NOvA and the Competition

Peter Shanahan

PAC Preparatory Meeting

10 November 2017

In partnership with:

Recent NOvA Progress

- Long-baseline sterile neutrino search in "Neutral Current Disappearance"
  - Published 2016 analysis: Phys. Rev. D 96, 072006 (2017)
  - Presented updated analysis at NuFact in September: 46% more data, energy-dependent fit
- Cross-sections
  - Presented preliminary Neutral Current Coherent π^0 cross section at NuInt in June
  - Working toward upcoming Wine & Cheese with this result and Charged Current π^0 cross section
- 3-flavor Oscillations
  - Updated results with all available neutrino-mode data - 46% more than 2016 results.
  - Improved detector simulation
  - Improved selection in both ν_μ and ν_e analyses
    - Equivalent to 17% more exposure in ν_e, 17% higher efficiency in ν_μ
  - For ν_μ, finer energy binning optimized for maximal mixing rejection, use use of energy resolution binning
  - Updated neutrino interaction model

New T2K Results Presented in August 2017

- Using 14.7×10^{20} protons-on-target (POT) for neutrino mode, 7.6×10^{20} POT anti neutrino
- Improved reconstruction and event selection equivalent to 30% increase in exposure
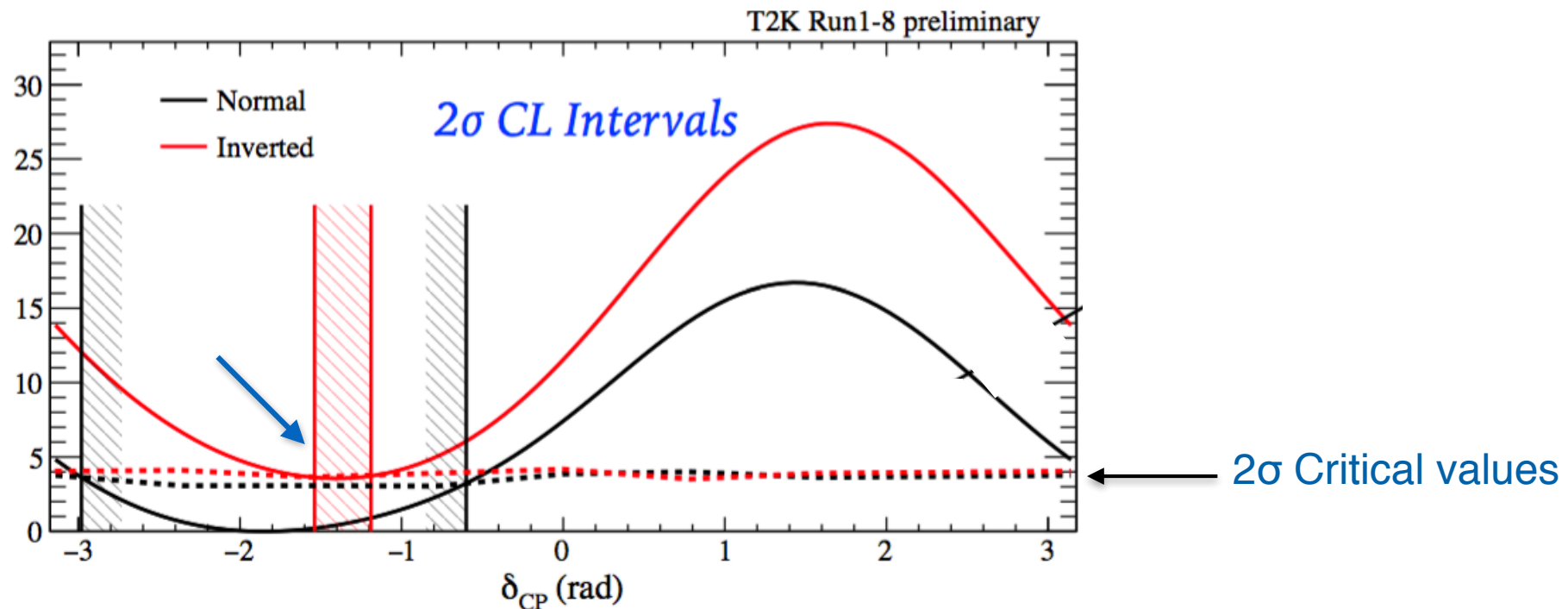
Mark Hartz, KEK Colloquium, 8/4/17
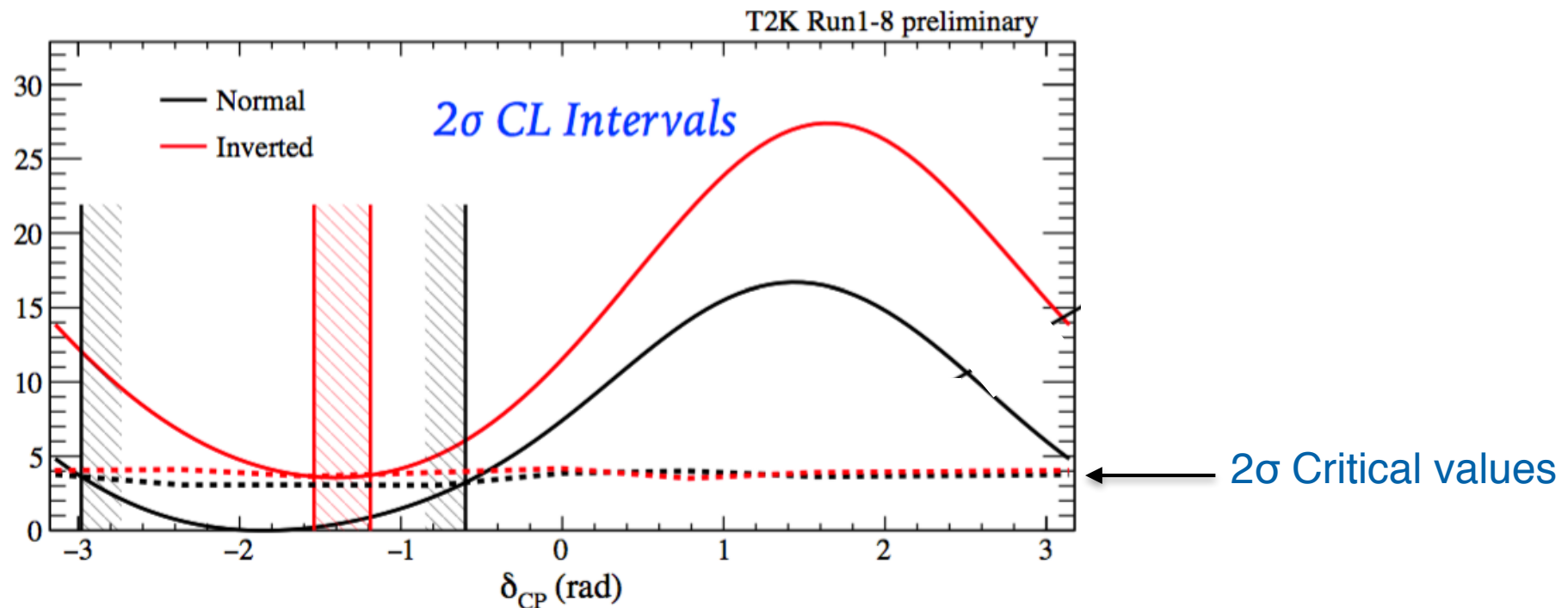
Best fit: Normal Hierarchy, $\delta_{CP} = -0.58\pi$ $(=1.42\pi)$, $\sin^2(\theta_{23}) = 0.53$

CP-Conserving values of δ_{CP} (0 and π) fall outside 2σ CL Interval

New T2K Results Presented in August 2017

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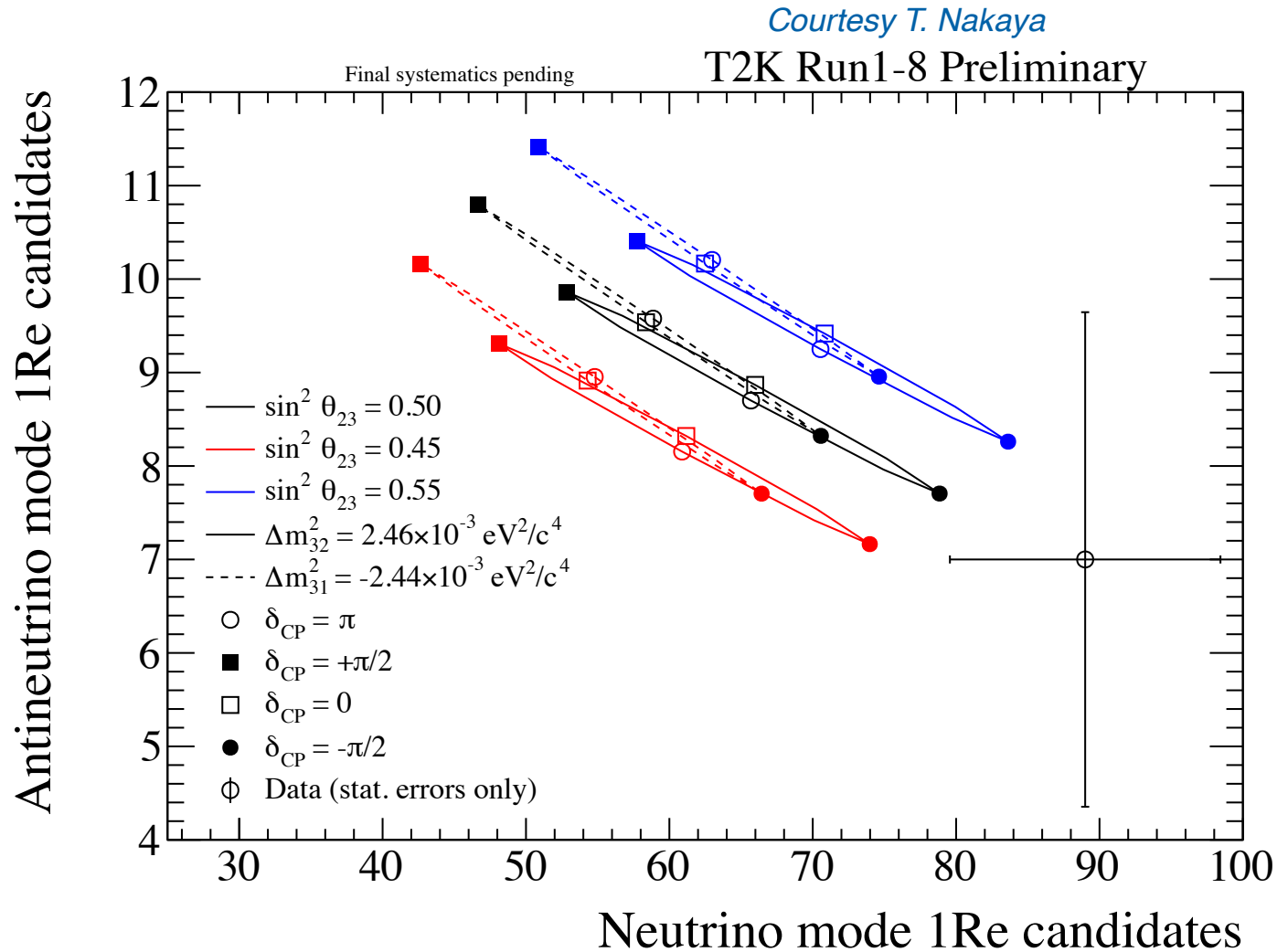
Mark Hartz, KEK Colloquium, 8/4/17

