SAC Neutrino Working group summary

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The questions of the current neutrino program

LBL Program:

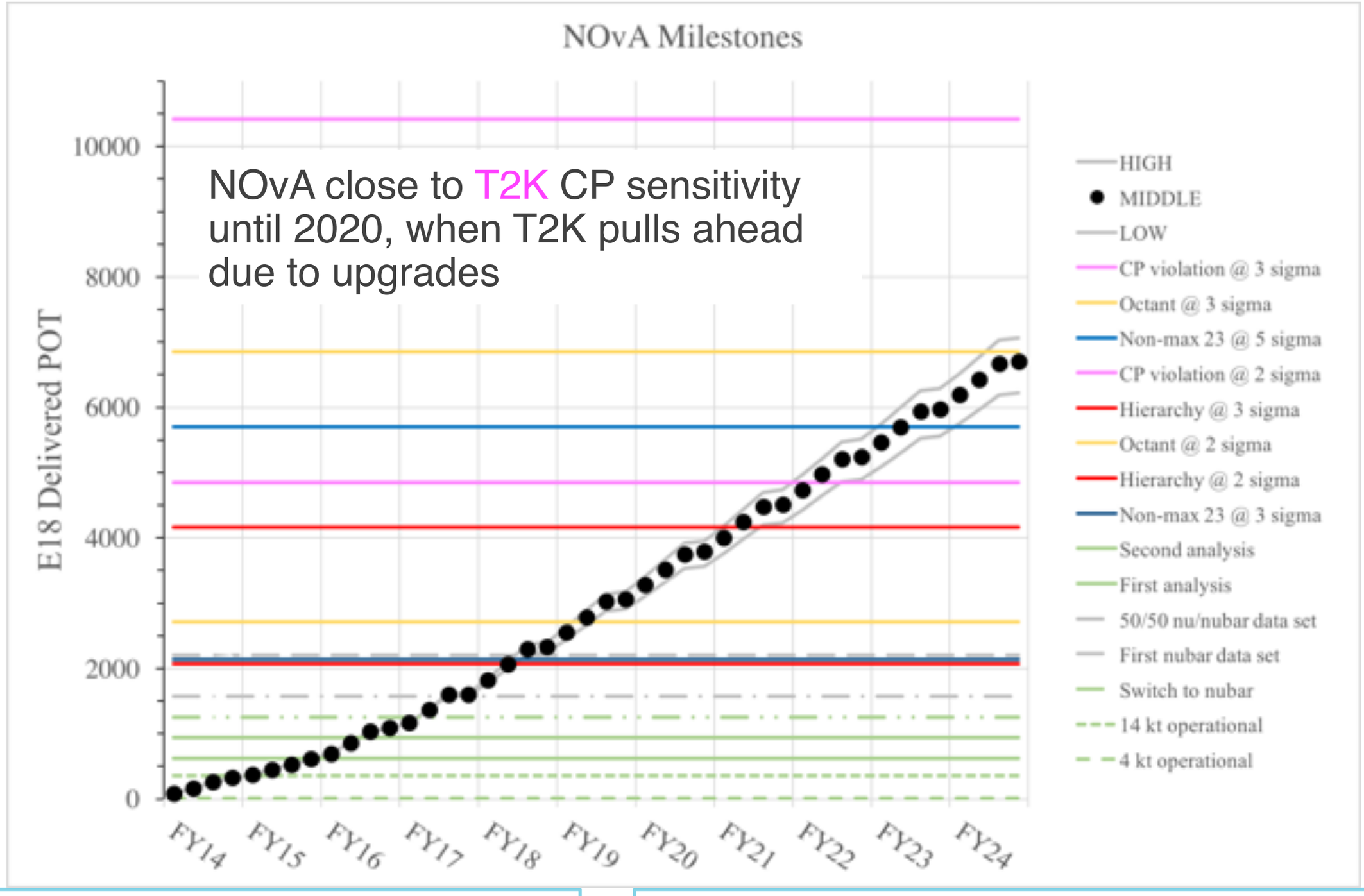
- The octant - is theta_23 maximal if not is it greater or smaller
- IS there CP violation in the neutrino sector, is so what is the phase ?
- Mass hierarchy, is vu_1 or vu_3 the lightest ?
- Testing the 3-neutrino paradigm

Current SBL Program:

- Is there a light sterile neutrino? Measure nu_e appearance and nu_mu disappearance
- What is the nature of the low energy excess seen by MiniBooNE?
- Cross section measurements, specifically LAr
- R+D and measurements needed for for DUNE

- Caveat: What is possible depends on what the true parameters are.

