration

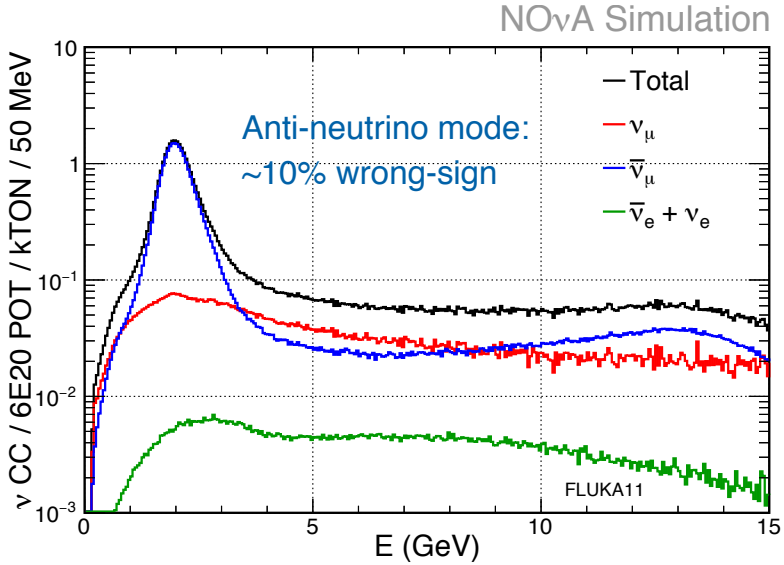
- 200 Physicists, Engineers and
- 47 Institutions in 7 Countries

NuMI Beam

- Highest power neutrino beam in the world - 700 kW design
- ν and $\bar{\nu}$ beam modes
  - Direction of focusing horn current



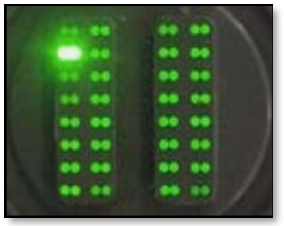


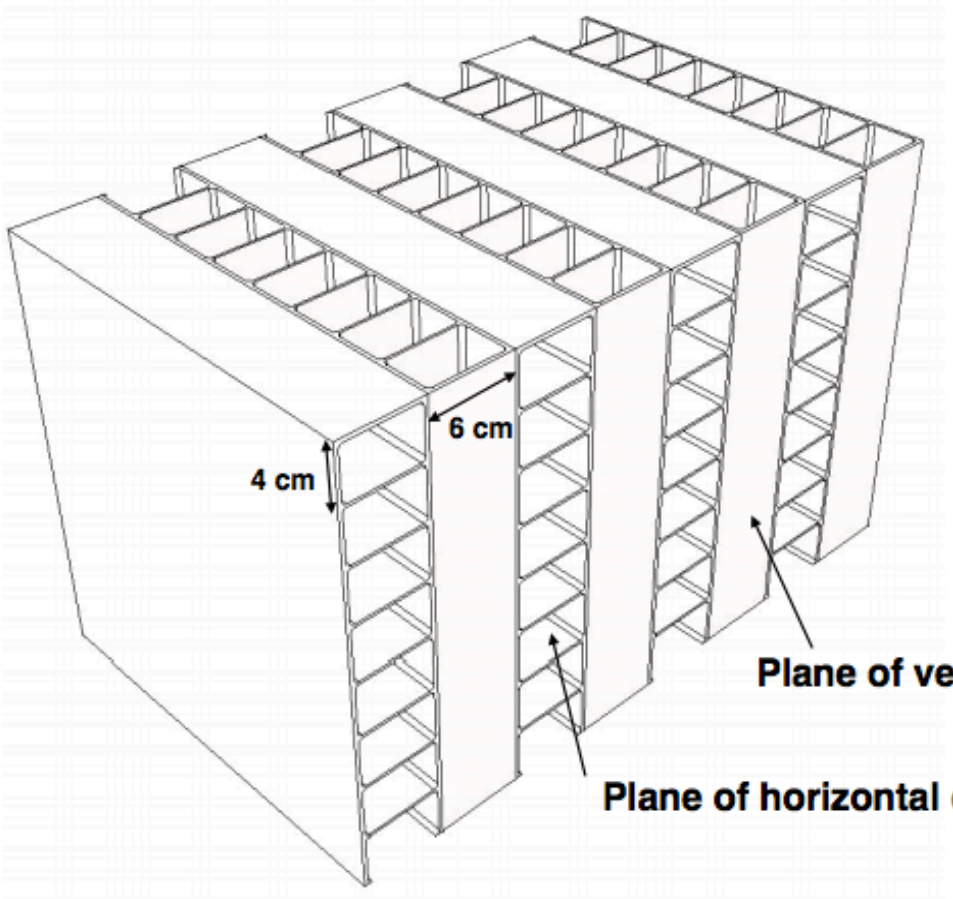


NOvA Detector Technology

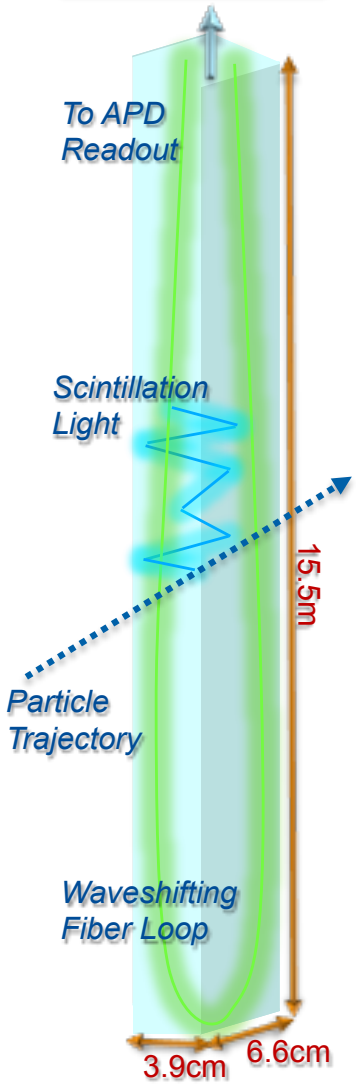
- Low-Z Tracking Calorimeters
  - PVC Cell Structure
  - Filled with Mineral Oil + 5% pseudocumene

32 cells read out into 1 Avalanche PhotoDiode



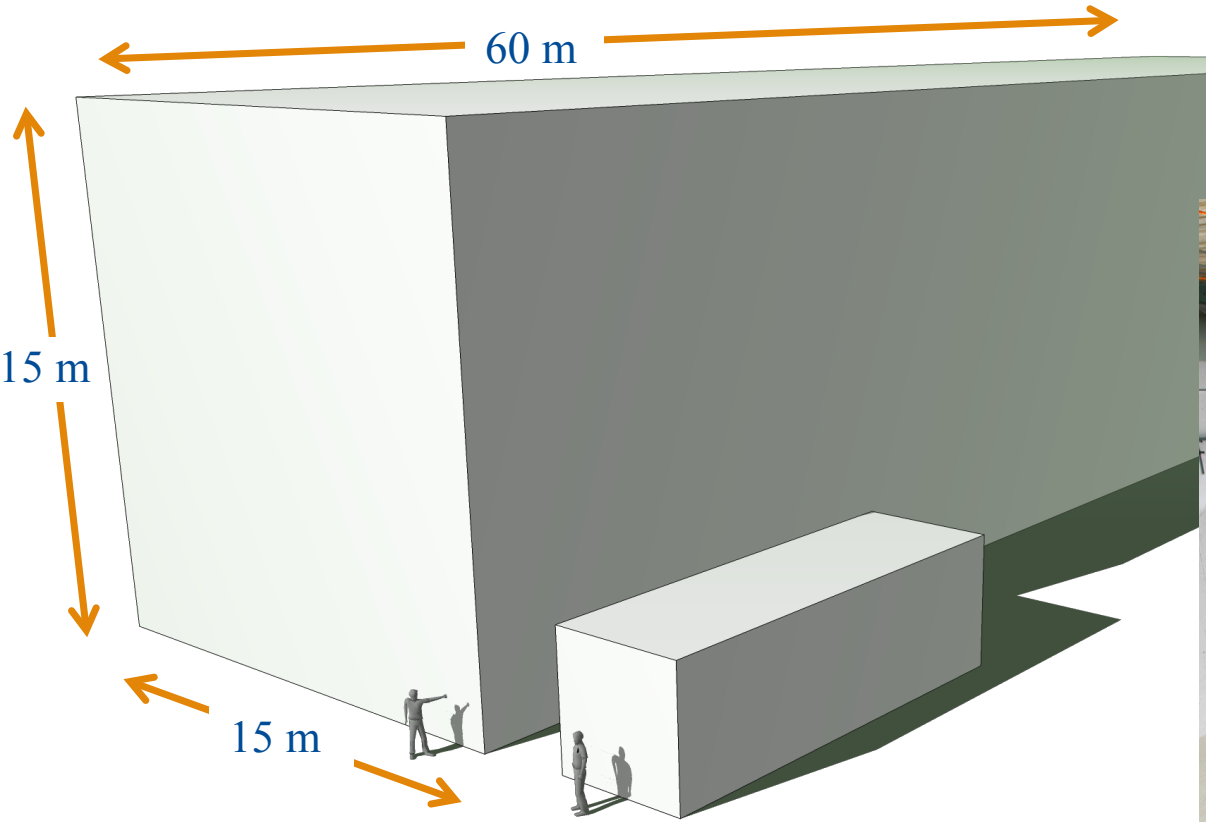


Excellent electromagnetic shower characterization with 6 samples per radiation length