T2K Run1-8 preliminary

2σ CL Intervals

Normal — Inverted

2σ Critical values

δ$_{CP}$ (rad)

Best fit: Normal Hierarchy, δ$_{CP}$=-0.58π (=1.42π), sin^2(θ$_{23}$)=0.53

Closing in on 2σ on Mass Hierarchy

T2K ν_e Event Counts

- Observed ν_e event count favors

Courtesy T. Nakaya

T2K Run1-8 Preliminary

Final systematics pending

Antineutrino mode 1Re candidates (y-axis, 4 to 12)

Neutrino mode 1Re candidates (x-axis, 30 to 100)

Legend:
- —— $\sin^2 \theta_{23} = 0.50$
- —— $\sin^2 \theta_{23} = 0.45$
- —— $\sin^2 \theta_{23} = 0.55$
- —— $\Delta m^2_{32} = 2.46 \times 10^{-3} \text{ eV}^2/\text{c}^4$
- ---- $\Delta m^2_{31} = -2.44 \times 10^{-3} \text{ eV}^2/\text{c}^4$
- ○ $\delta_{CP} = \pi$
- ■ $\delta_{CP} = +\pi/2$
- □ $\delta_{CP} = 0$
- ● $\delta_{CP} = -\pi/2$
- ⌀ Data (stat. errors only)

Looking Ahead - NOvA

- Reminder: In June we showed evolution of sensitivities assuming
  - Analysis improvements equivalent to 25% exposure gain (2/3 of the way there)
  - improved systematic uncertainties (test beam),
  - 17% more neutrinos/proton from target reoptimization,
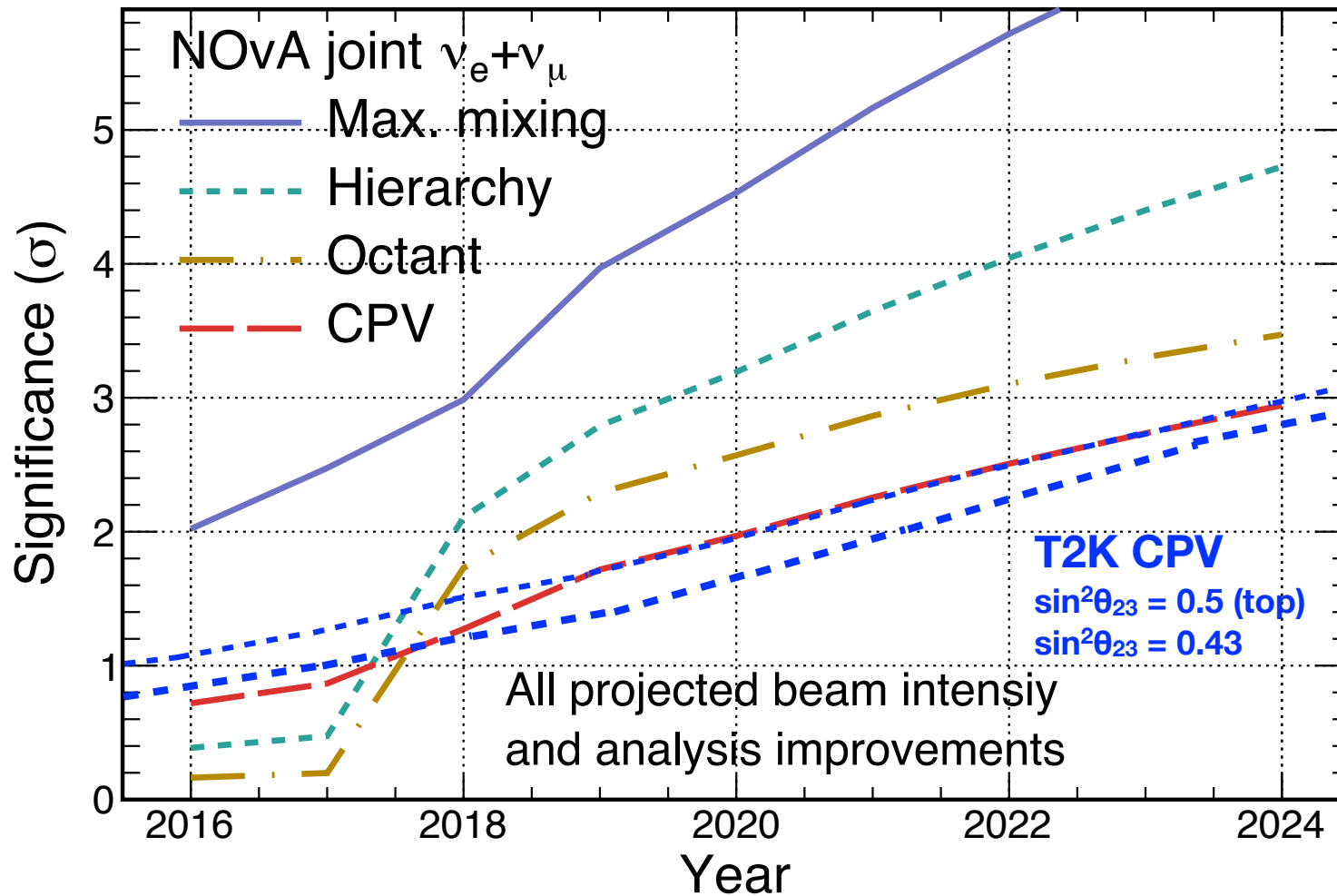 - PIP-1+ delivering 800 kW starting in 2019, 900 kW starting 2021

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

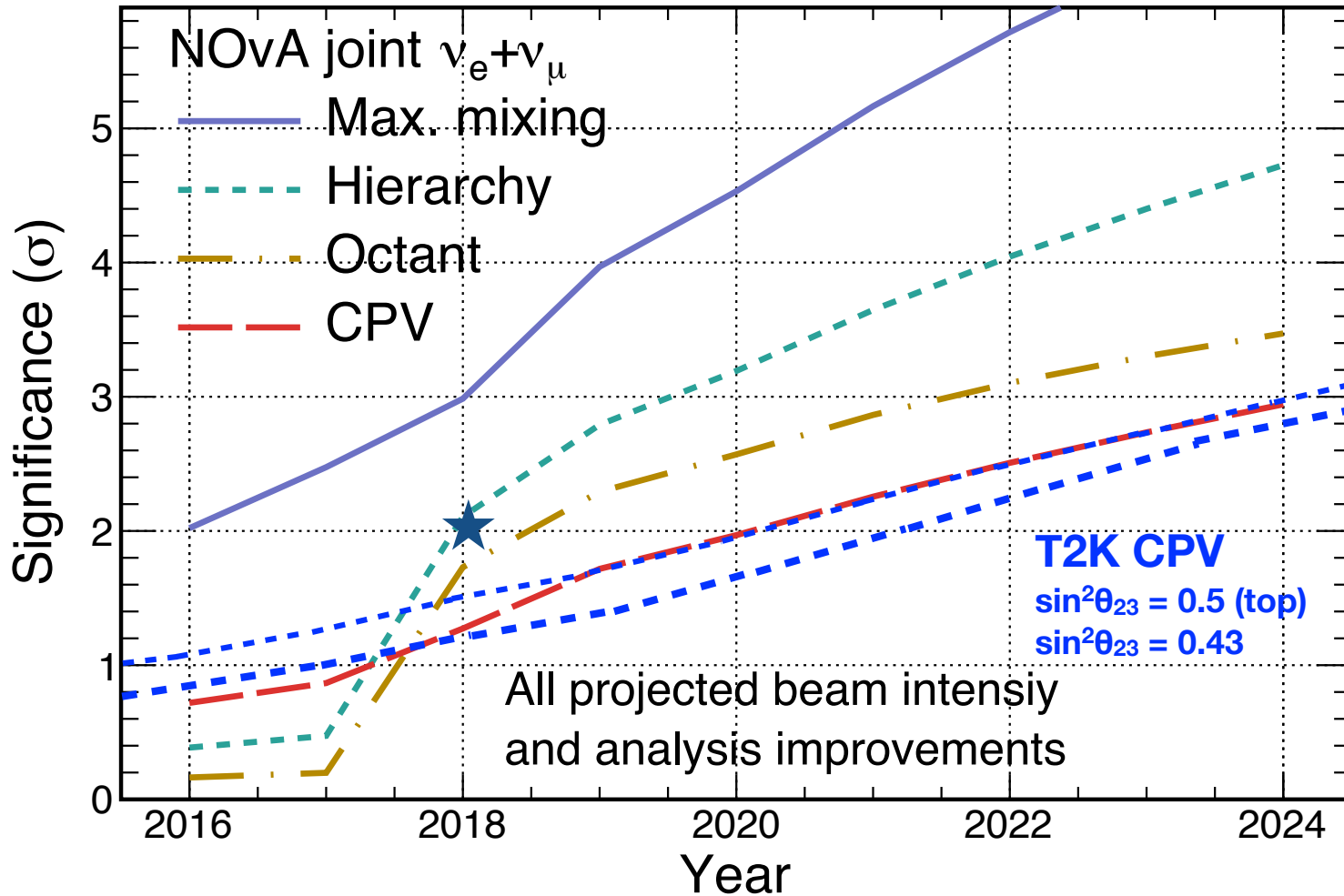NOvA joint $\nu_e+\nu_\mu$
— Max. mixing
--- Hierarchy
-·- Octant
— CPV