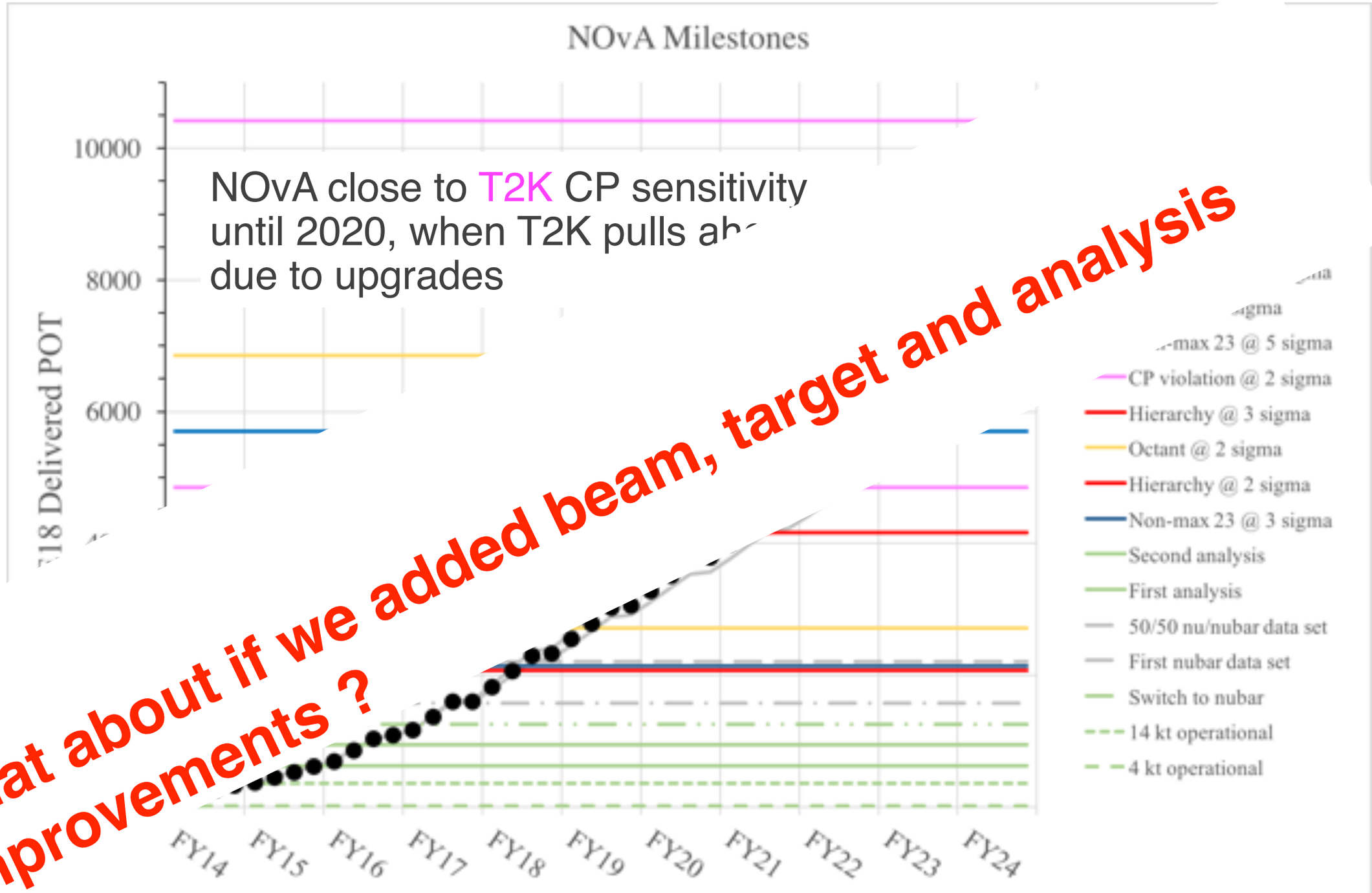
What we could learn from NOvA with current performance



2021: 3σ on the mass hierarchy
~1 year ahead of the competition (ORCA, JUNO).
T2K is projecting 2σ on CP violation.

2025: 3σ on the octant
At that point T2K might have 3σ on CP violation thanks to beam, analysis improvements.

Fermilab



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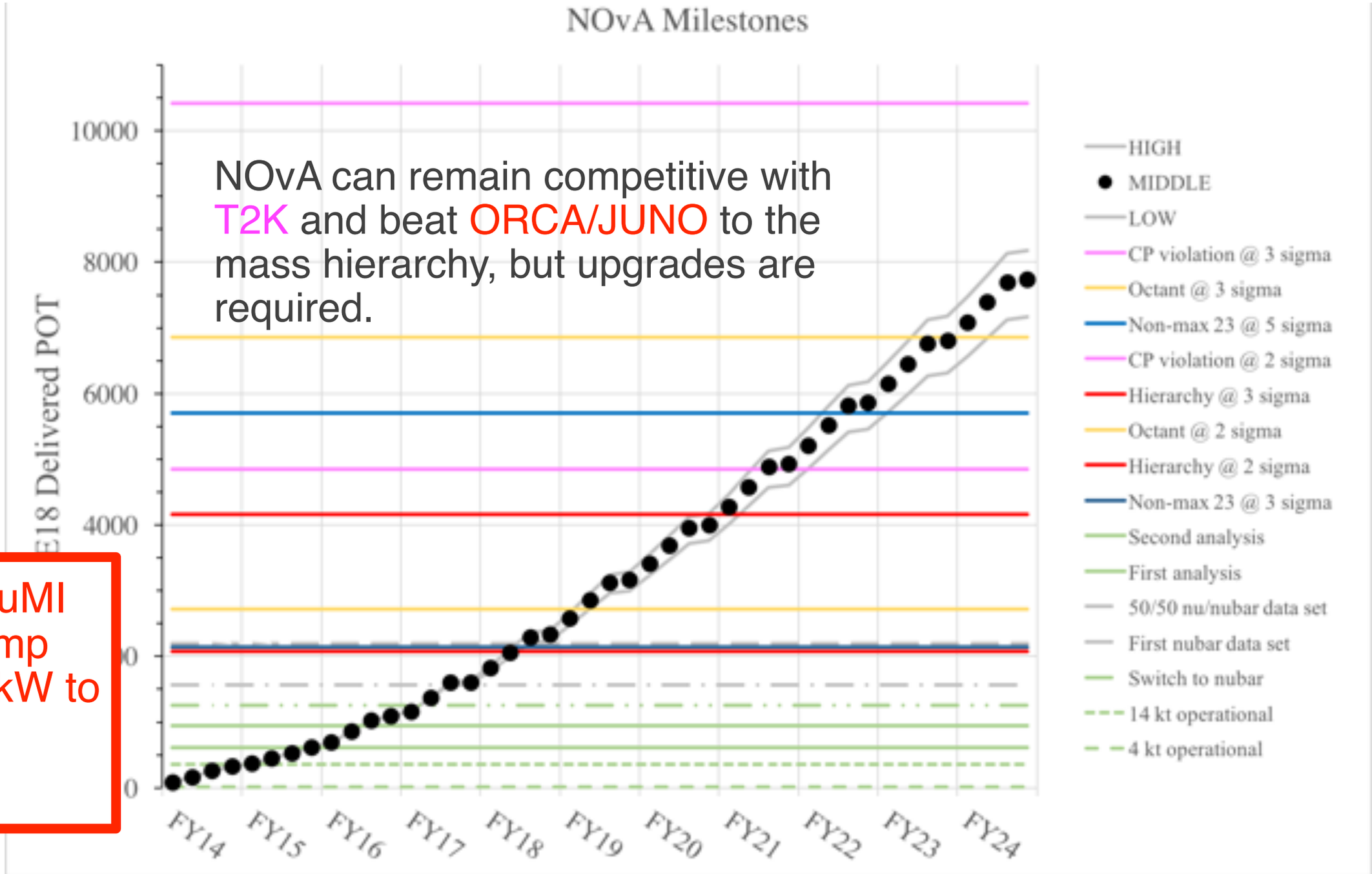
What we could learn from NOvA: Extended Reach