Single Cell

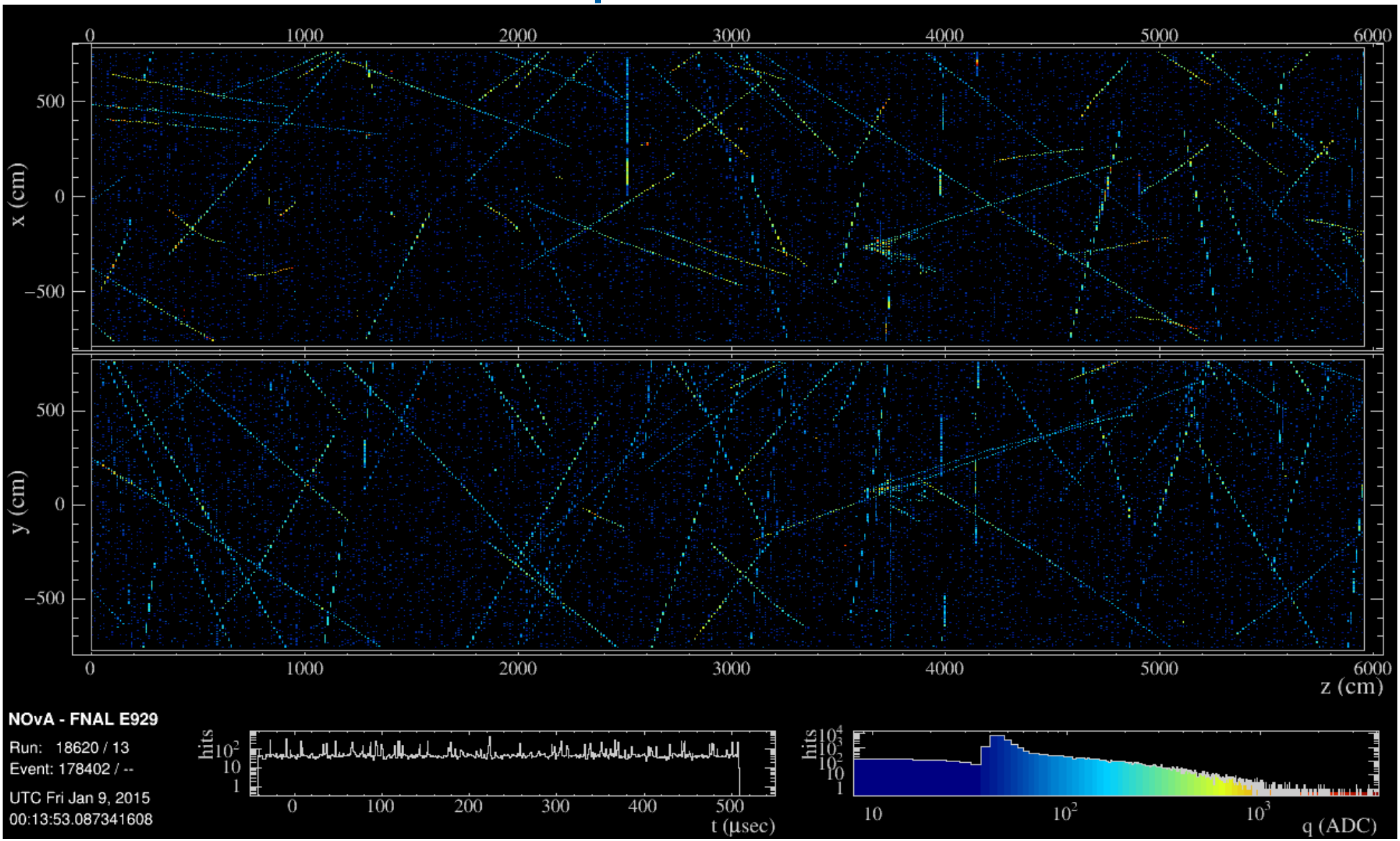
NOvA Detectors



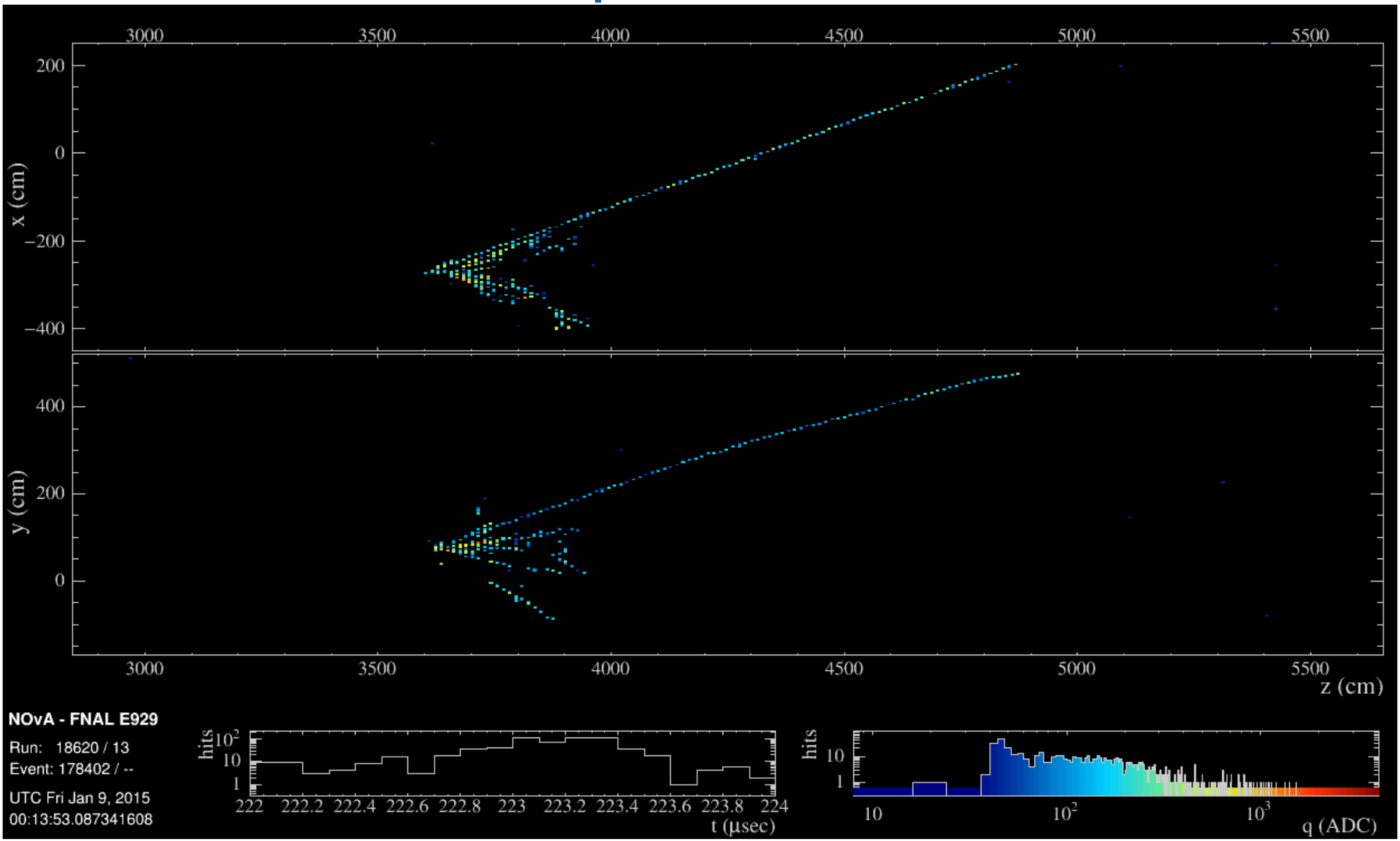
- Far Detector
  - 14 kT
  - 895 planes

- Near Detector
  - 293 tons, including muon catcher
  - used to measure neutrino beam flavor and energy spectrum before oscillations

NOvA Far Detector Beam Spill Event

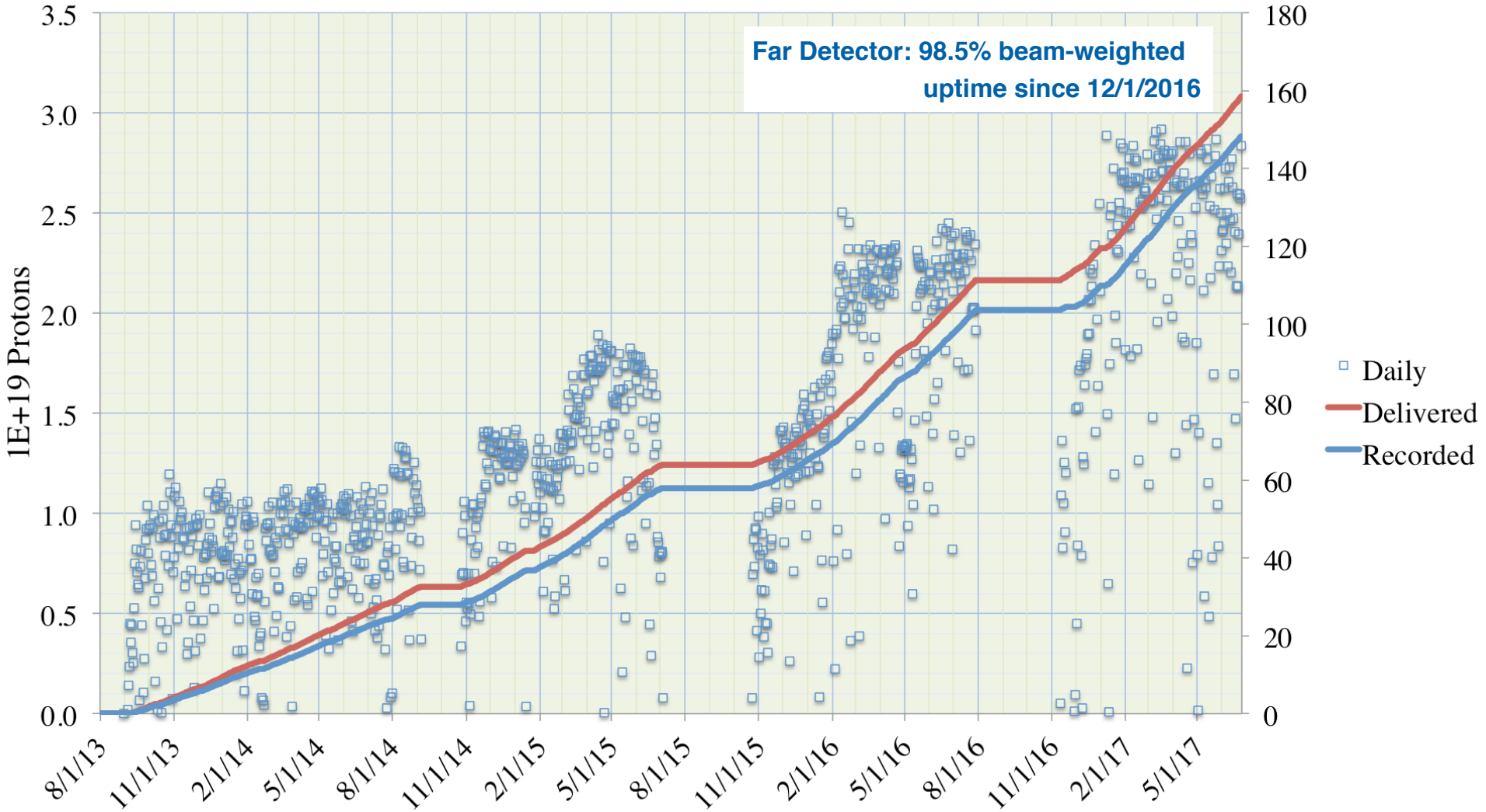


NOvA Far Detector Beam Spill Event - Zoomed

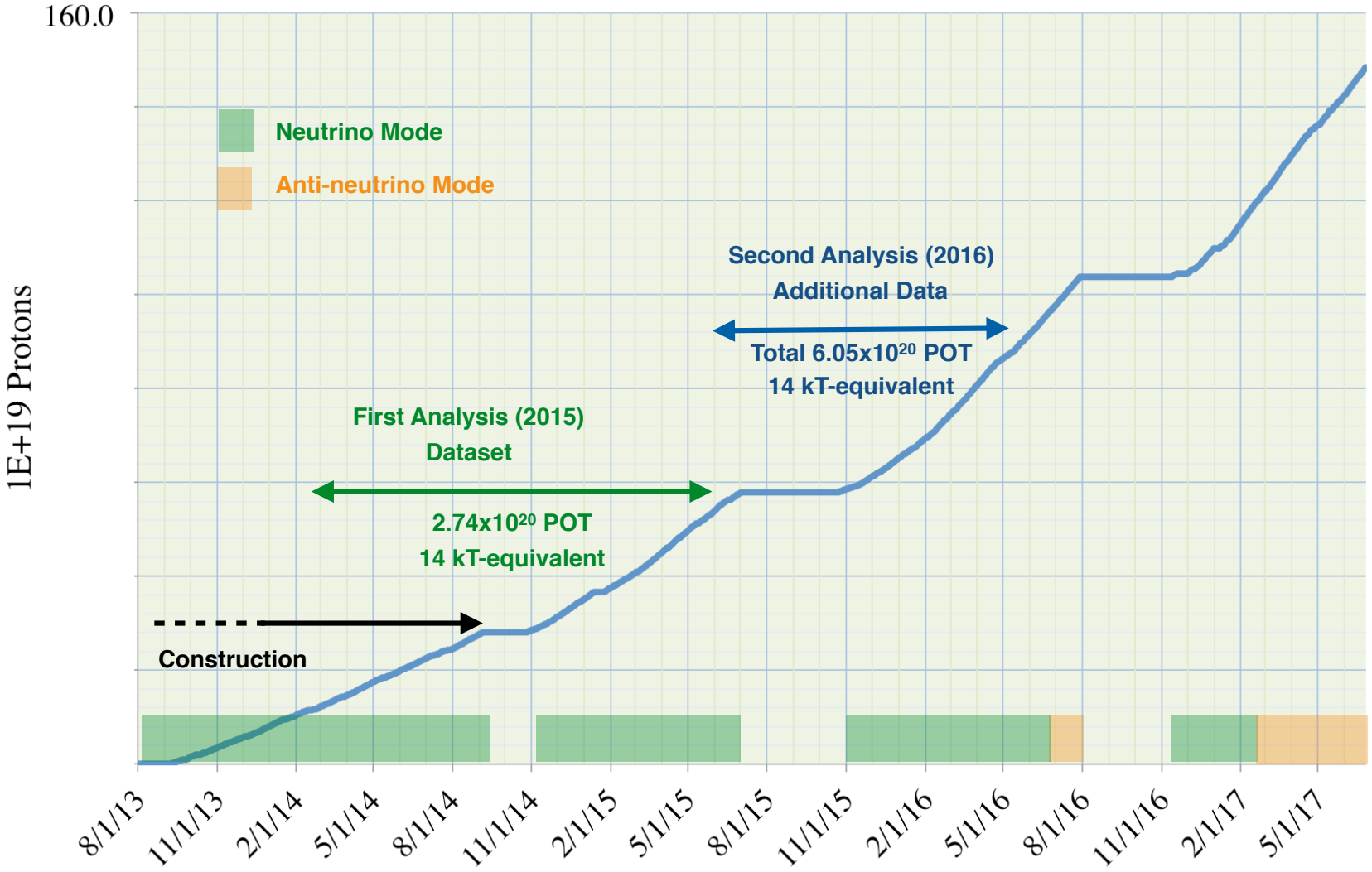


NuMI Performance

- Protons delivered to the NuMI target (POT) recorded at Far Detector
  - Routine 700 kW (NuMI-only-equivalent) running achieved in January