All projected beam intensiy and analysis improvements
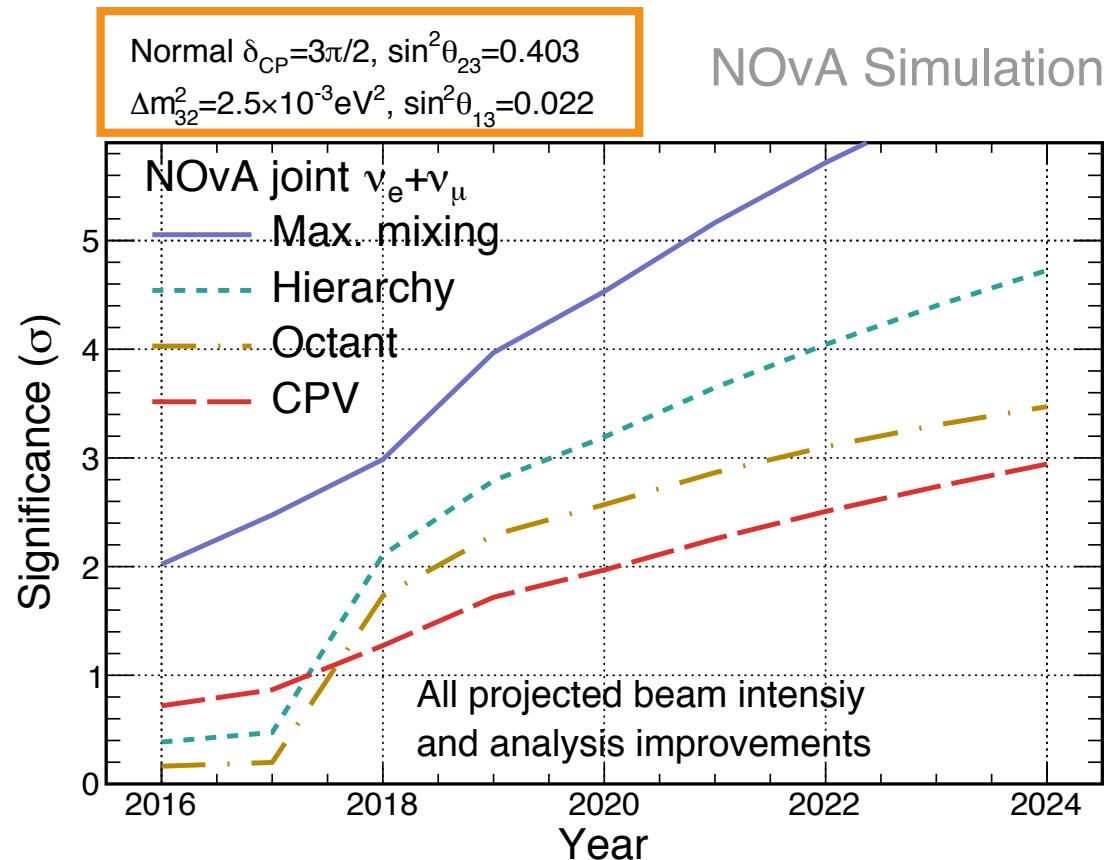
NOvA and the Competition

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

Lower Octant

NOvA in close race
with T2K on
CP Violation

NOvA joint $\nu_e+\nu_\mu$

— Max. mixing
---- Hierarchy
—·— Octant
— — CPV

T2K CPV
$\sin^2\theta_{23}$ = 0.5 (top)
$\sin^2\theta_{23}$ = 0.43

All projected beam intensiy
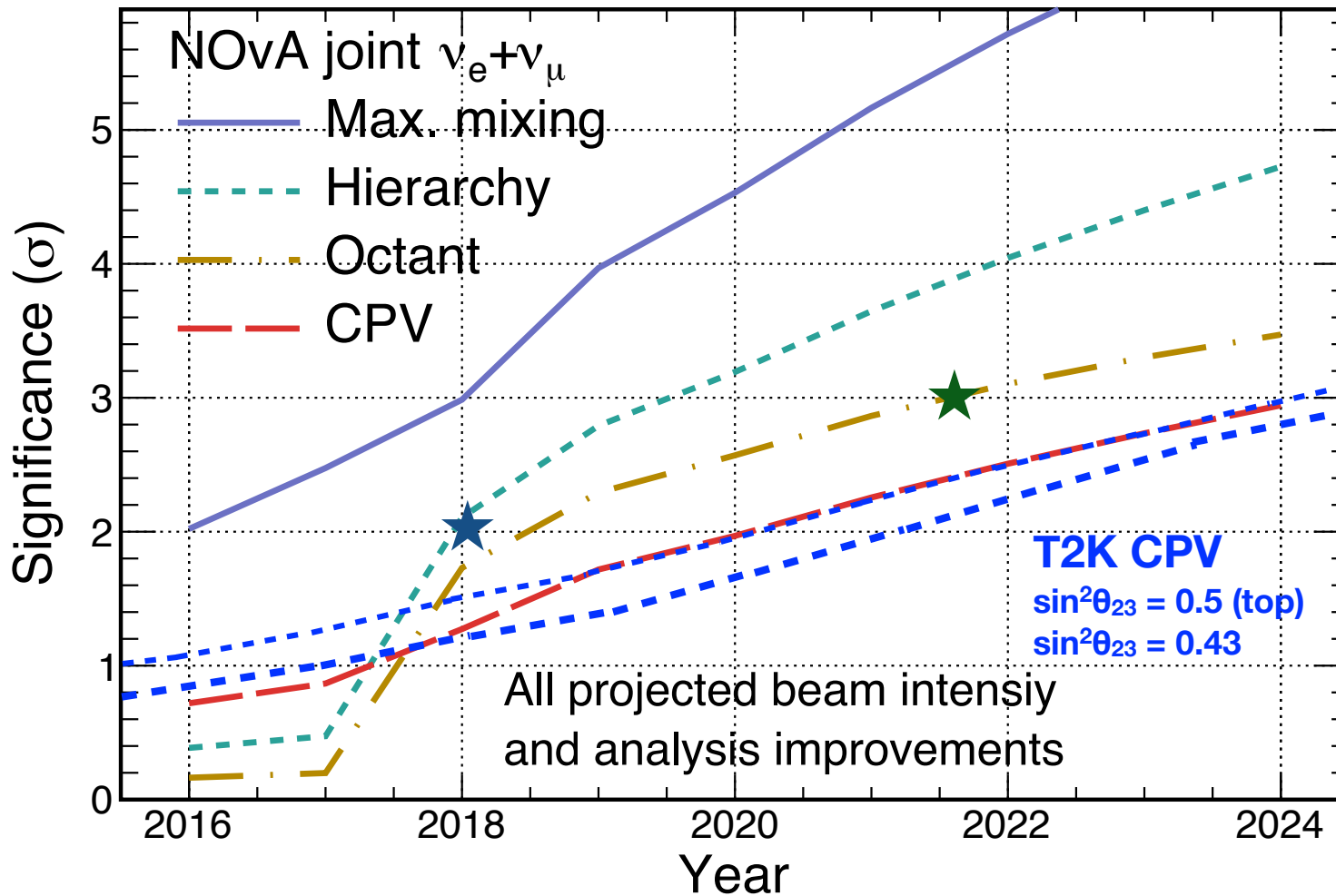and analysis improvements

Significance (σ)

Year

NOvA and the Competition

Normal $\delta_{CP}=3\pi/2$, $\sin^2\theta_{23}=0.403$

$\Delta m^2_{32}=2.5\times10^{-3}eV^2$, $\sin^2\theta_{13}=0.022$
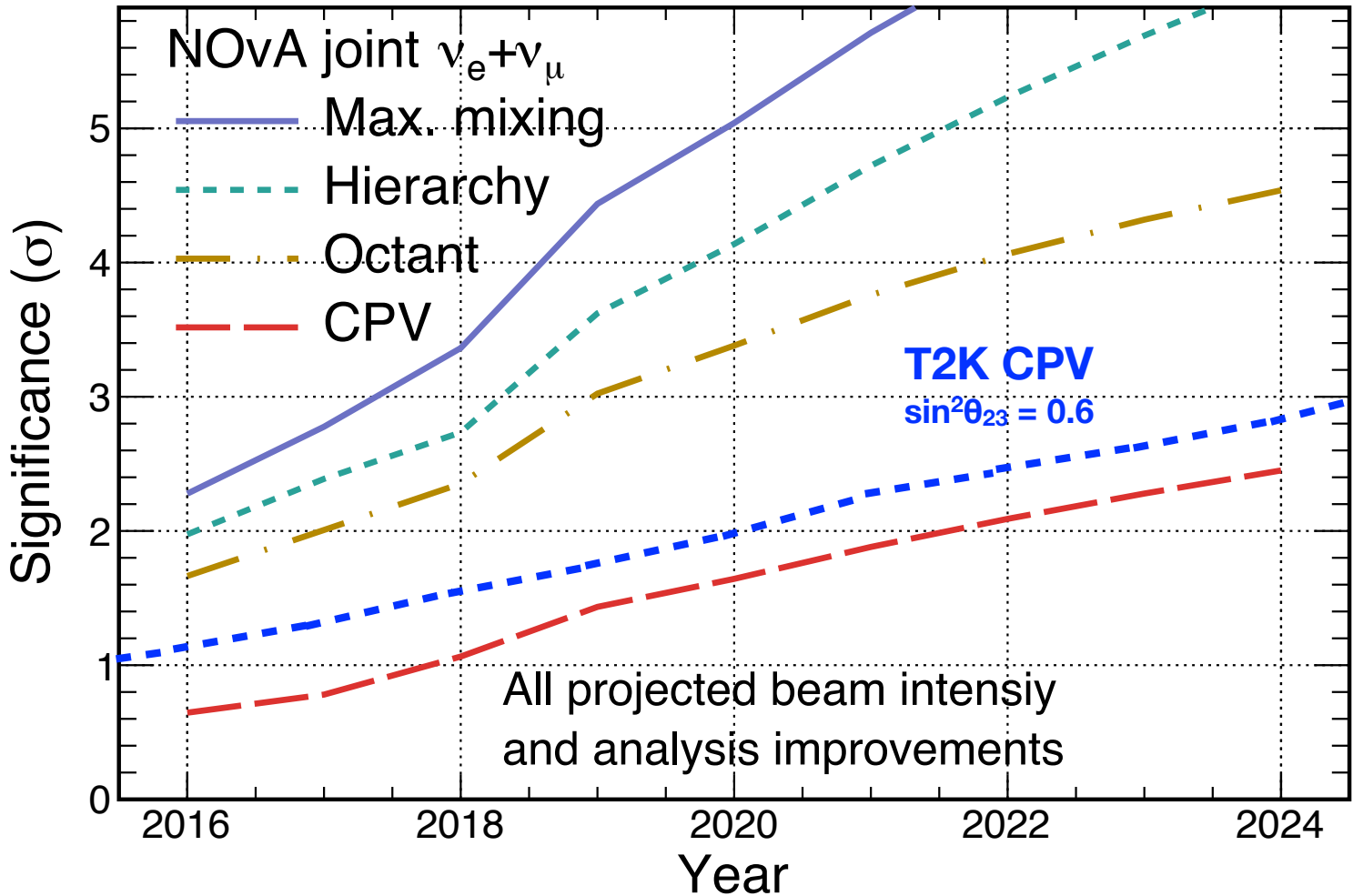
NOvA Simulation