PIP1+, NuMI power ramp from 700kW to 900kW

2020: 3σ on the mass hierarchy
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2024: 3σ on the octant
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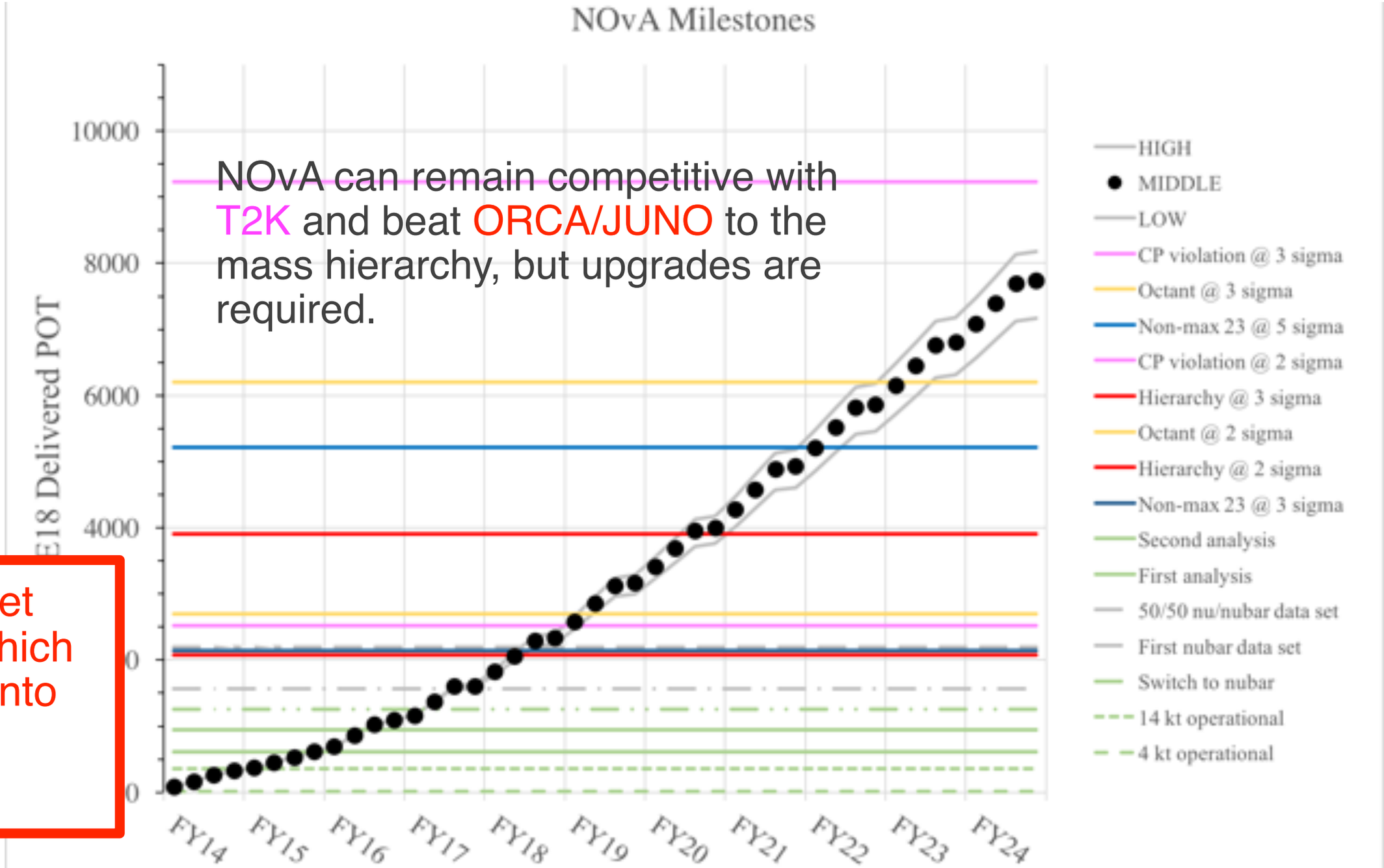

New target design which extends into horn 1.