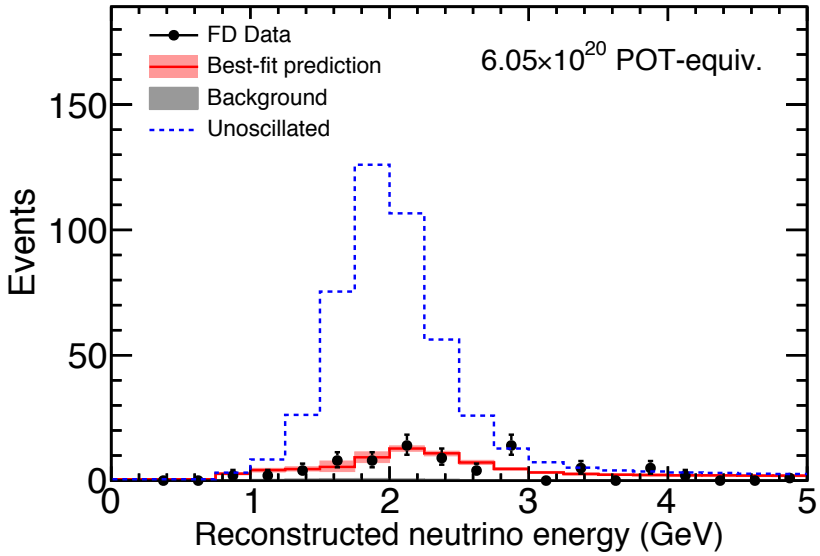
NOvA Data-taking

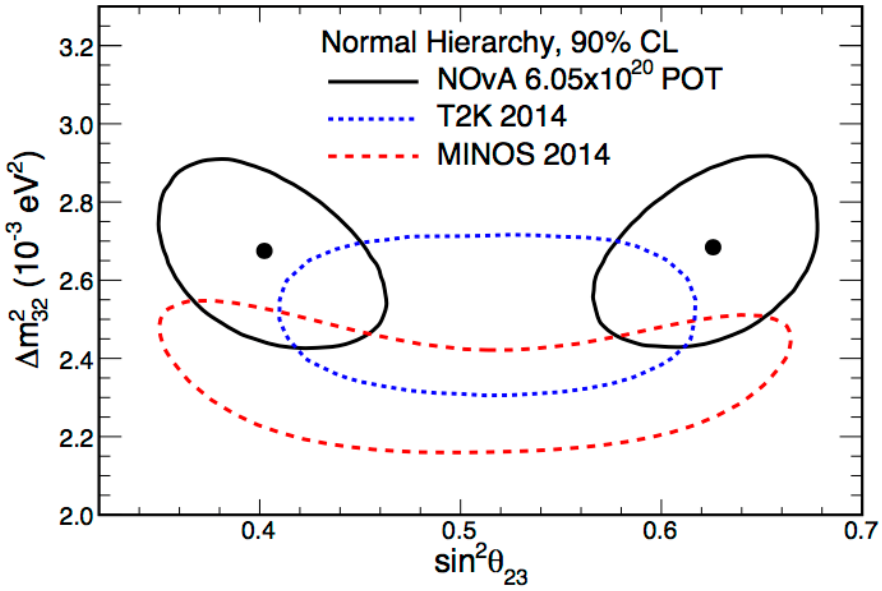


Recent NOvA Publications

- Finalized Neutrino 2016 Results

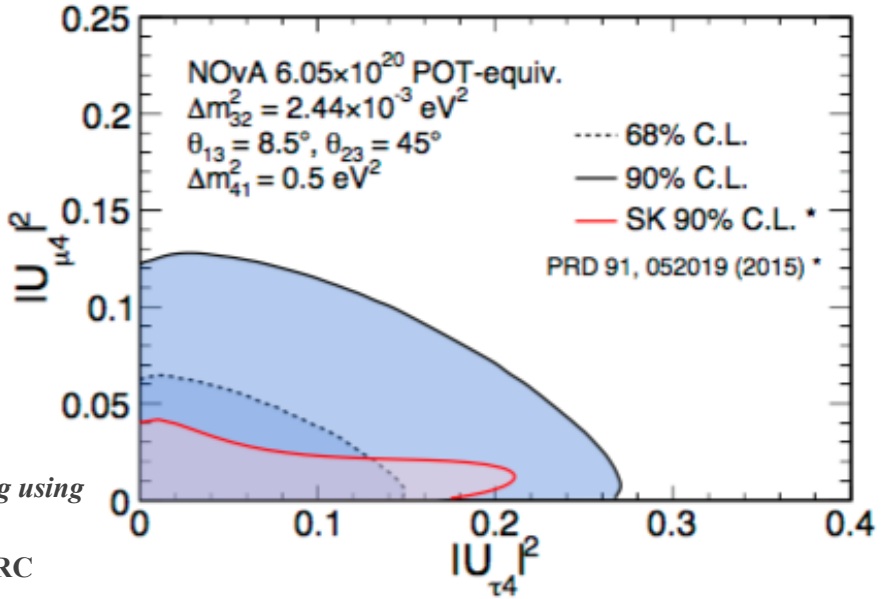
Measurement of the neutrino mixing angle θ_{23} in NOvA
PRL 118, 151802 (2017) *12 citations*





- ν_μ disappearance
  - Maximal mixing disfavored at 2.6 σ

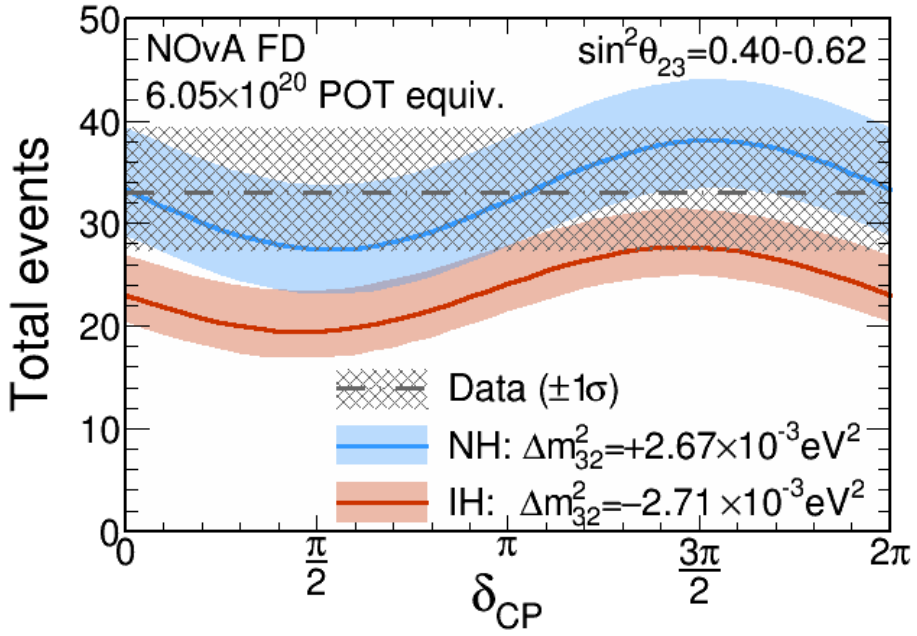
- Flavor-independent disappearance
  - NOvA's first limits on sterile neutrinos via neutral current disappearance



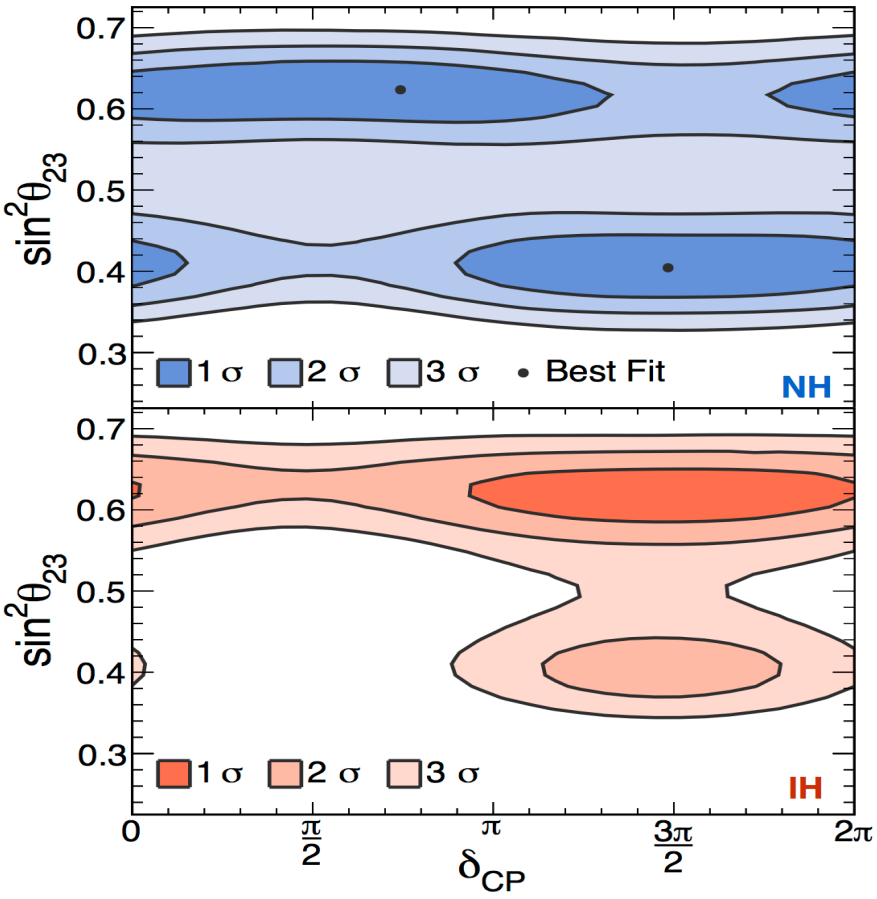
Search for active-sterile neutrino mixing using neutral-current interactions in NOvA
arXiv:1706.04592, Submitted to PRD RC

Recent NOvA Publications

- Update to Neutrino 2016 ν_e appearance
  - Observed 33 events on background of 8.2±0.8
  - **Uses improved selection with CVN deep learning algorithm* equivalent to 30% better exposure**



Constraints on Oscillation Parameters from ν_e appearance and ν_μ disappearance in NOvA
PRL 118, 231801 (2017) *10 citations*



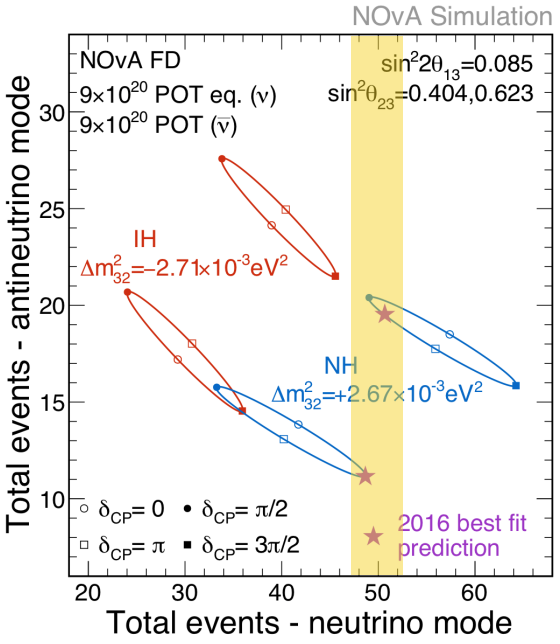
- Full joint ν_μ/ν_e fit constrains oscillation parameters
  - Lower octant/Inverted hierarchy disfavored at 93% CL for all values of δ_{CP}