NOvA joint $\nu_e+\nu_\mu$

— Max. mixing
---- Hierarchy
-·-·- Octant
— — CPV

All projected beam intensiy
and analysis improvements

T2K CPV
$\sin^2\theta_{23} = 0.5$ (top)
$\sin^2\theta_{23} = 0.43$

Significance (σ)

Year

Lower Octant

NOvA in close race
with T2K on
CP Violation

Earliest possible 2σ
T2K Mass Hierarchy

NOvA and the Competition

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

Lower Octant

NOvA in close race with T2K on CP Violation

Earliest possible 2σ T2K Mass Hierarchy

Earliest JUNO 3σ Mass Hierarchy

T2K CPV
$\sin^2\theta_{23} = 0.5$ (top)
$\sin^2\theta_{23} = 0.43$

All projected beam intensiy and analysis improvements

NOvA and the Competition

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

Upper Octant

T2K stays ahead

T2K CPV
$\sin^2\theta_{23}=0.6$

NOvA joint $\nu_e+\nu_\mu$
- Max. mixing
- Hierarchy
- Octant
- CPV

All projected beam intensiy
and analysis improvements

Significance (σ)

Year

Combined NOvA-T2K Analysis

- NOvA and T2K have met 3 times in past 18 months

- First informal meeting in March 2016 at Fermilab
  - Leadership of Collaboration and Analysis
  - Agreed that combined oscillation fits would be appropriate when both experiments had mature analyses using neutrinos and antineutrinos, and particularly interesting milestones could be within reach: estimated 2021.
  - Agreed that in the near term, exchanges on neutrino interaction modeling would be helpful to both experiments, as well as lay groundwork for eventual joint fits.

- October 2017 NOvA-T2K Workshop at J-PARC
  - Attended by ~20 T2K, 13 from NOvA (enabled by US-Japan grant).
  - Resulted in much improved mutual understanding of each others' handling of neutrino cross-section uncertainties in oscillation analyses.
  - Defined first steps in non-trivial task of understanding correlations.
  - We plan to meet again in the US in ~October 2018.

The Value of Joint Fits

- Baseline and energy spectrum provide complementarity between NOvA and T2K

Factor	Type	Inverts for $\overline{\nu}$?	NOvA	T2K
Matter effect (mass ordering)	Binary	Yes	±19%	±10%
CP violation	Bounded, continuous	Yes	[−22…+22]%	[−29…+29]%
θ_{23} octant	Unbounded, continuous	No	[−22…+22]%	[−22…+22]%

Toy Example - NOvA 2016 Best Fit Points

- NOvA 2016 result has two best fit points
  - Normal Hierarchy, $\delta_{CP} \sim 3\pi/2$, Lower Octant (A)
  - Normal Hierarchy, $\delta_{CP} \sim \pi/2$, Upper Octant (B)

- Scale A and B to 2021 exposure
  - Neglects upcoming improvements

- Two Scenarios
  - If our result is point A, we would favor Normal Hierarchy at >3σ MH, and CP Violation at 2σ

  - For point B, NOvA by itself would be compatible with either Mass Hierarchy, and a wide range in δ_{CP}
    - But the MH and δ_{CP} are correlated: e.g., Inverted Hierarchy implies δ_{CP} near $3\pi/2$

Based on NOvA Simulation

NOvA FD — $\sin^2 2\theta_{13}=0.085$
18×10^{20} POT neutrino — $\sin^2\theta_{23}=0.404, 0.623$
18×10^{20} POT anti-neutrino

2021 est. Statistical Errors only

IH $\Delta m^2_{32}=-2.71\times10^{-3}eV^2$

NH $\Delta m^2_{32}=+2.67\times10^{-3}eV^2$

$\delta_{CP}= 0$ $\delta_{CP}= \pi/2$
$\delta_{CP}= \pi$ $\delta_{CP}= 3\pi/2$

2016 best fit prediction

Total events - antineutrino mode (vertical axis)
Total events - neutrino mode (horizontal axis)
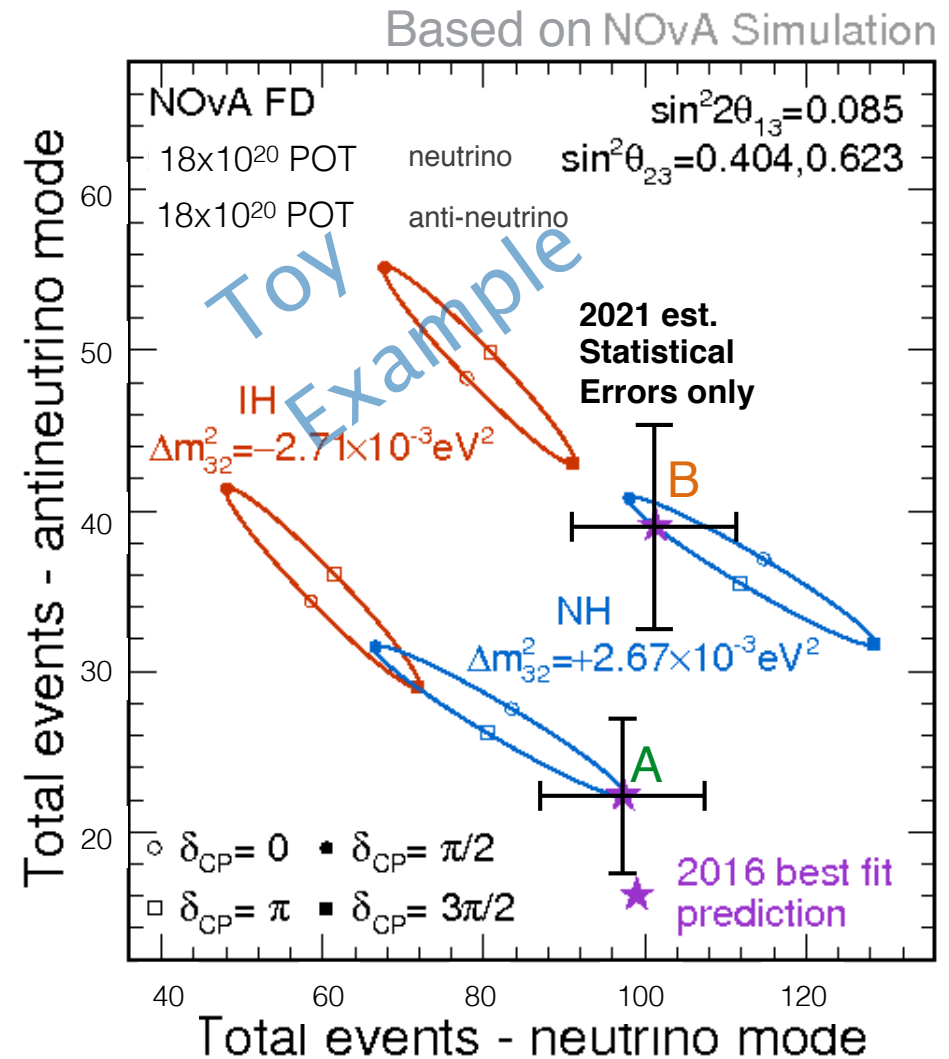
Toy Example - Adding T2K in 2021

- For point A, T2K's story would be similar to NOvA's
  - Strong preference for $\delta_{CP} \sim 3\pi/2$, preference for Normal Hierarchy

- For point B, T2K alone is also similar to NOvA
  - Compatible with either Mass Hierarchy and a wide range of δ_{CP}

- However, for point B
  - Inverted Hierarchy, T2K would favor CP-Conserving values of δ_{CP}, and disfavor δ_{CP} near $3\pi/2$
  - In tension with NOvA's preference for large CP violation for Inverted Hierarchy

Tension would provide sensitivity to Mass Hierarchy and CP Violation

Caveat!
My rough estimates, and scaling to 2021 based on 2017 T2K result
Original version courtesy T. Nakaya

T2K Run1-8 Preliminary

Final systematics pending

Legend:
- — $\sin^2 \theta_{23} = 0.50$
- — $\sin^2 \theta_{23} = 0.45$
- — $\sin^2 \theta_{23} = 0.55$
- — $\Delta m_{32}^2 = 2.46 \times 10^{-3}\ eV^2/c^4$
- -- $\Delta m_{31}^2 = -2.44 \times 10^{-3}\ eV^2/c^4$
- ○ $\delta_{CP} = \pi$
- ■ $\delta_{CP} = +\pi/2$
- □ $\delta_{CP} = 0$
- ● $\delta_{CP} = -\pi/2$
- ⌀ Data (stat. errors only)

2021-Scaled NOvA 2016 best fit for B (rough estimate)

2021-Scaled NOvA 2016 best fit for A (rough estimate)

T2K 2017 best fit with 2017 errors

Y-axis: Antineutrino mode 1Re candidates

Summary

- NOvA is working toward updated analyses with 9×10^{20} protons-on-target in neutrino mode
  - 46% more data, 17% increase in effective exposure with selection improvements
- Extended NOvA reach: Analysis improvements, more neutrinos per proton, and PIP-1+
- With these improvements
  - NOvA has comparable sensitivity to CP Violation as T2K to 2024
  - NOvA pulls well ahead of JUNO in 3σ Mass Hierarchy sensitivity

- NOvA and T2K have started collaborating toward an eventual joint fit
  - Joint fits will enhance the sensitivity of the easy scenarios, and greatly improve the more difficult ones.