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Fermilab

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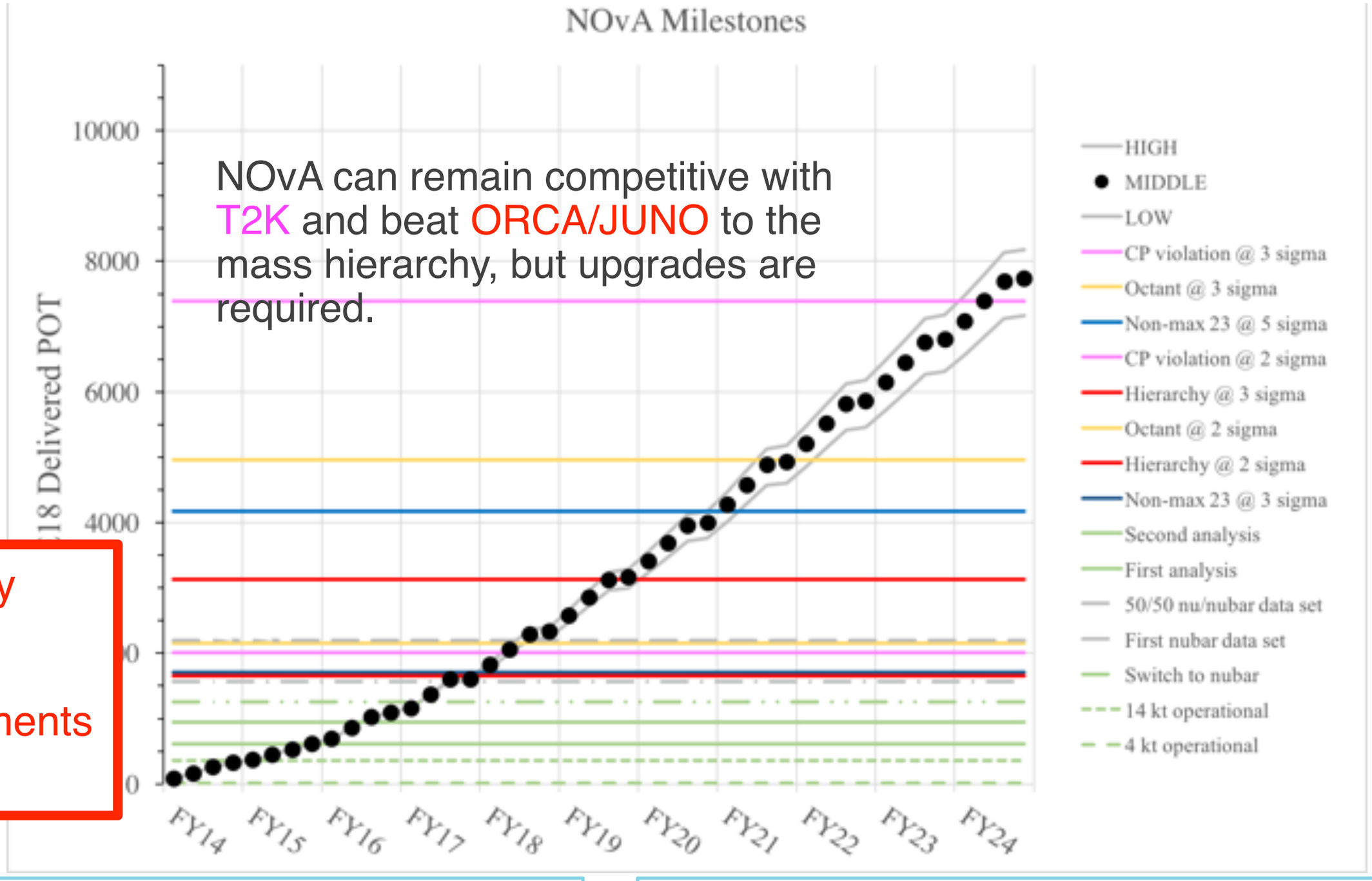

Plus likely (20%) analysis improvements

2019: 3σ on the mass hierarchy
~1 year ahead of the competition (ORCA, JUNO).
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2021: 3σ on the octant
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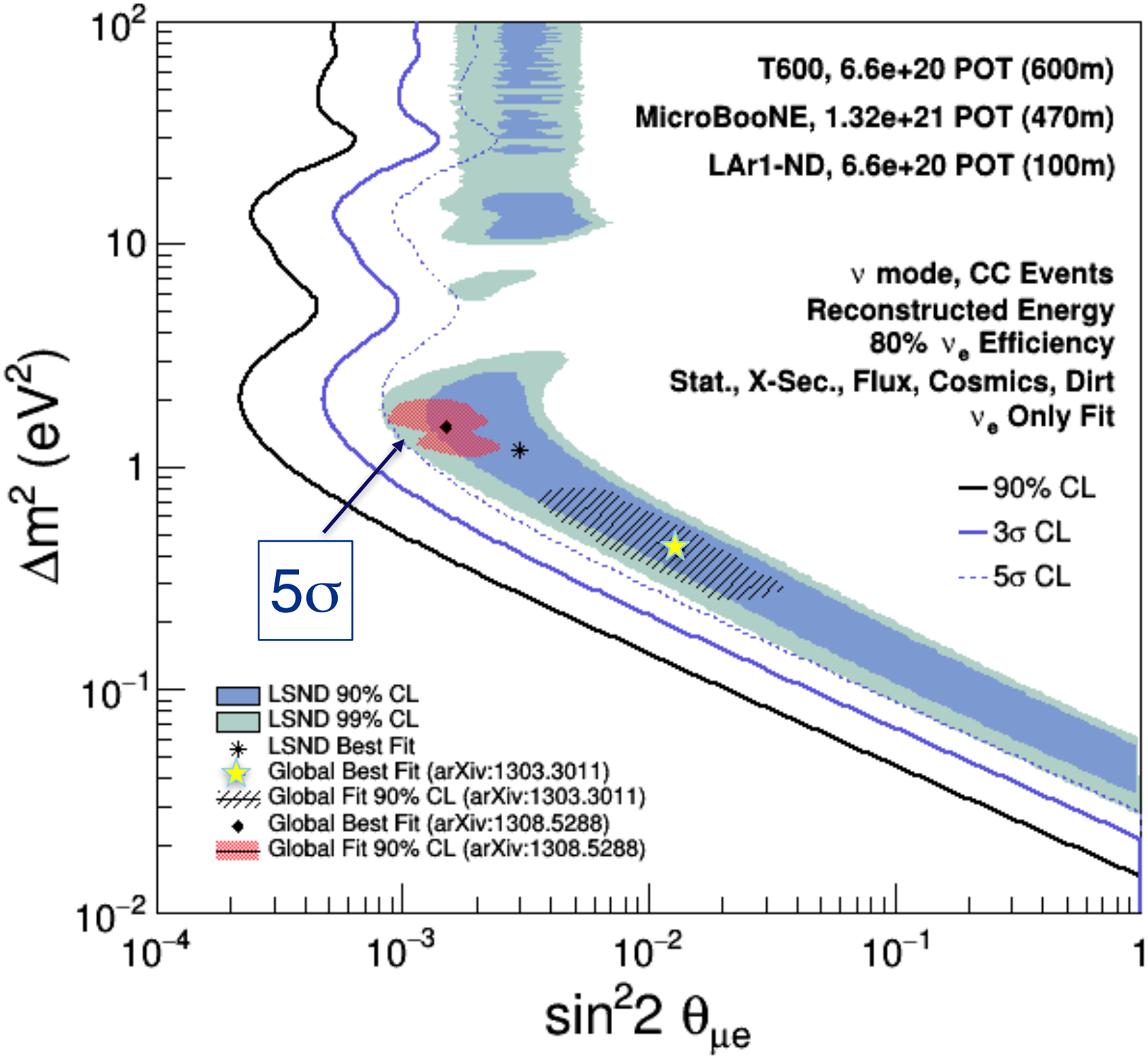
What we will learn from SBN