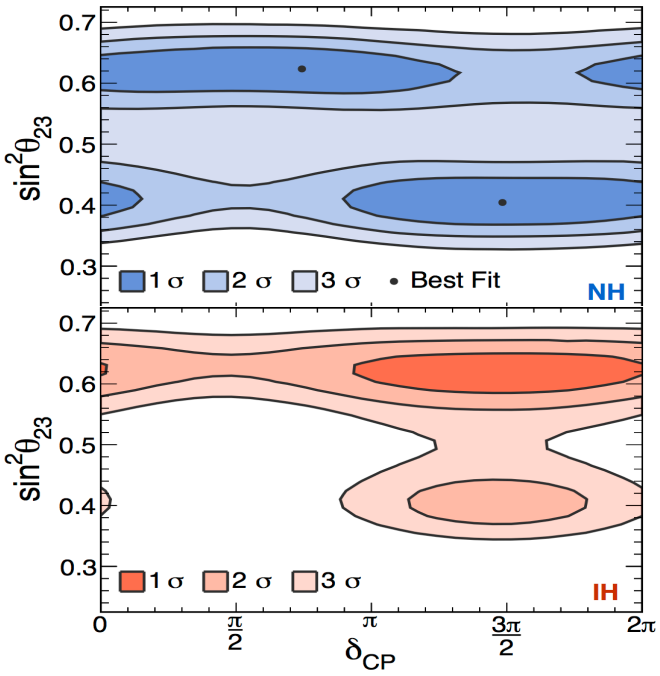
* "A Convolutional Neural Network Neutrino Even Classifer", 2016 JINST 11 P09001

Antineutrino running

- At our current best fit, continued neutrino-mode running alone will not be sufficient to resolve remaining degeneracies

Caveat - simplistic view
of oscillation probabilities

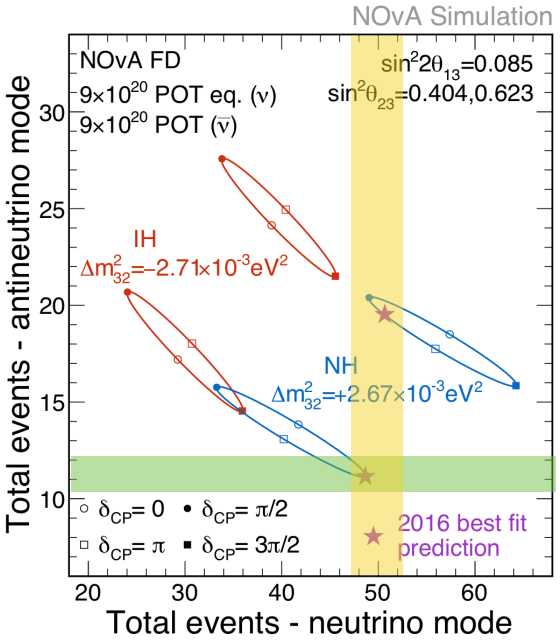


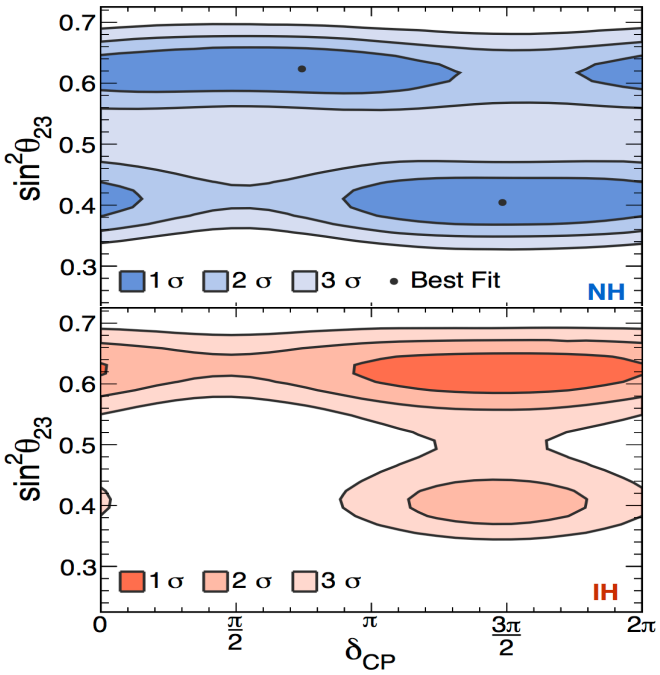


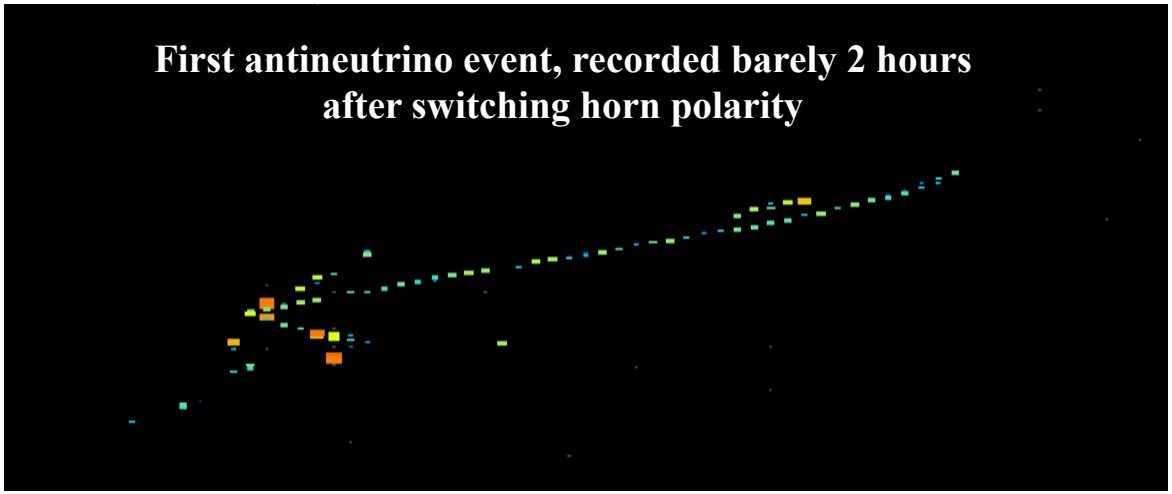
Antineutrino running

- At our current best fit, continued neutrino-mode running alone will not be sufficient to resolve remaining degeneracies
- Antineutrino running confers the most benefit in the near-medium term
- Longer term, a 50/50 mix of neutrino and antineutrino running is optimal

Caveat - simplistic view
of oscillation probabilities

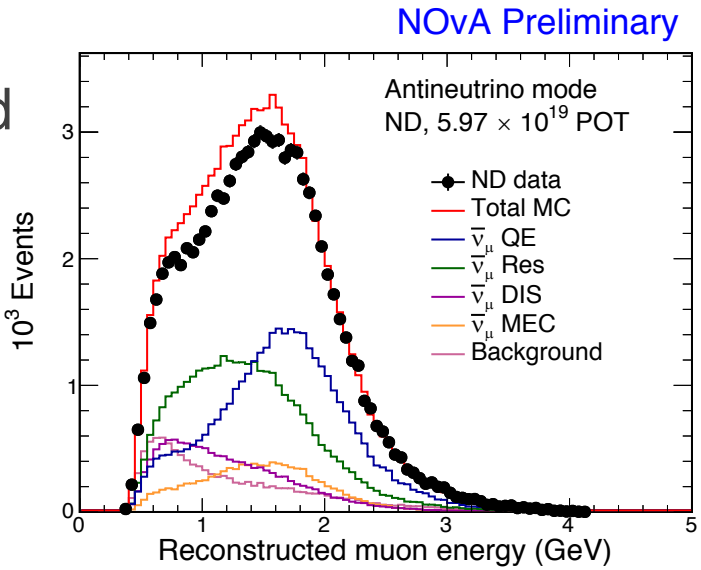


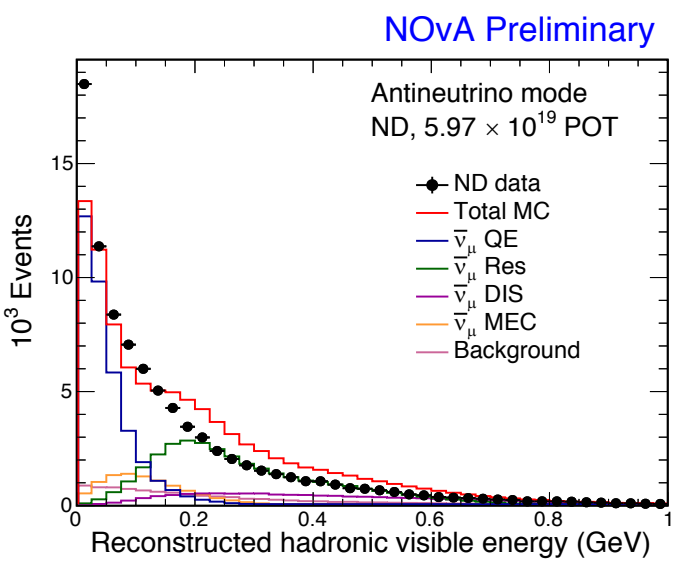




Analysis Progress

- Detector response and cross-section modeling updates
  - Near Detector distributions shown at February EMG using earlier version of simulation





- ν_μ Disappearance
  - Improved energy estimator
  - Use of energy resolution binning in oscillation fit
- ν_e Appearance
  - Improved selection (CVN) allows loosening other cuts
  - Improved energy estimator
- Reconstruction
  - Use of deep learning to individual tracks and showers has promise for improved energy estimation, and any application where more precise event ID is useful

Upcoming Analysis Goals

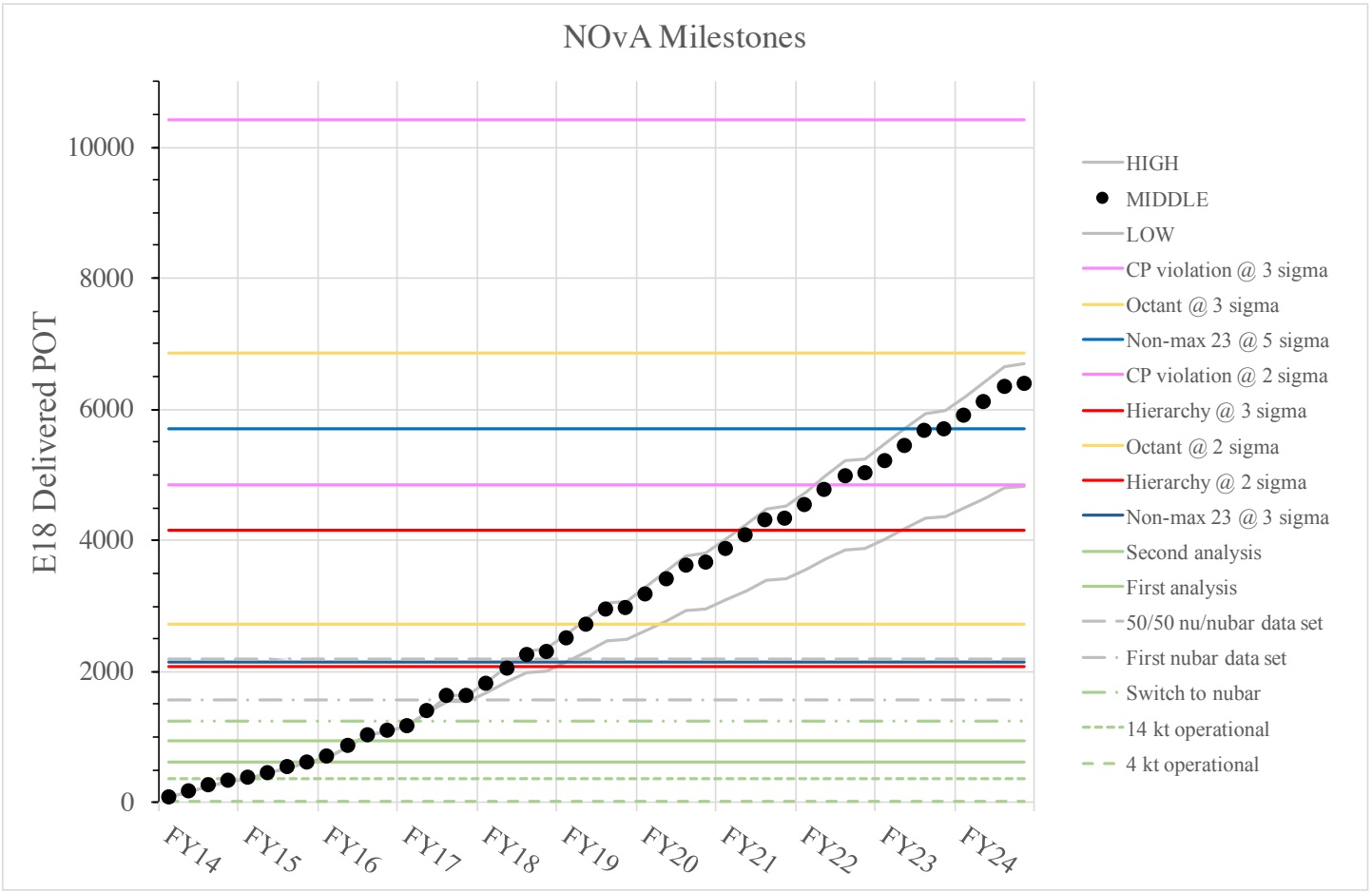
- Fall 2017 - Updates with 9.1x10^{20} POT neutrino mode with Simulation and Reconstruction improvements
  - ν_μ Disappearance
  - Combined ν_μ and ν_e
  - NC Disappearance