Illustrating the value of joint fits

- From T2K-II proposal - impact of external determination of Mass Hierarchy on T2K CP Violation reach
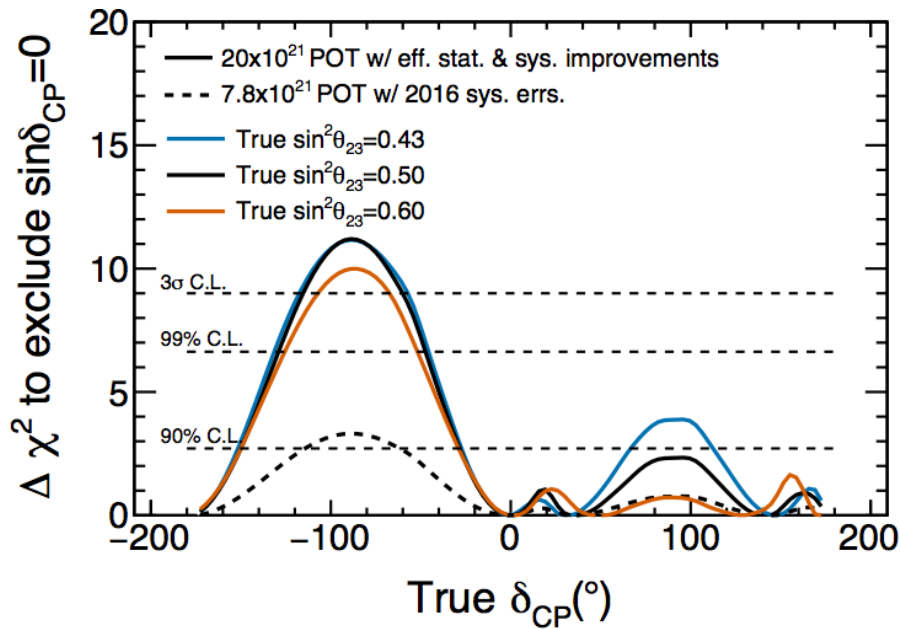
Assuming MH is Unknown
(True Normal MH)
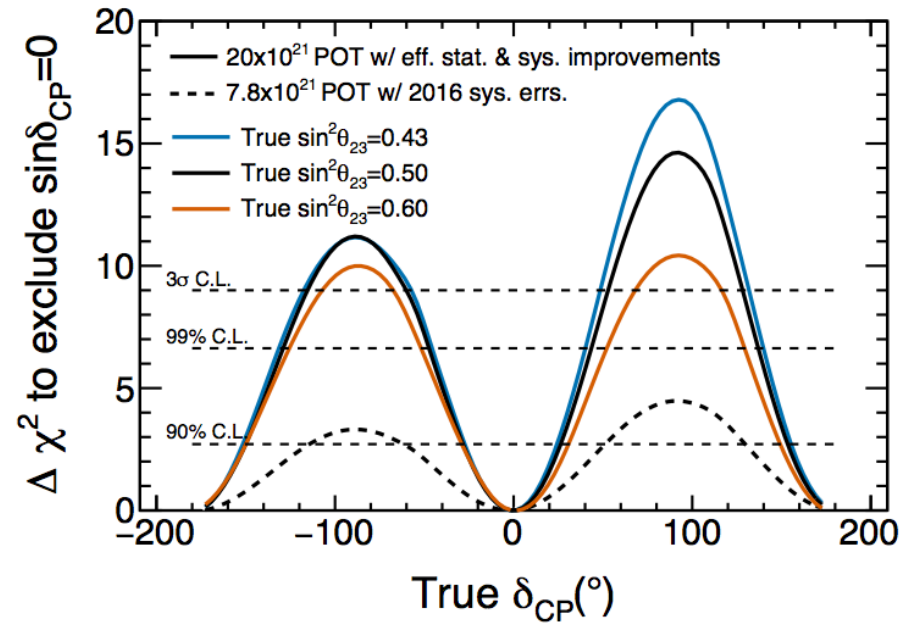
Assuming MH Determined
by other experiments
(True Normal MH)

NOvA Exposure & Physics Milestones

Assuming: Normal Hierarchy
$\sin^2(\theta_{23})=0.403$
$\delta_{CP}=3\pi/2$
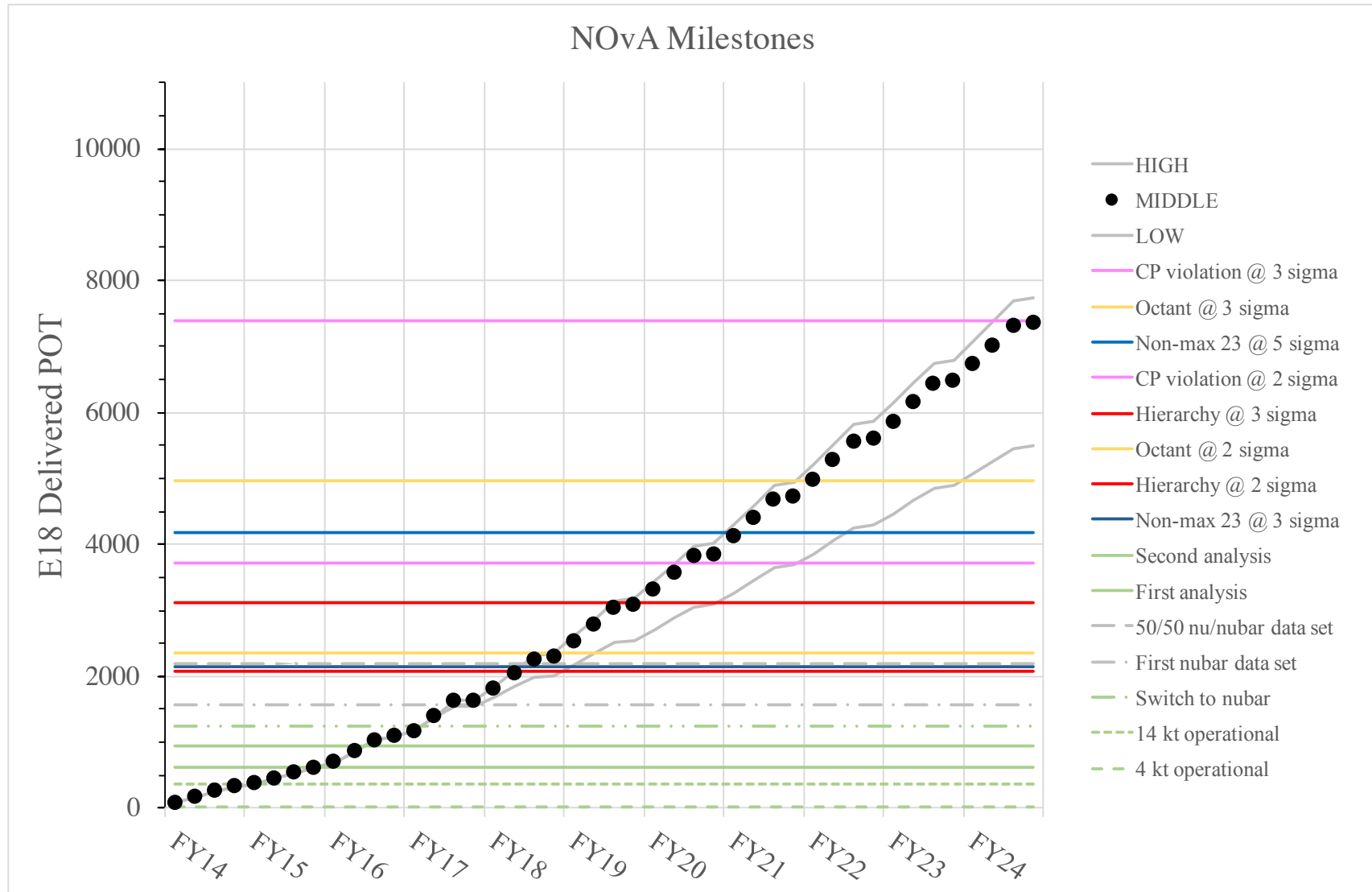
NuMI Beam

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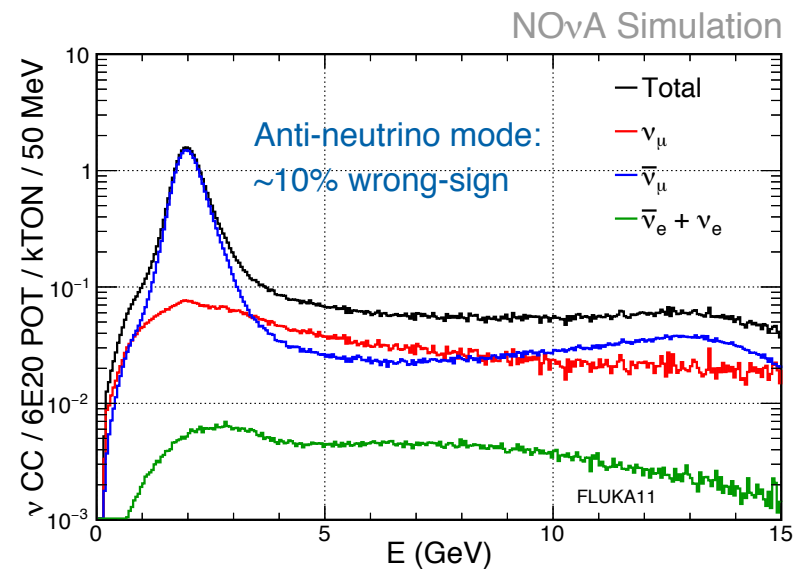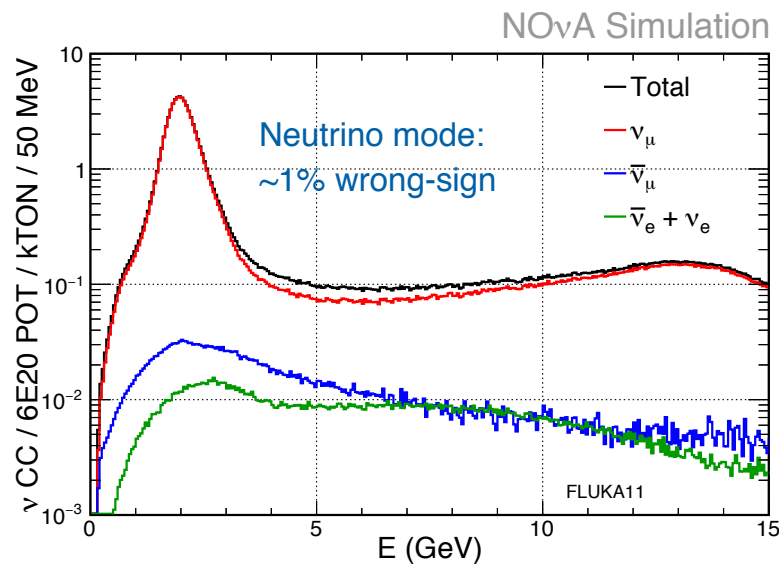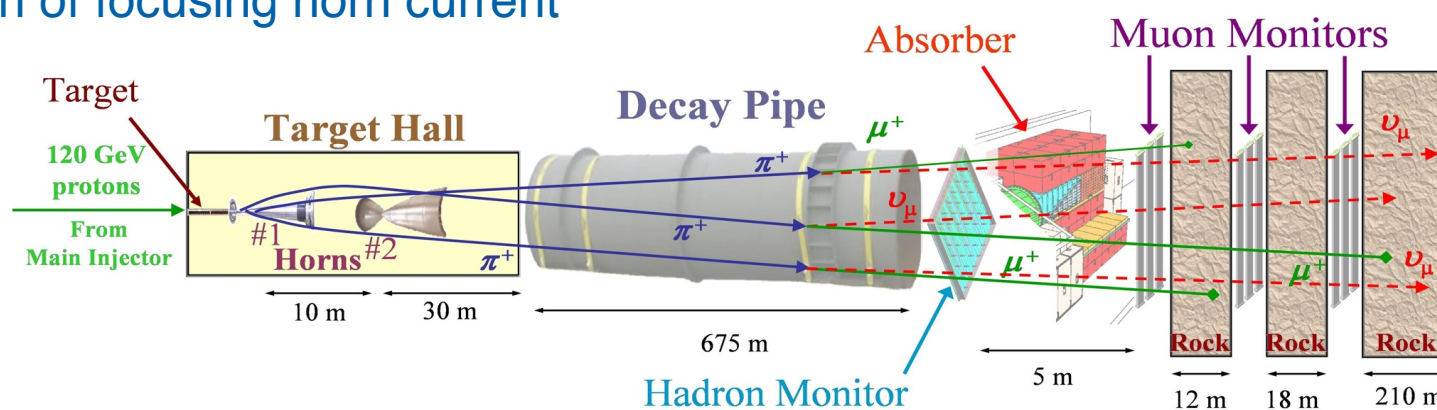
NOvA Detector Technology