SBN $\nu_\mu \rightarrow \nu_e$ Oscillation Sensitivity

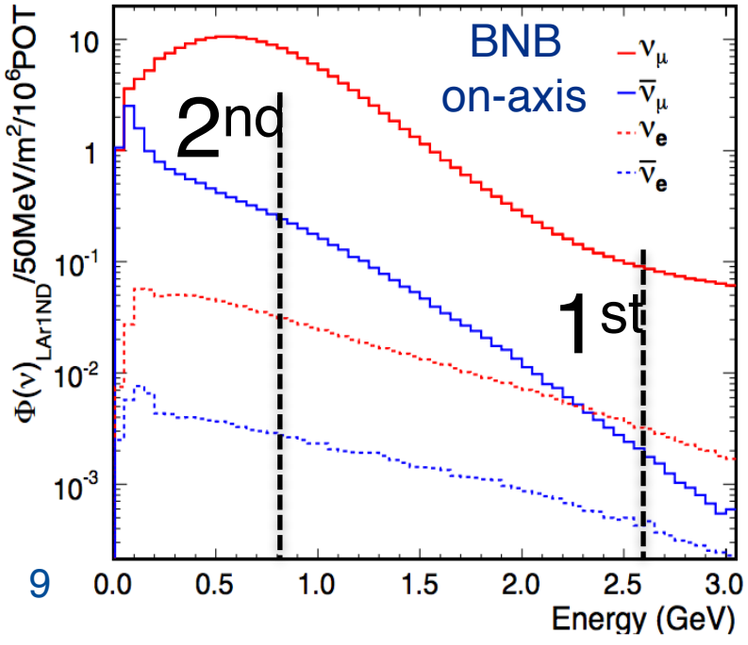


~2021: 5σ coverage of LSND allowed region

What if SBN sees a signal?

- Keep SBN running to measure nu_s measurements?
- Build new detector in DUNE or Booster neutrinos lines to measure nu_s?
- DUNE sensitivities will be significantly changed if there are additional neutrinos

What we will learn from SBL: Neutrino Cross sections & LAr TPC R&D



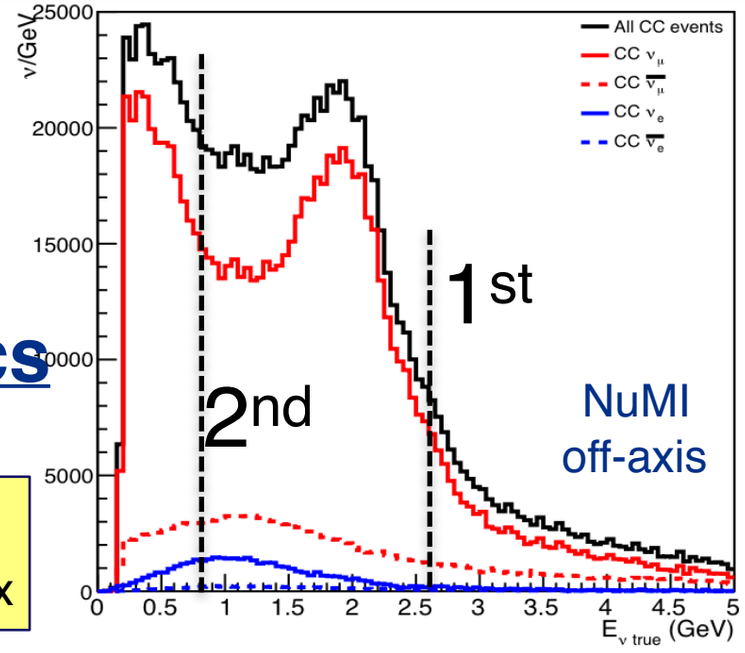
SBND: **1.5M** ν_μ CC/year, **12k** ν_e CC/year

+ low rate channels - e.g. coherent (10^4), strange prod (10^3), neutrino-electron (10^2)