- Cross-section analyses
  - ν_μ and ν_e inclusive cross sections
  - Analysis of multinuclear contribution to cross-sections

- First NOvA antineutrino results for Neutrino 2018
  - Up to 9 (neutrino) + 8 (antineutrino) x 10^{20} POT
  - First NOvA anti-ν_μ disappearance result
  - First NOvA joint $\nu_\mu + \nu_e$, $\overline{\nu}_\mu + \overline{\nu}_e$ result

NOvA Sensitivity Milestones

Assuming Current Analysis and Beam Power



Dots are median of last six weeks running. Upper line is best of last 6 weeks, bottom is worst of last six weeks.

Future years assumed to be 40 weeks of running /yr

Sensitivities depend on the values of the parameters we want to measure.

These sensitivities are calculated using $\sin^2(\theta_{23})=0.403$, Normal Hierarchy, and $\delta_{CP}=3\pi/2$

These are close to the current global best fit

Highlights

FY18 - 2σ MH, 3σ non-maximal mixing

FY19 - 2σ θ_{23} octant

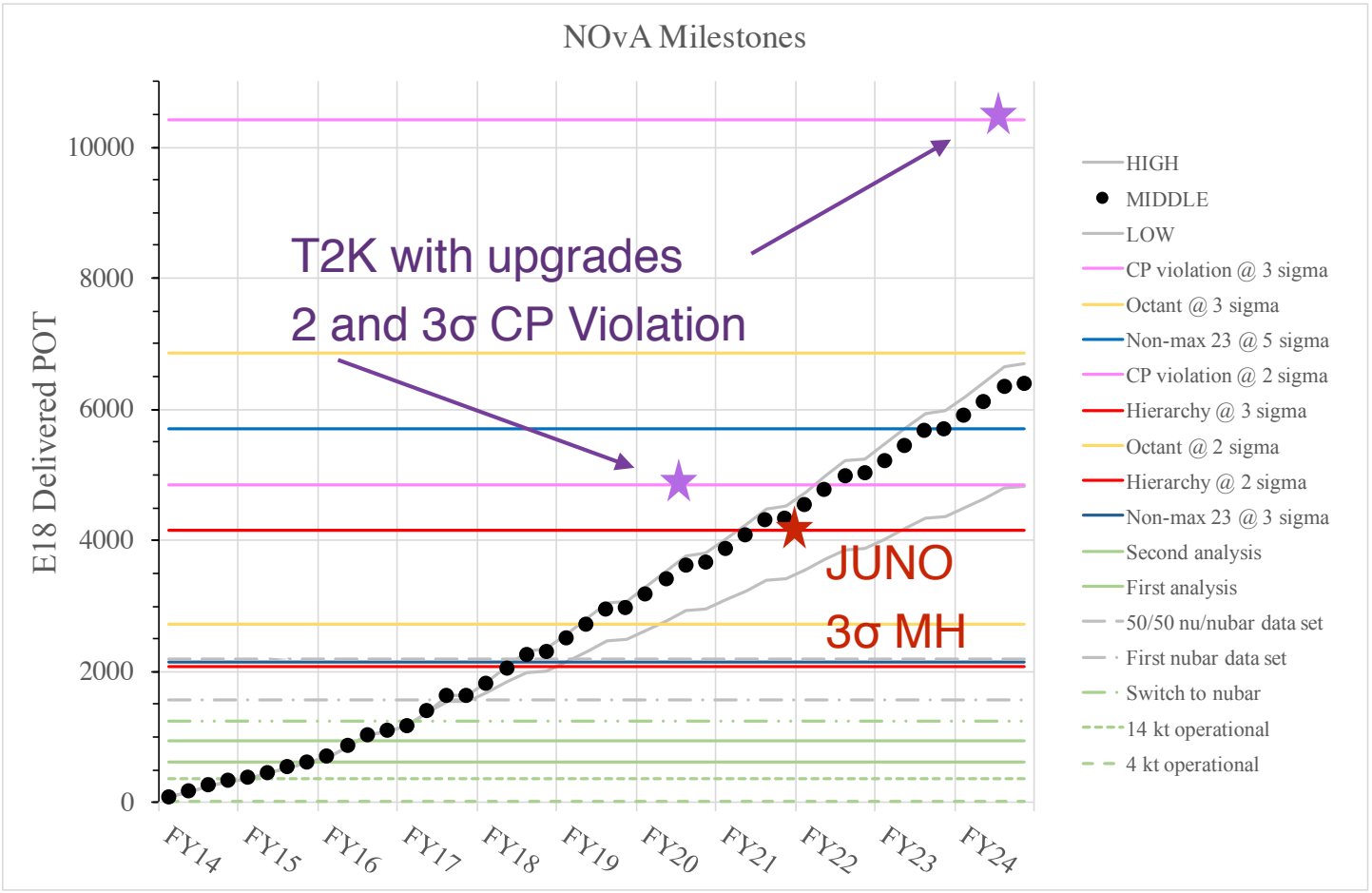
FY21 - 3σ MH

FY22 - 2σ CP Violation

FY23 - 5σ non-max mixing

NOvA Sensitivity Milestones - Competition

Assuming Current Analysis and Beam Power



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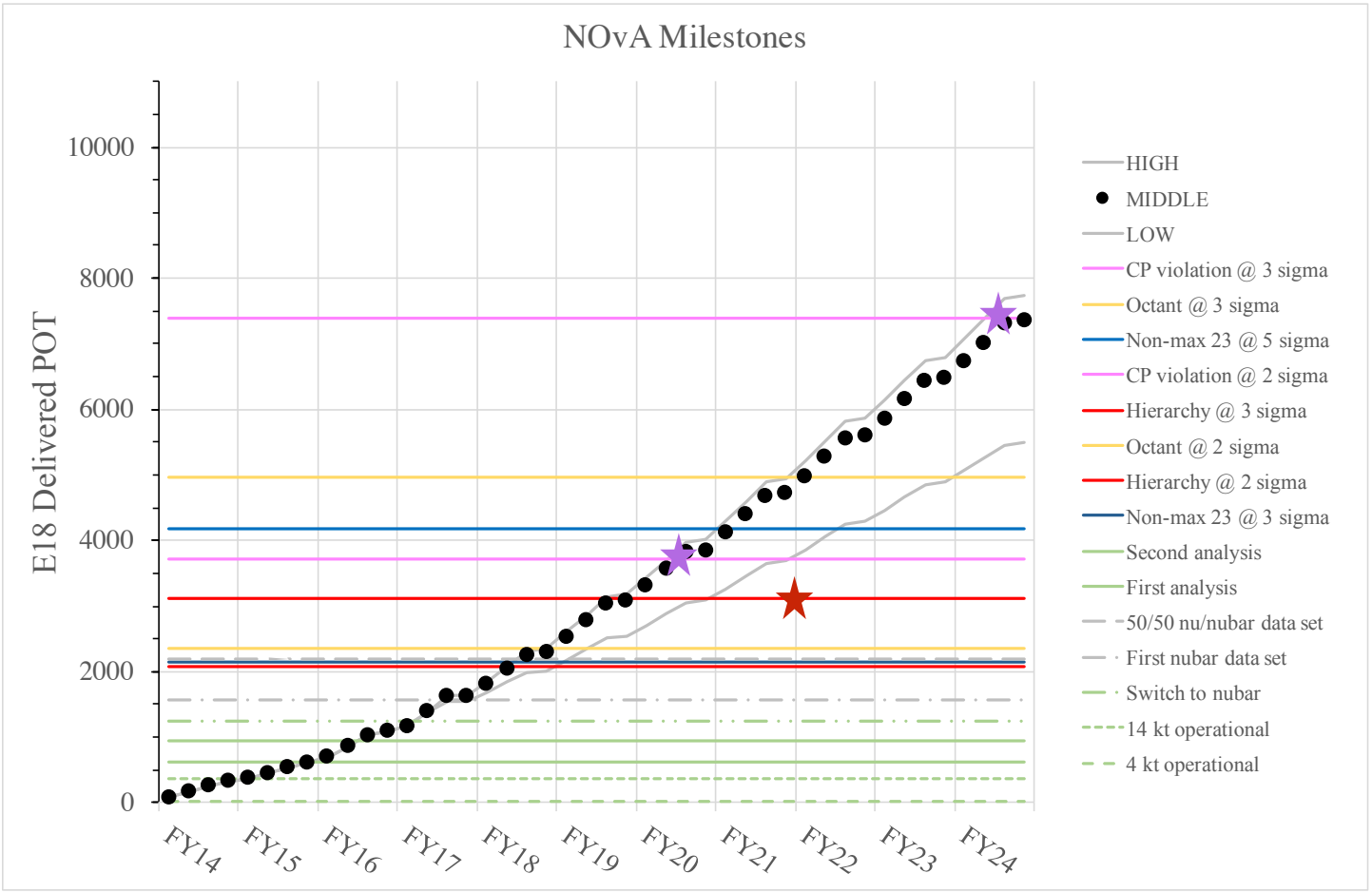
Highlights

FY18 - 2σ MH, 3σ non-maximal mixing
FY19 - 2σ θ_{23} octant
FY21 - 3σ MH
FY22 - 2σ CP Violation
FY23 - 5σ non-max mixing