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

32 cells read out into 1 Avalanche PhotoDiode
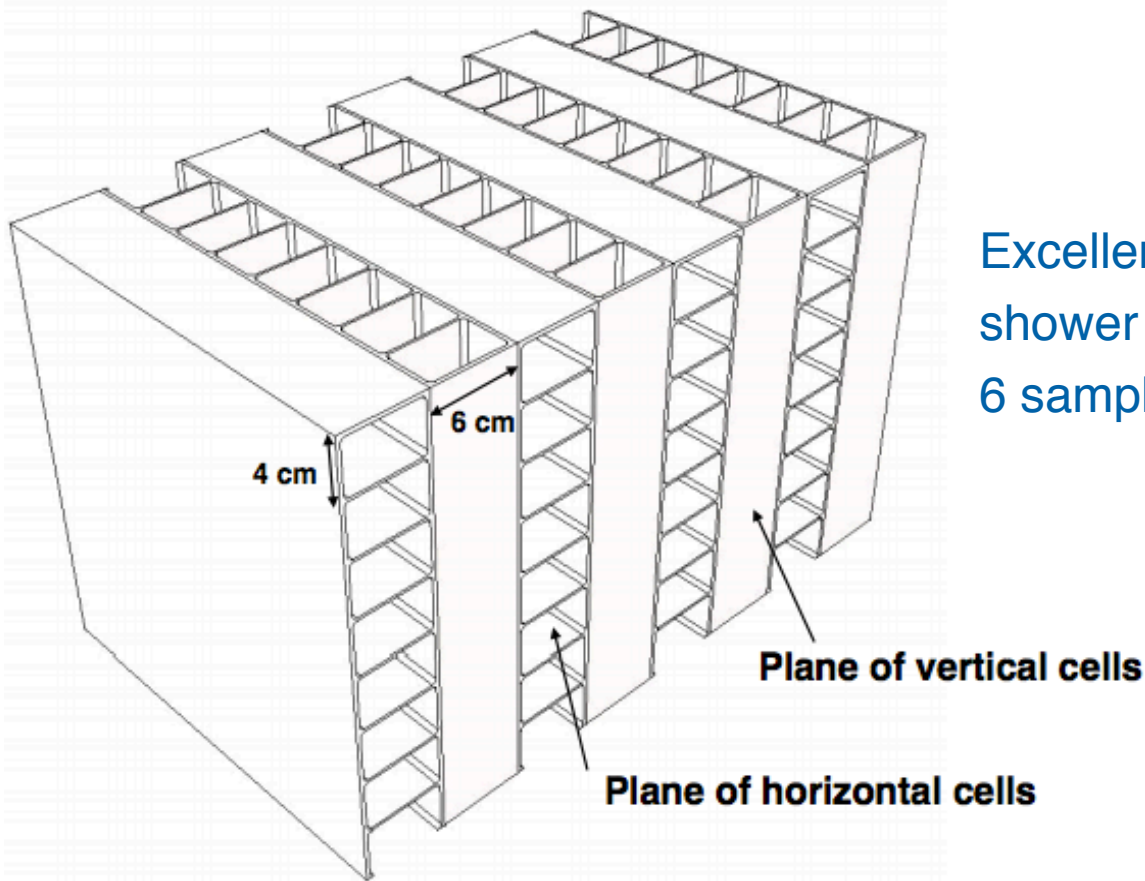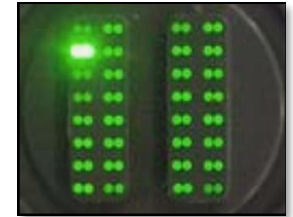
Excellent electromagnetic shower characterization with 6 samples per radiation length

6 cm

4 cm

Plane of vertical cells

Plane of horizontal cells

To APD Readout

Scintillation Light

Particle Trajectory

15.5m

Single Cell

Waveshifting Fiber Loop

3.9cm   6.6cm

NOvA Detectors

60 m

15 m

15 m
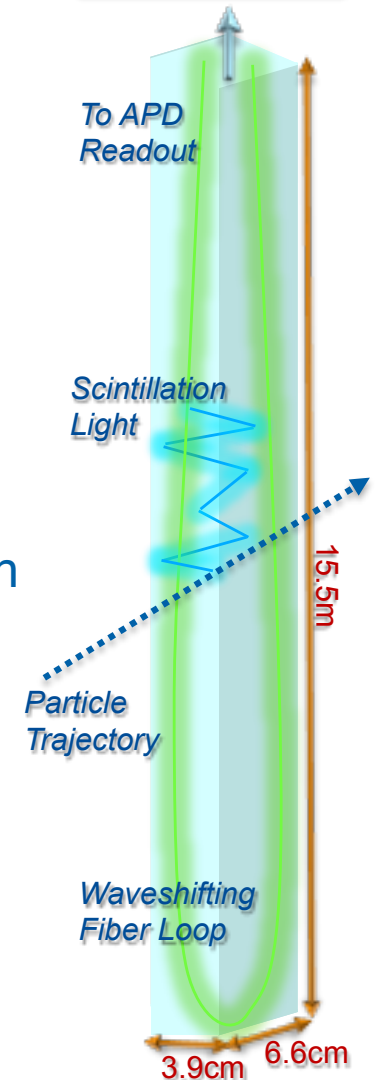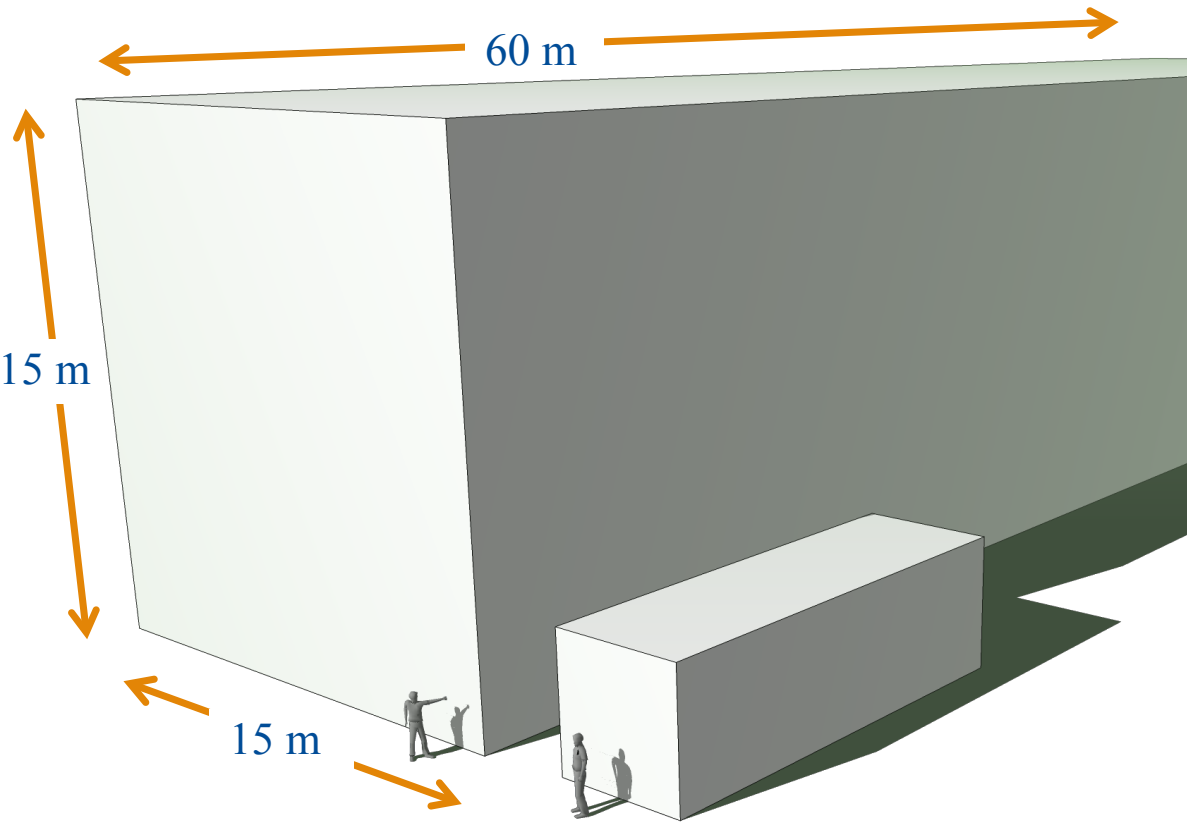
- Far Detector
  - 14 kT
  - 895 planes
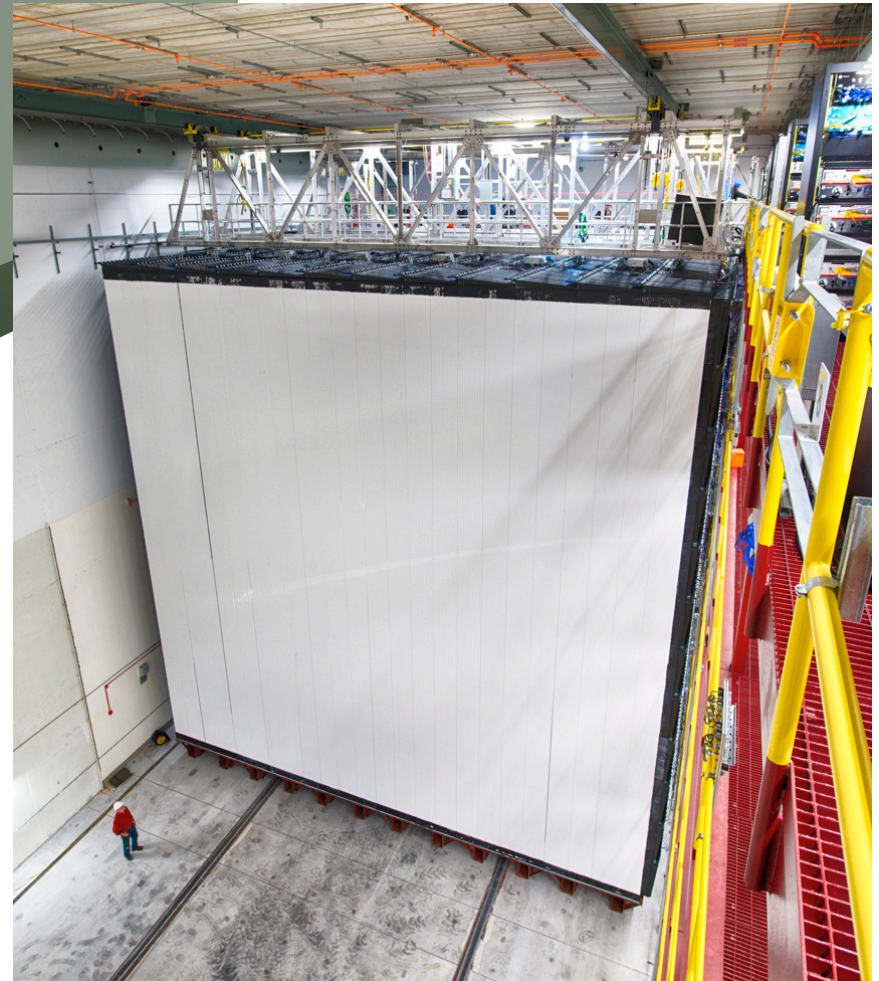
- Near Detector
  - 293 tons, including muon catcher
 - used to measure neutrino beam flavor and energy spectrum before oscillations