Neutrino Interaction Physics

ICARUS: **10^5** NuMI off-axis events/year

many at the DUNE 1st osc. max



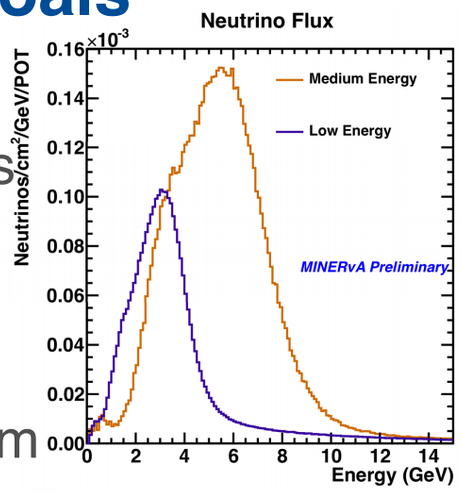
Minerva – Physics Goals

Completing last Low-Energy Cross Section Measurements

- Quasi-Elastic studies: double-diff, improved reco
- ratios: Pb/CH, Fe/CH

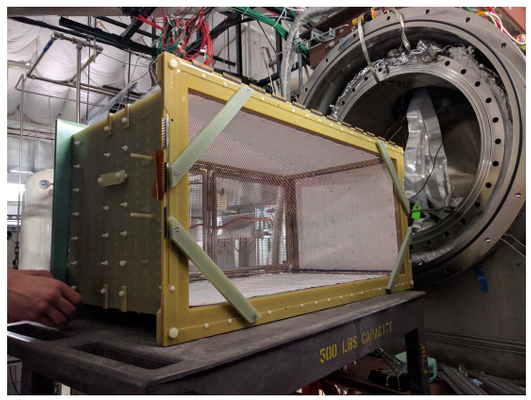
Current Medium-Energy Beam

- Accumulated 3x exposure of LE neutrino mode dataset
- Expect similar anti-neutrino exposure through FY18
- Will be able to probe nuclear effect for several channels - Deep Inelastic Scattering



LArIAT – "the little cryostat that could"

- Run III has begun
  - Successful utilization of FTBF
- R&D on detector parameters
  - TPC wire spacing
  - Light collection devices
  - Mesh cathode
- Particle identification efficiency and separation
- Determine reconstruction eff and calorimetric resolution
- publications are on the way



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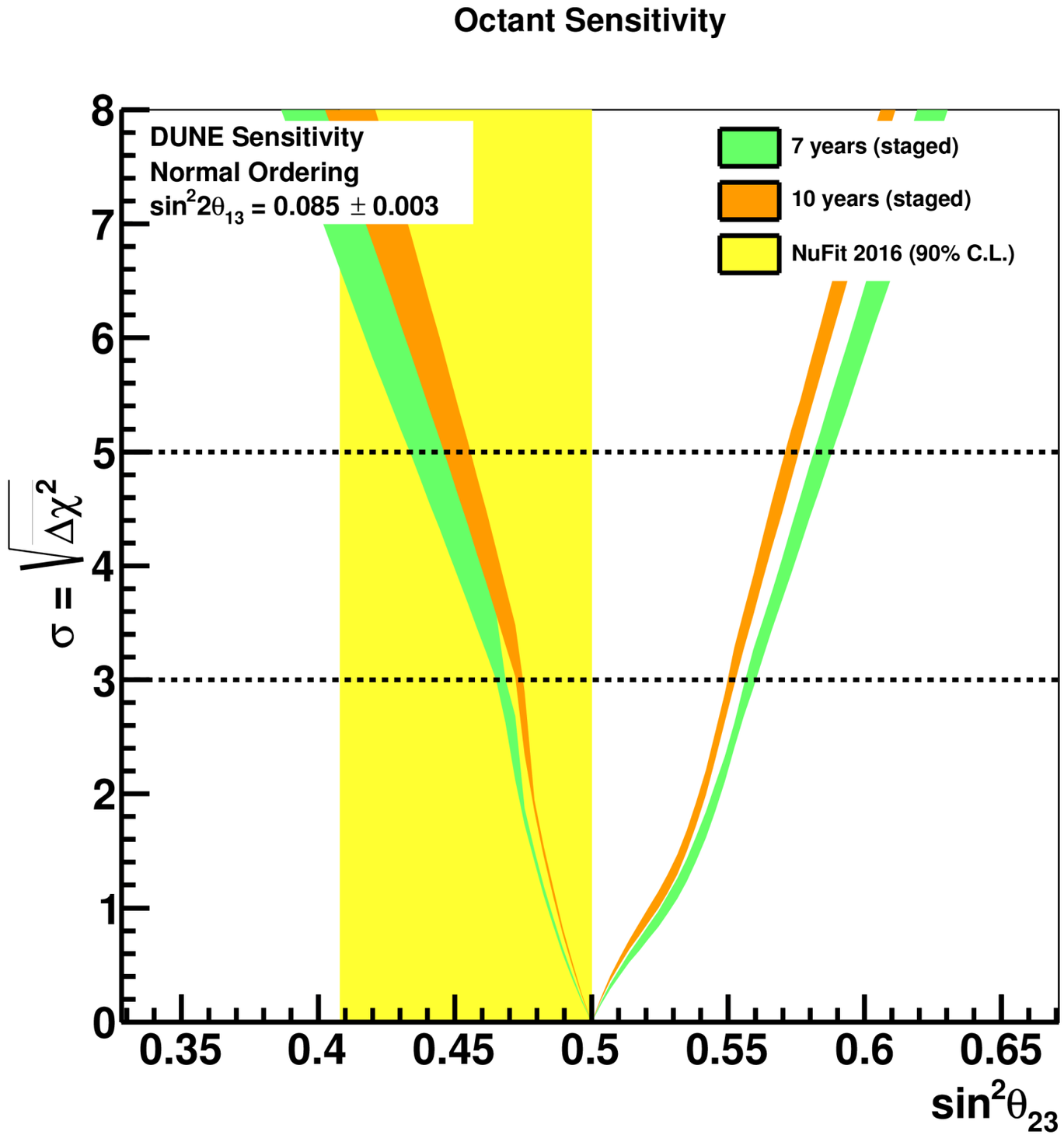
Fermilab