These opportunities are not unique to Fermilab

NOvA Sensitivity Milestones

Assuming PIP-1+, Target System Optimization, Analysis Improvements



PIP-1+: 800 kW in FY19, 900 kW in FY21

Analysis improvements equivalent to 25% increase in exposure

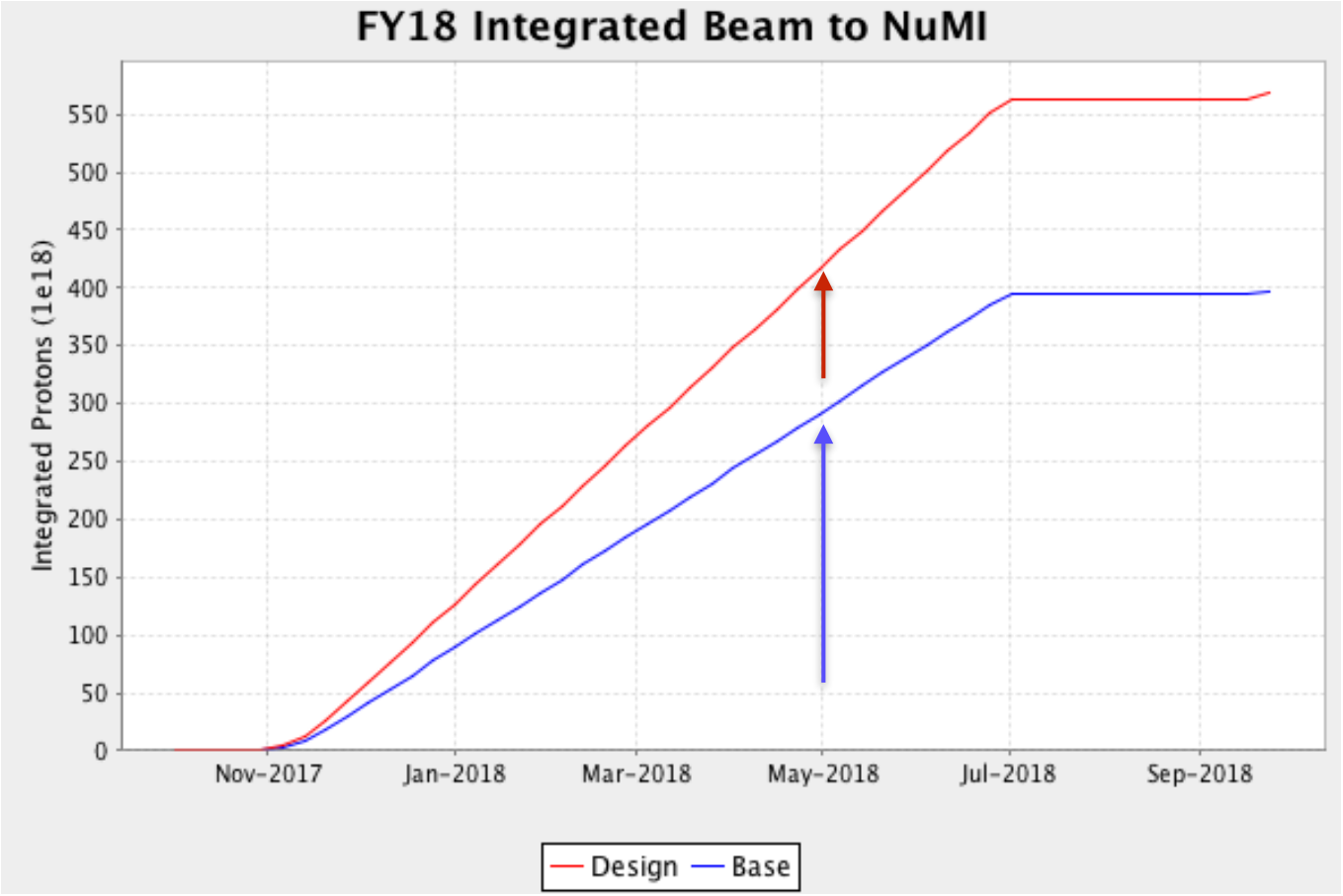
Target system optimization for 17% more neutrinos per proton

3σ CP Violation is possible

NOvA in race with T2K for CP Violation

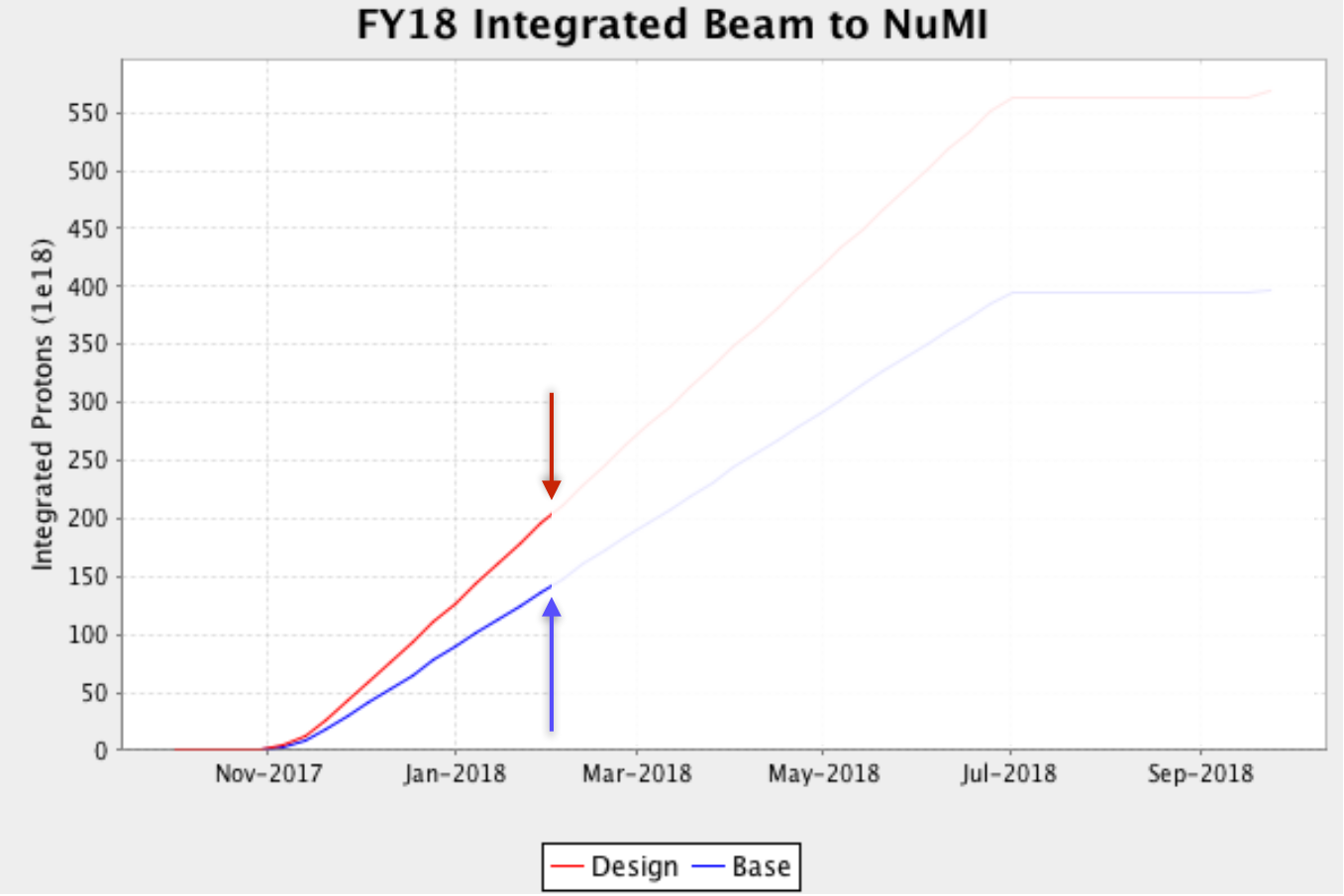
NOvA pulls ahead of JUNO for Mass Hierarchy

NOvA Data by Neutrino 2018



Protons-on-Target 10^{20}	*End FY17*	*May 1, Neutrino 2018 Cutoff*	*End FY 18*
Neutrinos	*9.1*	*9.1*	*9.1*
Antineutrinos	*3.8*	*6.6-8.0*	*7.7-9.4*

Short-term Impact of Shortened “37%” FY18 Run



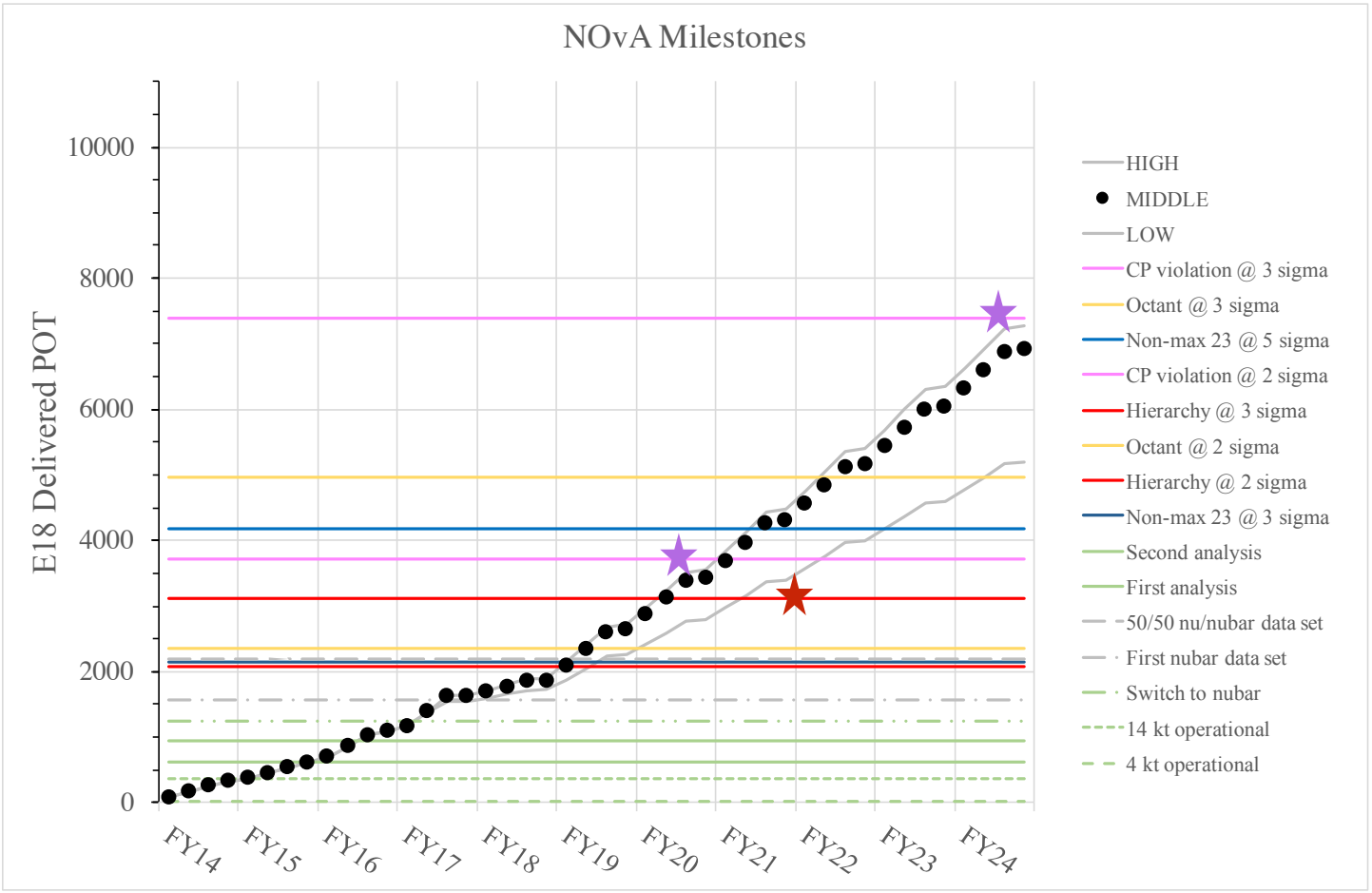
Protons-on-Target 10^{20}	*End FY17*	*March 1 Run End*	*End FY 18*
Neutrinos	*9.1*	*9.1*	
Antineutrinos	*3.8*	*5.2-5.8*	

Comparison of Nominal and Shortened FY18 Run for Neutrino18

- Antineutrino Exposure
  - Nominal: 8.0×10^{20} (upper curve)
  - Shortened: 5.2×10^{20} (lower curve)
- Statistics
  - Nominal: 4.8 signal, 1.2 wrong-sign, 4.0 background
  - Shortened: 3.2 signal, 0.8 wrong-sign, 2.6 background
- **95% CL Mass Hierarchy determination for Normal Hierarchy, Lower Octant**
  - Nominal: 15% of δ_{CP} values (a priori, so better taking into account best fit of data in-hand)
  - Shortened: no values of δ_{CP}