NuMI Performance

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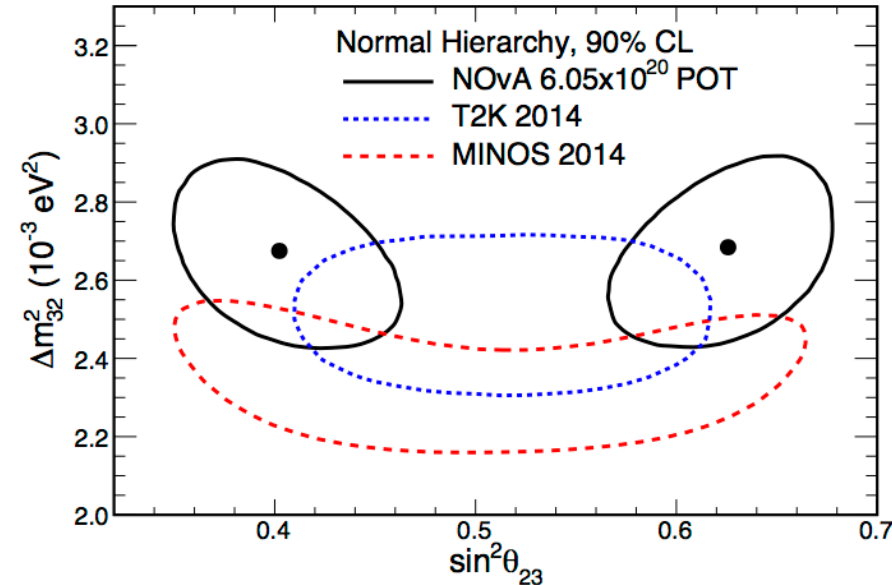 - Routine 700 kW (NuMI-only-equivalent) running achieved in January

Far Detector: 98.5% beam-weighted uptime since 12/1/2016

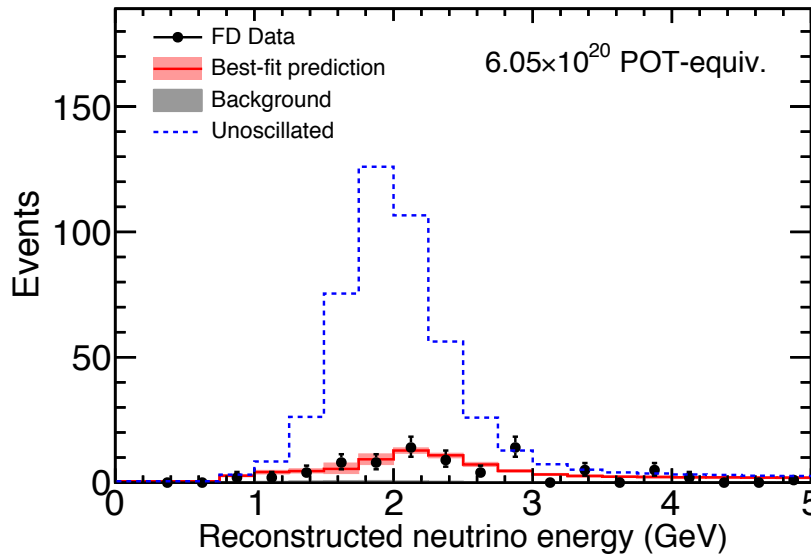□ Daily
— Delivered
— Recorded
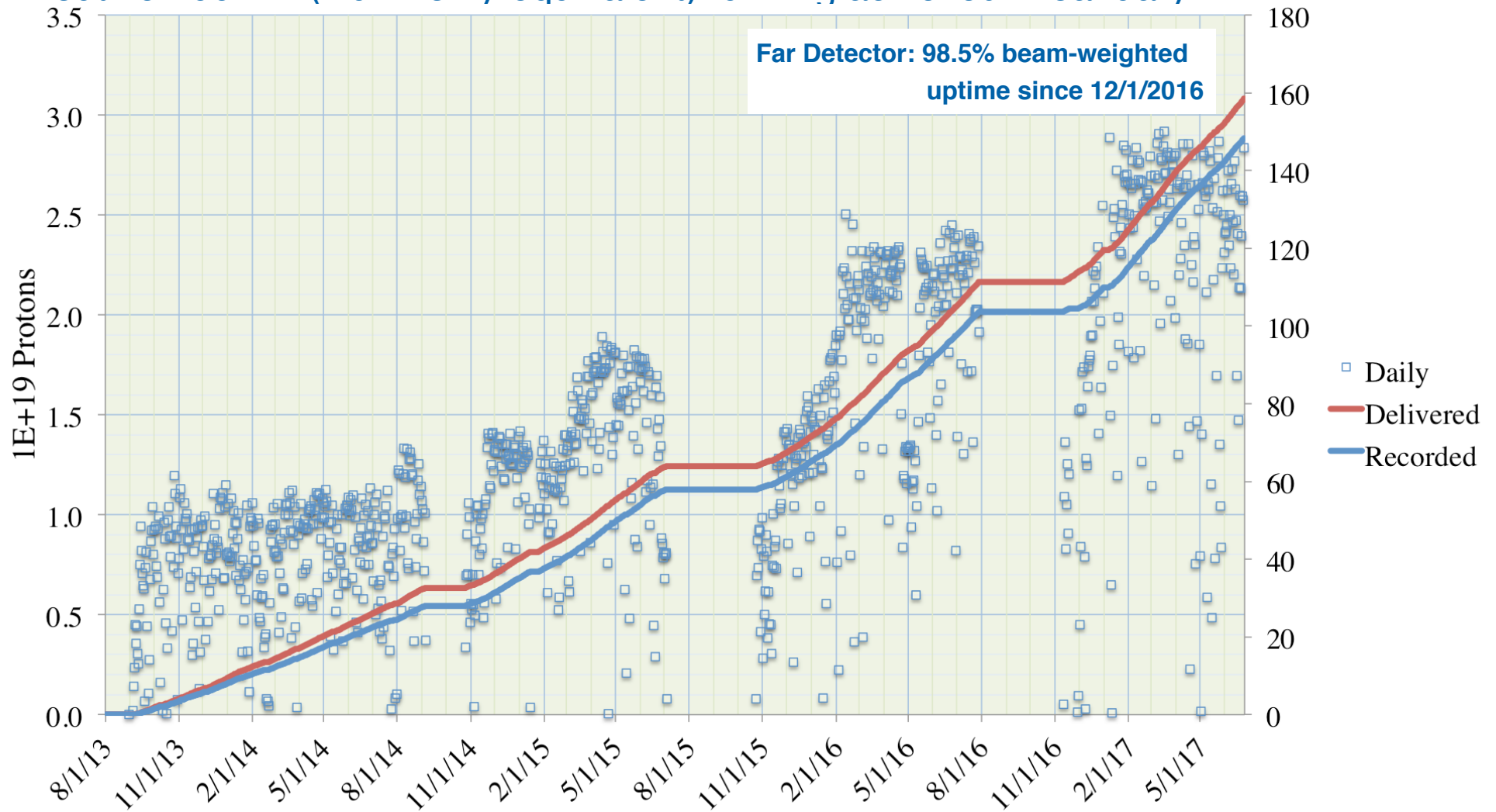
NOvA Data-taking