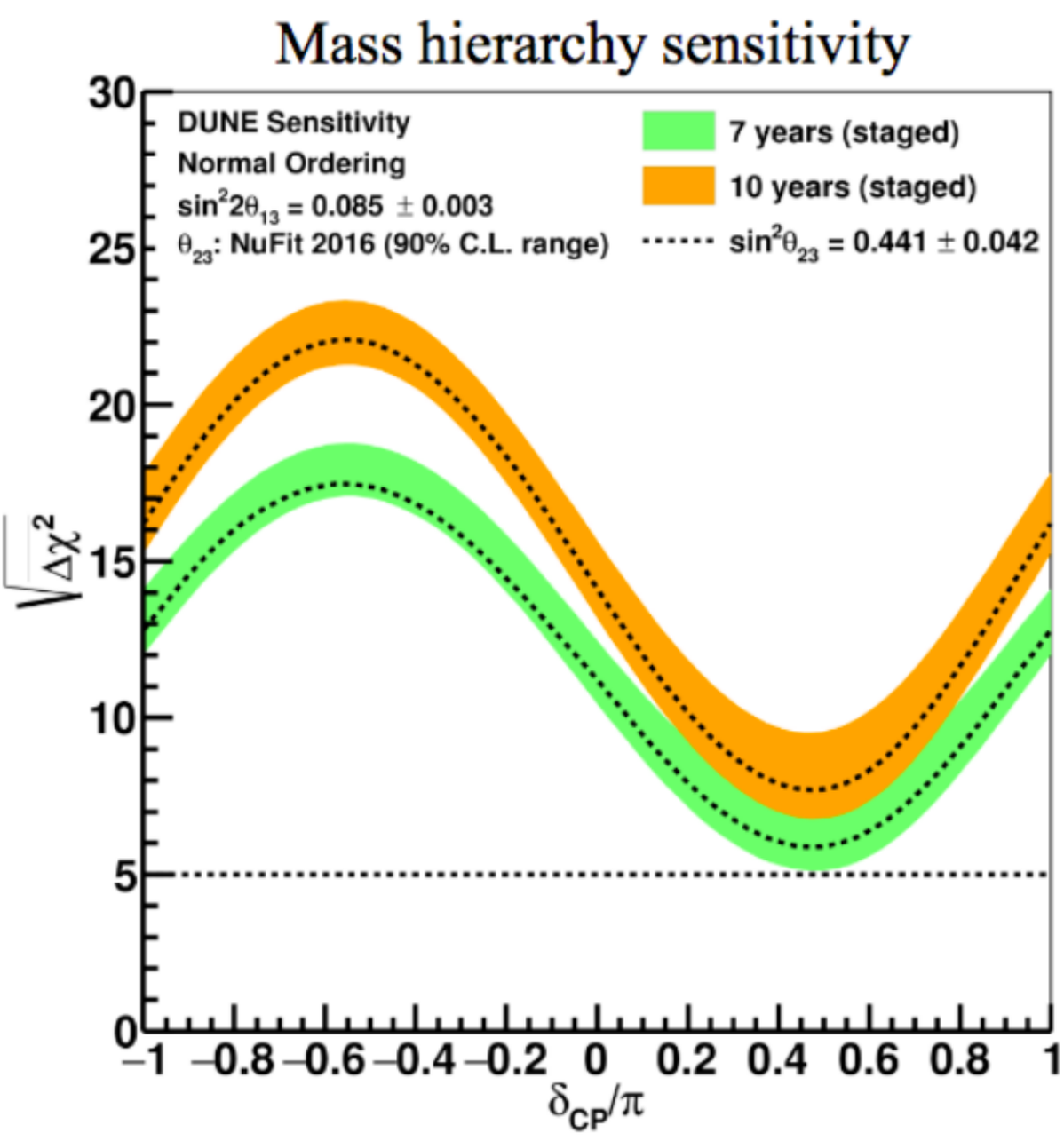
What we will learn from DUNE: Octant Determination

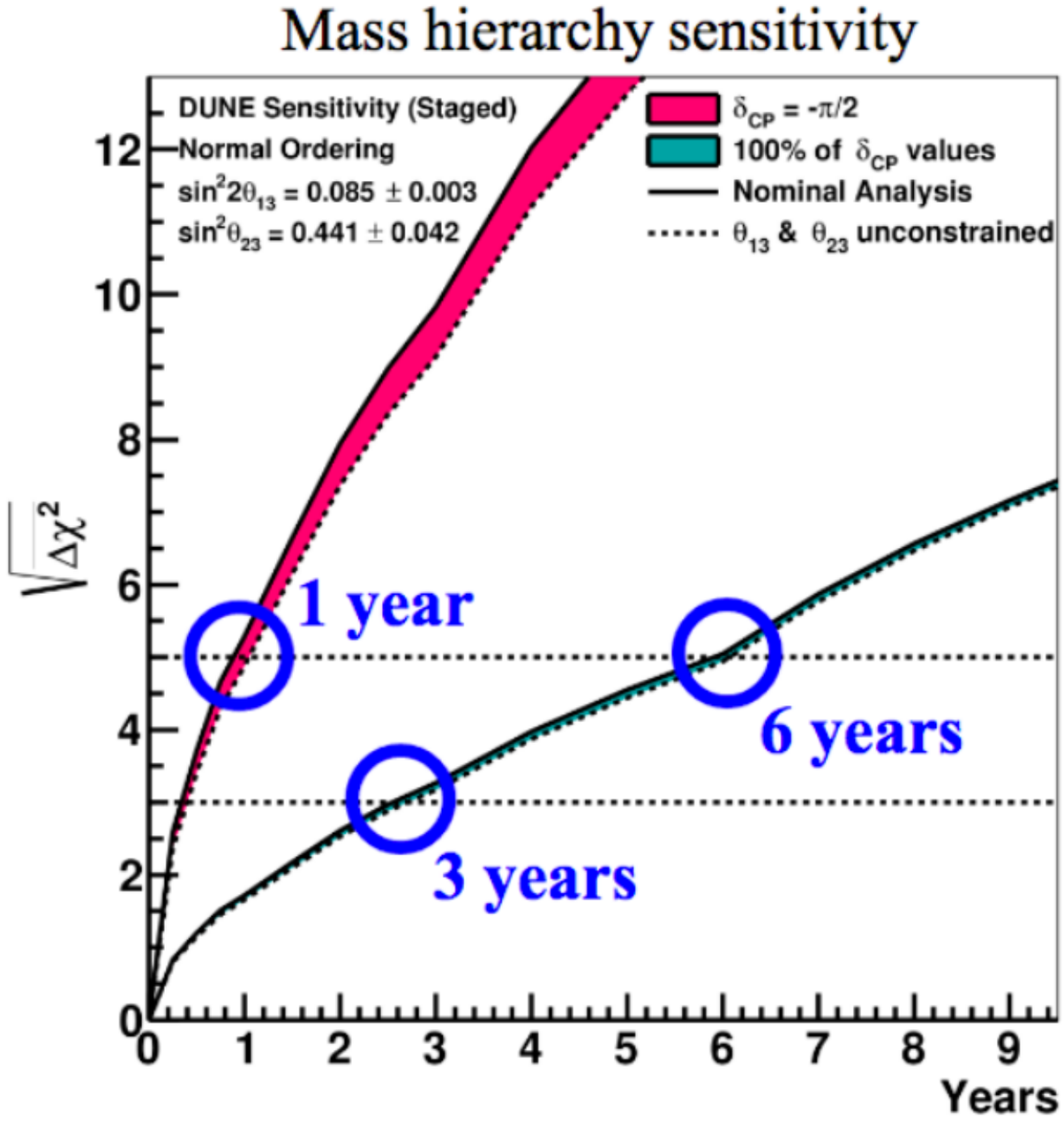
- For $\sin^2\theta_{23} < 0.43$ or $\sin^2\theta_{23} > 0.59$, can determine the octant to 5σ within 7 years.
- As approach $\sin^2\theta_{23} = 0.5$ value becomes harder to measure