Long-Term Impact of Shortened FY18 Run

Assuming Short FY18, then PIP-1+, Target Optimization, Analysis Improvements



NOvA does not catch up to T2K on CP Violation

NOvA stays ahead of JUNO on Mass Hierarchy at 3σ

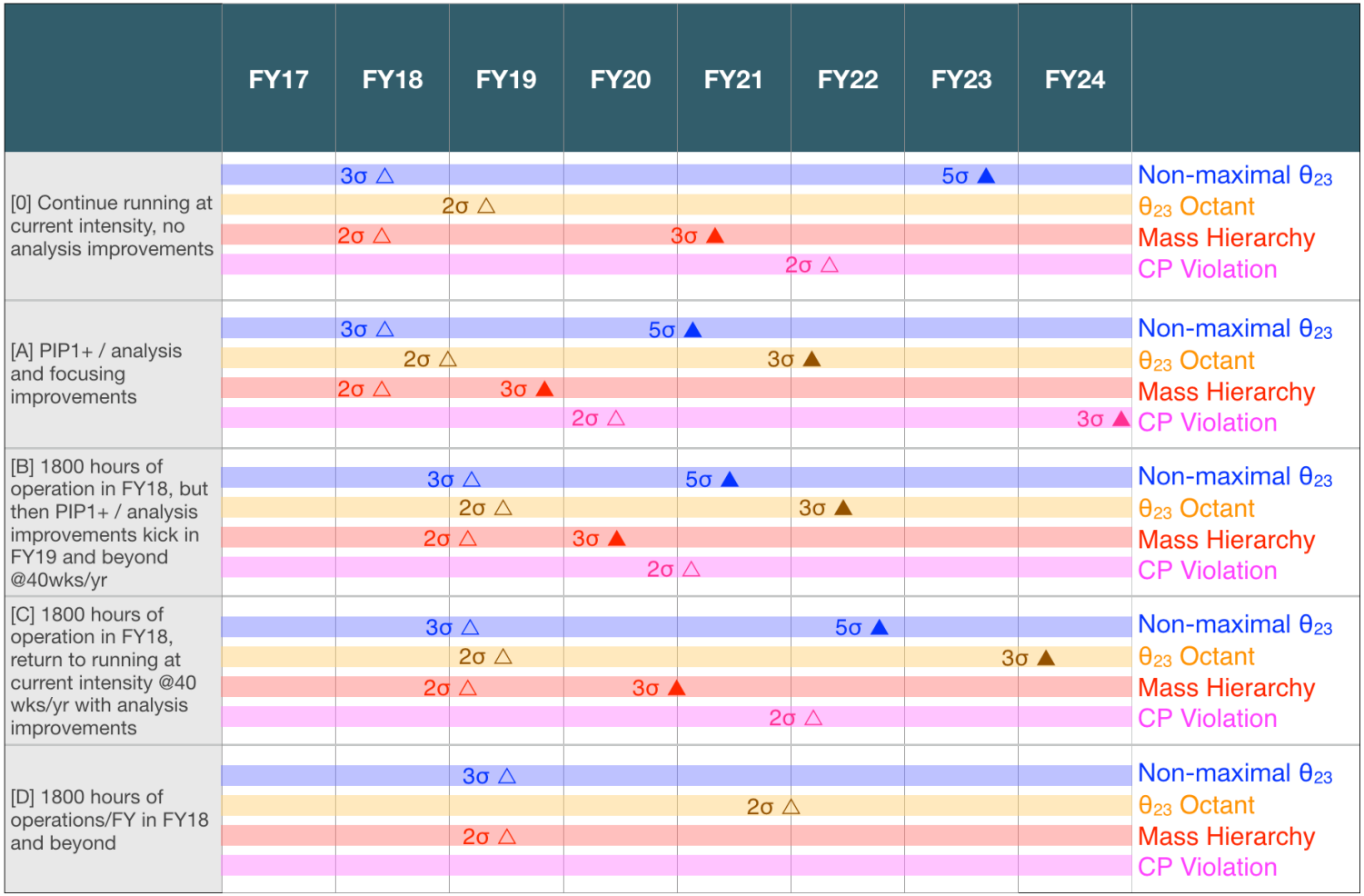
Summary

- Accelerator complex is providing excellent beam to NuMI
- NOvA is running very well
- NOvA has published 4 papers with 6×10^{20} POT, 5th on the arXiv
  - 3/3 PRLs have been “Editors Suggestions”, indicative of interest in the Community
- With reasonable investment, NOvA is in the running to beat the competition to several upcoming milestones
  - T2K on 2σ and 3σ CP Violation
  - Potential 2σ Mass Hierarchy from global fits
  - JUNO on 3σ Mass Hierarchy
- A shortened FY18 run would impact NOvA
  - Virtually eliminate possibility of 2σ Mass Hierarchy result for Neutrino ’18
  - Risk the race for 3σ Mass Hierarchy to JUNO
  - Cede the race for 2σ and 3σ CP Violation to T2K
  - Reduce the competitiveness of students and postdocs on the job market

Extras

Ongoing Impact of Shortened FY18 Run

Calculated for $\sin^2(\theta_{23})=0.404$, Normal Hierarchy, and $\delta_{CP}=3\pi/2$

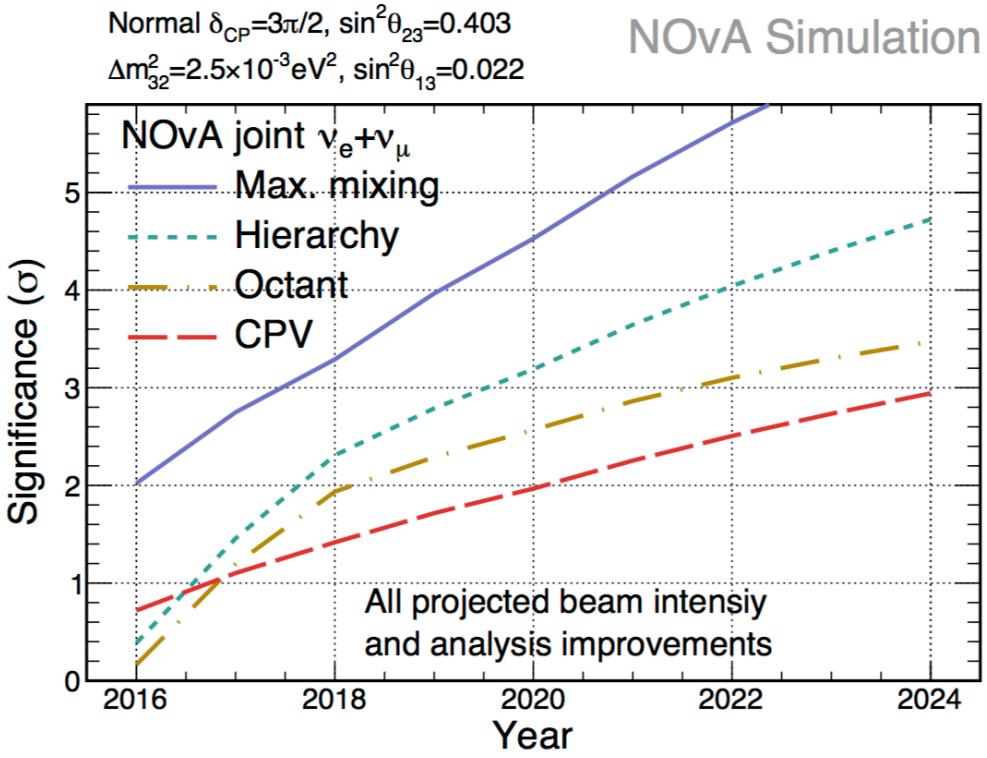


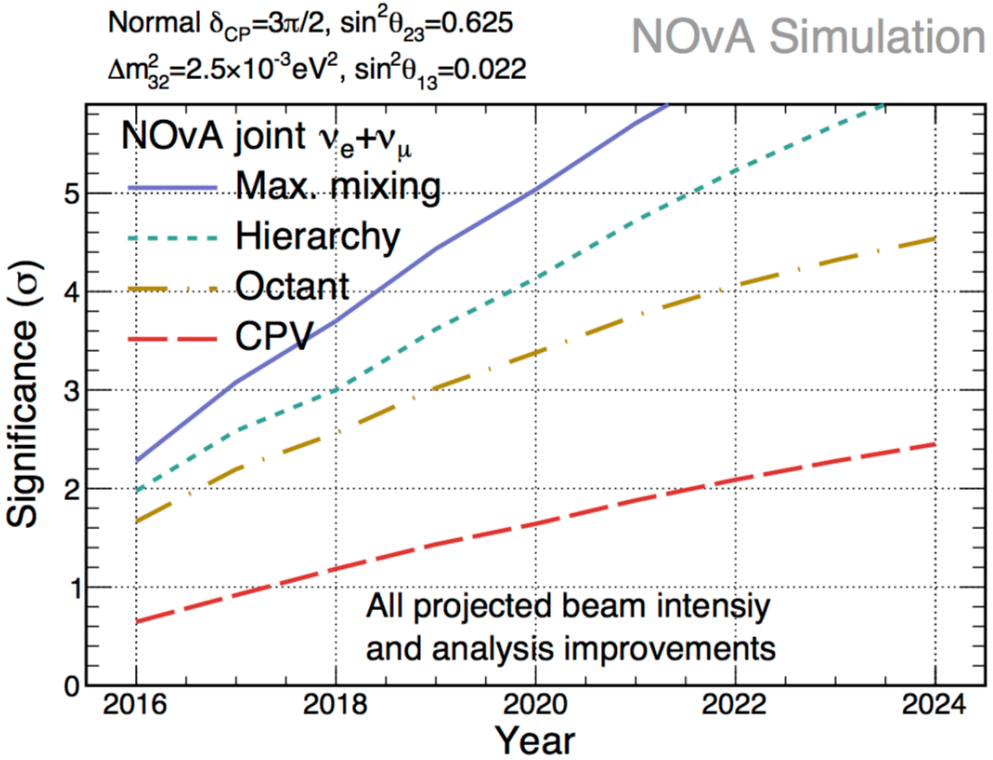
T2K

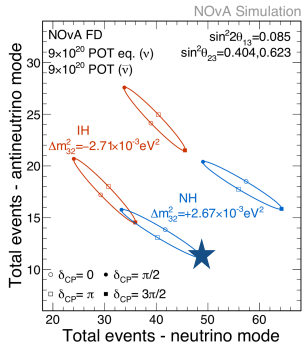
- J-PARC PAC minutes from January 2017 reflect sense of competition in T2K

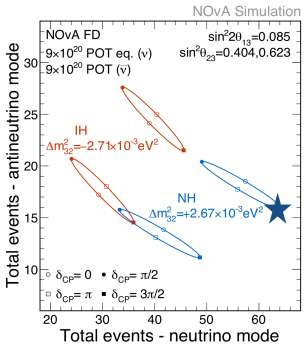
> assess the status of neutrino oscillations. The 7.3×10^{20} goal would allow T2K to keep pace with NOvA in 2017. In the future, T2K requests 9.0×10^{20} per year to be competitive with the assumed NOvA plans to collect 6.0×10^{20} POT per year. The PAC endorses efforts to maximize the integrated POT after the 2017 summer shutdown, in

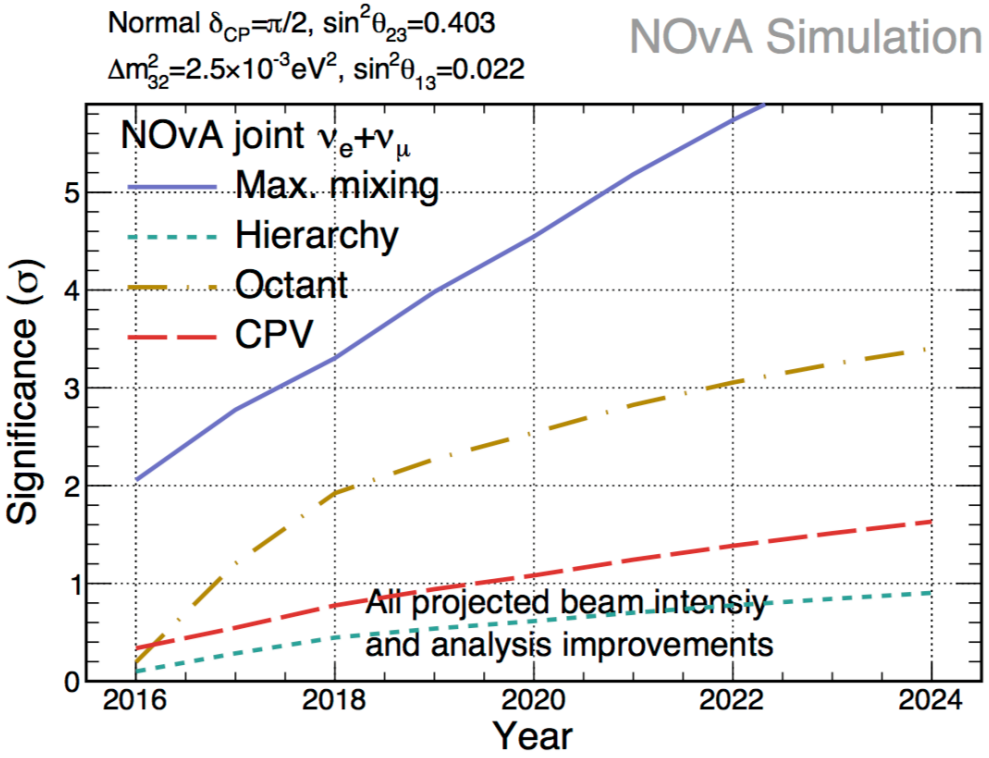
- T2K-II Proposal
  - Extend exposure to 20×10^{20} POT (from 7×10^{20} POT)
    - Running through 2026
    - 1.3 MW beam power through increased PPP and reduced cycle time
  - Increase neutrino flux per POT by 10%
    - Horn power supply upgrades
  - Increase selection efficiency in SuperKamiokande by up to 40%