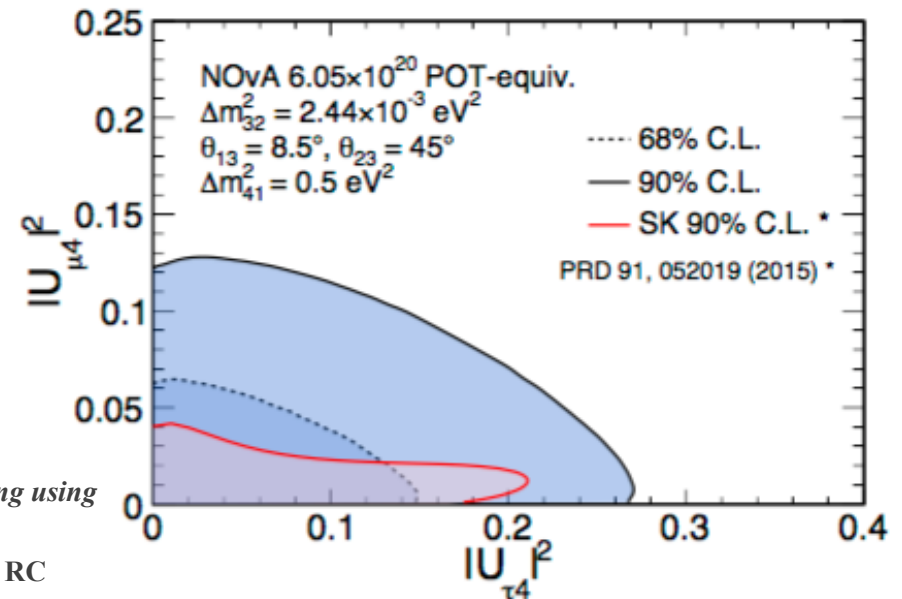- NOvA Run History - Recoredd POT for Far Detector
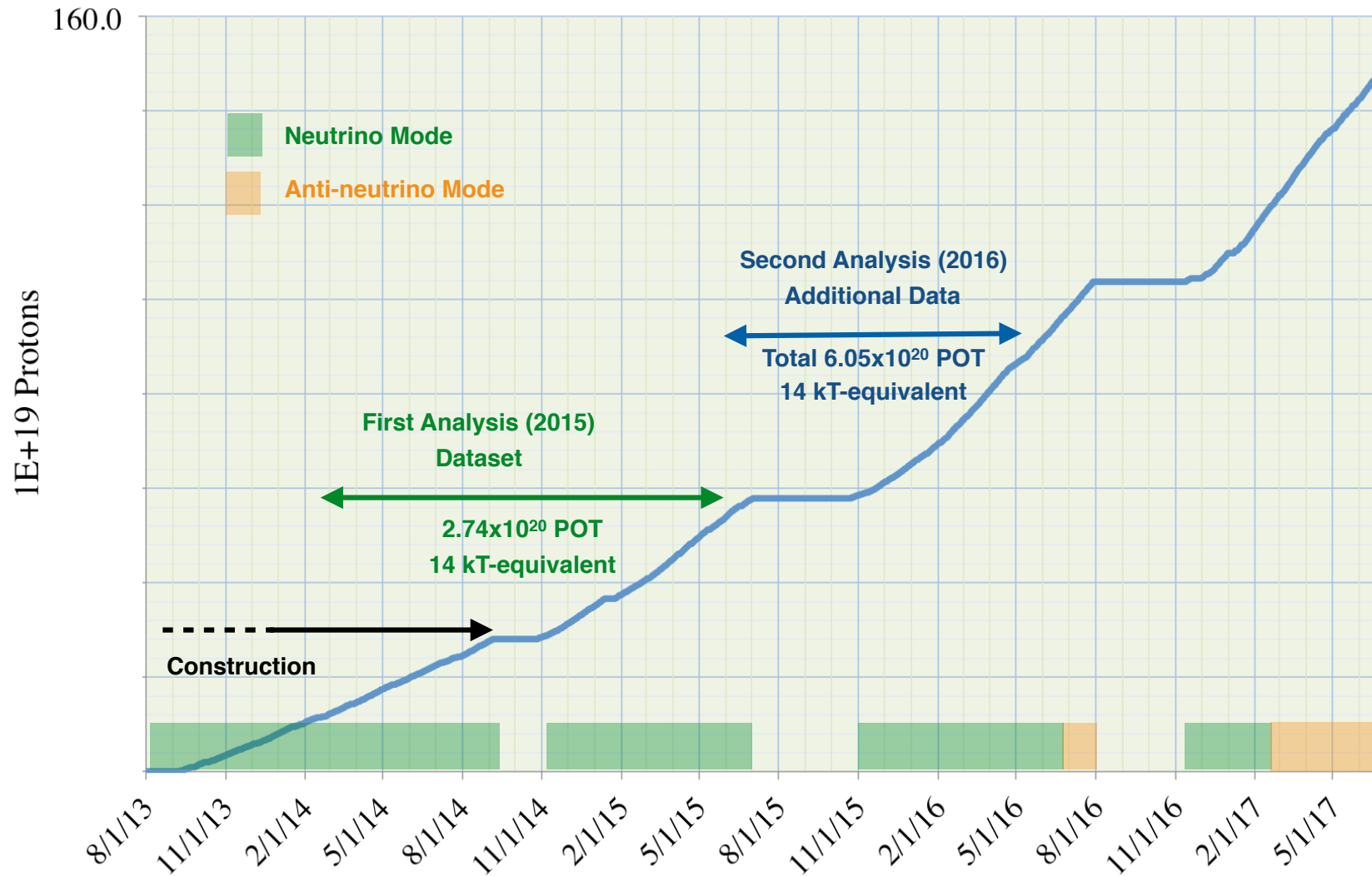
Recent NOvA Publications

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

- Finalized Neutrino 2016 Results

- ν_μ disappearance
  - Maximal mixing disfavored at 2.6 σ

- Flavor-independent disappearance
  - NOvA's first limits on sterile neutrinos via neutral current disappearance
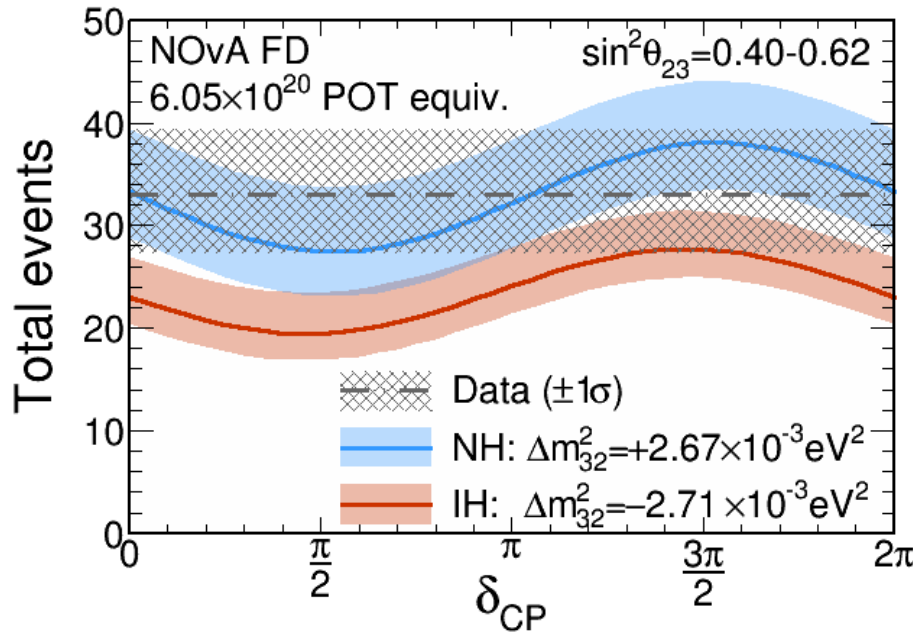
Search for active-sterile neutrino mixing using neutral-current interactions in NOvA
arXiv:1706.04592, Submitted to PRD RC

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
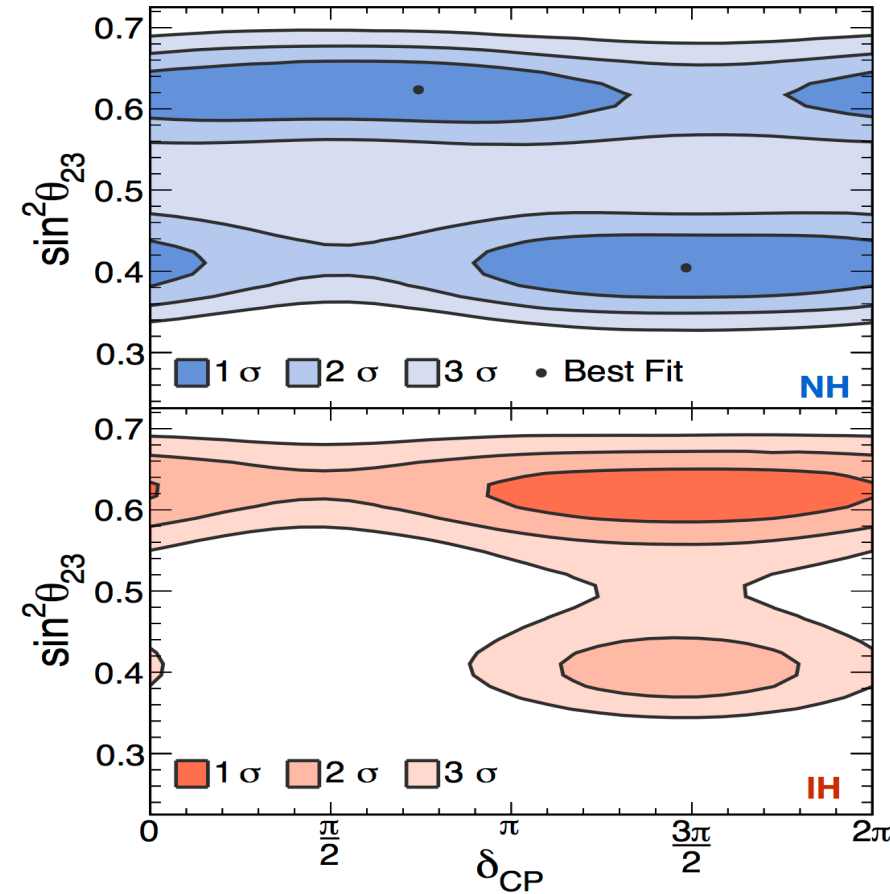**PRL 118, 231801 (2017)**   *10 citations*

  - 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