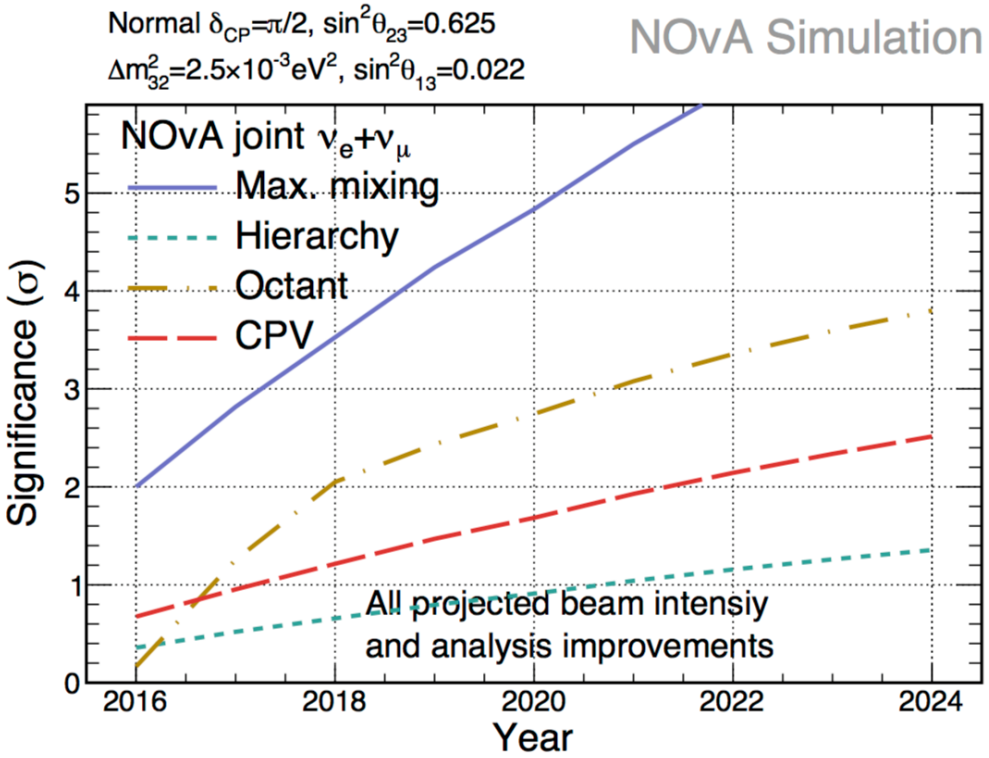

Normal $\delta_{CP}=3\pi/2$, $\sin^2\theta_{23}=0.403$
$\Delta m^2_{32}=2.5\times10^{-3}eV^2$, $\sin^2\theta_{13}=0.022$
NOvA Simulation
NOvA joint $\nu_e+\nu_\mu$
Max. mixing
Hierarchy
Octant
CPV
All projected beam intensiy
and analysis improvements
Significance (σ)
Year
0
1
2
3
4
5
2016
2018
2020
2022
2024

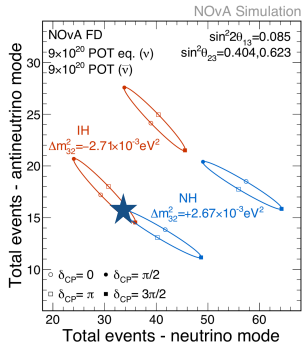

Normal $\delta_{CP}=3\pi/2$, $\sin^2\theta_{23}=0.625$
$\Delta m^2_{32}=2.5\times10^{-3}eV^2$, $\sin^2\theta_{13}=0.022$
NOvA Simulation
NOvA joint $\nu_e+\nu_\mu$
Max. mixing
Hierarchy
Octant
CPV
All projected beam intensiy
and analysis improvements
Significance (σ)
Year
0
1
2
3
4
5
2016
2018
2020
2022
2024

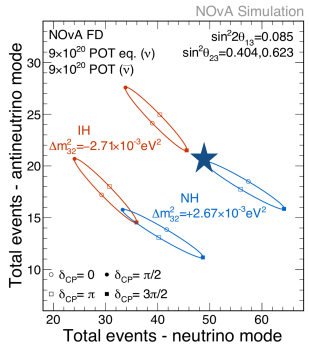

NOvA Simulation
NOvA FD
9×10^{20} POT eq. (ν)
9×10^{20} POT ($\bar{\nu}$)
$\sin^2 2\theta_{13}=0.085$
$\sin^2\theta_{23}=0.404,0.623$
IH
$\Delta m^2_{32}=-2.71\times10^{-3}eV^2$
NH
$\Delta m^2_{32}=+2.67\times10^{-3}eV^2$
$\delta_{CP}=0$ • $\delta_{CP}=\pi/2$
$\delta_{CP}=\pi$ ▪ $\delta_{CP}=3\pi/2$
Total events - antineutrino mode
Total events - neutrino mode
10
15
20
25
30
20
30
40
50
60


NOvA Simulation
NOvA FD
9×10^{20} POT eq. (ν)
9×10^{20} POT ($\bar{\nu}$)
$\sin^2 2\theta_{13}=0.085$
$\sin^2\theta_{23}=0.404,0.623$
IH
$\Delta m^2_{32}=-2.71\times10^{-3}eV^2$
NH
$\Delta m^2_{32}=+2.67\times10^{-3}eV^2$
$\delta_{CP}=0$ • $\delta_{CP}=\pi/2$
$\delta_{CP}=\pi$ ▪ $\delta_{CP}=3\pi/2$
Total events - antineutrino mode
Total events - neutrino mode
10
15
20
25
30
20
30
40
50
60


Normal $\delta_{CP}=\pi/2$, $\sin^2\theta_{23}=0.403$
$\Delta m^2_{32}=2.5\times10^{-3}eV^2$, $\sin^2\theta_{13}=0.022$
NOvA Simulation
NOvA joint $\nu_e+\nu_\mu$
Max. mixing
Hierarchy
Octant
CPV
All projected beam intensiy
and analysis improvements
Significance (σ)
Year
0
1
2
3
4
5
2016
2018
2020
2022
2024


Normal $\delta_{CP}=\pi/2$, $\sin^2\theta_{23}=0.625$
$\Delta m^2_{32}=2.5\times10^{-3}eV^2$, $\sin^2\theta_{13}=0.022$
NOvA Simulation
NOvA joint $\nu_e+\nu_\mu$
Max. mixing
Hierarchy
Octant
CPV
All projected beam intensiy
and analysis improvements
Significance (σ)
Year
0
1
2
3
4
5
2016
2018
2020
2022
2024


NOvA Simulation
NOvA FD
9×10^{20} POT eq. (ν)
9×10^{20} POT ($\bar{\nu}$)
$\sin^2 2\theta_{13}=0.085$
$\sin^2\theta_{23}=0.404,0.623$
IH
$\Delta m^2_{32}=-2.71\times10^{-3}eV^2$
NH
$\Delta m^2_{32}=+2.67\times10^{-3}eV^2$
$\delta_{CP}=0$ • $\delta_{CP}=\pi/2$
$\delta_{CP}=\pi$ ▪ $\delta_{CP}=3\pi/2$
Total events - antineutrino mode
Total events - neutrino mode
10
15
20
25
30
20
30
40
50
60


NOvA Simulation
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Total events - antineutrino mode
Total events - neutrino mode
10
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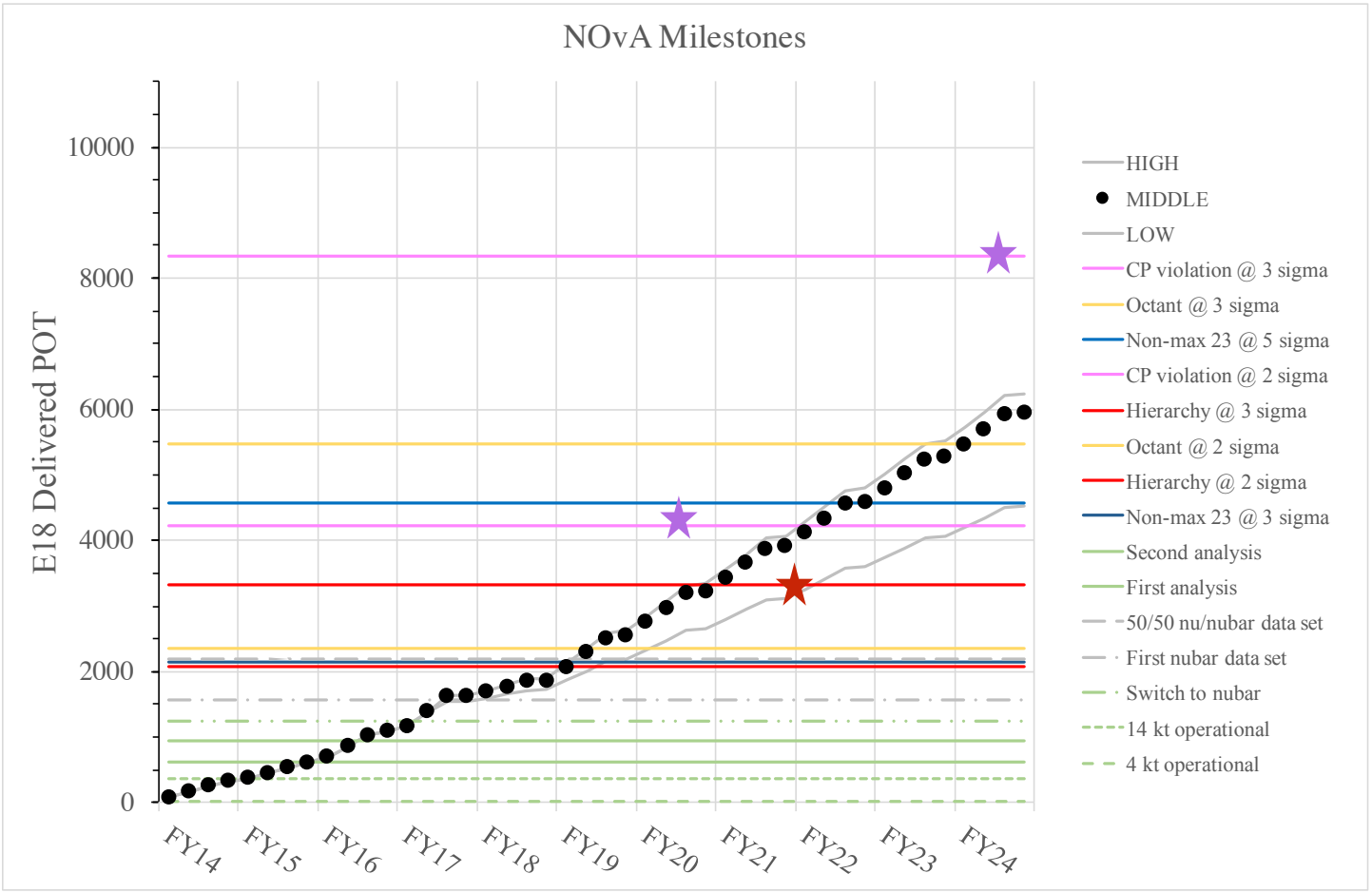
50
60

Long-Term Impact of Shortened FY18 Run

Assuming Short FY18, Analysis Improvements, no beam improvements



NOvA does not catch up to T2K on CP Violation

NOvA stays ahead of JUNO on Mass Hierarchy at 3σ