What we will learn from DUNE: Mass Hierarchy

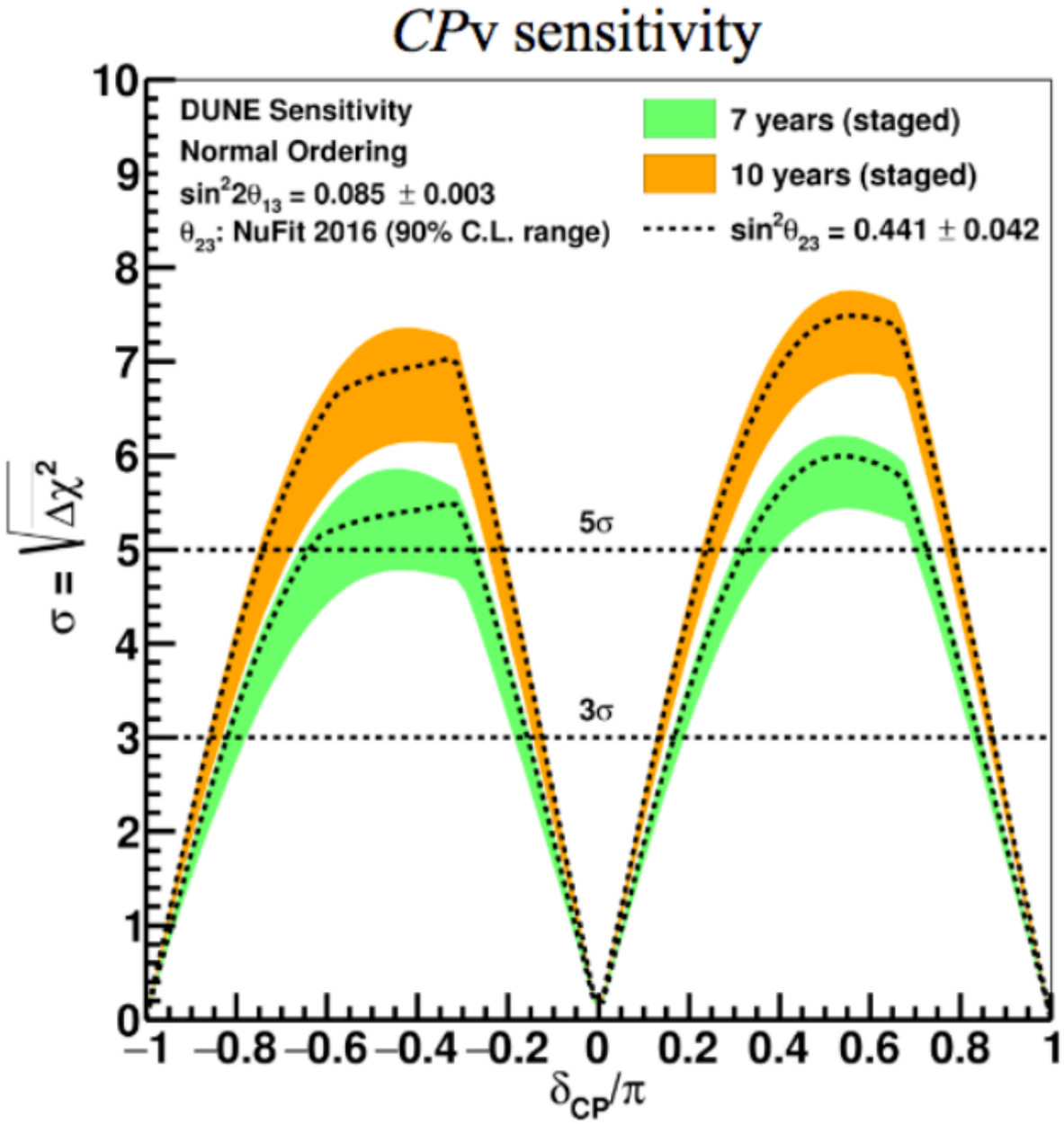
- 5σ results as soon as 1 year if parameters are favorable.
- Complete coverage by year 6 independent of δ.

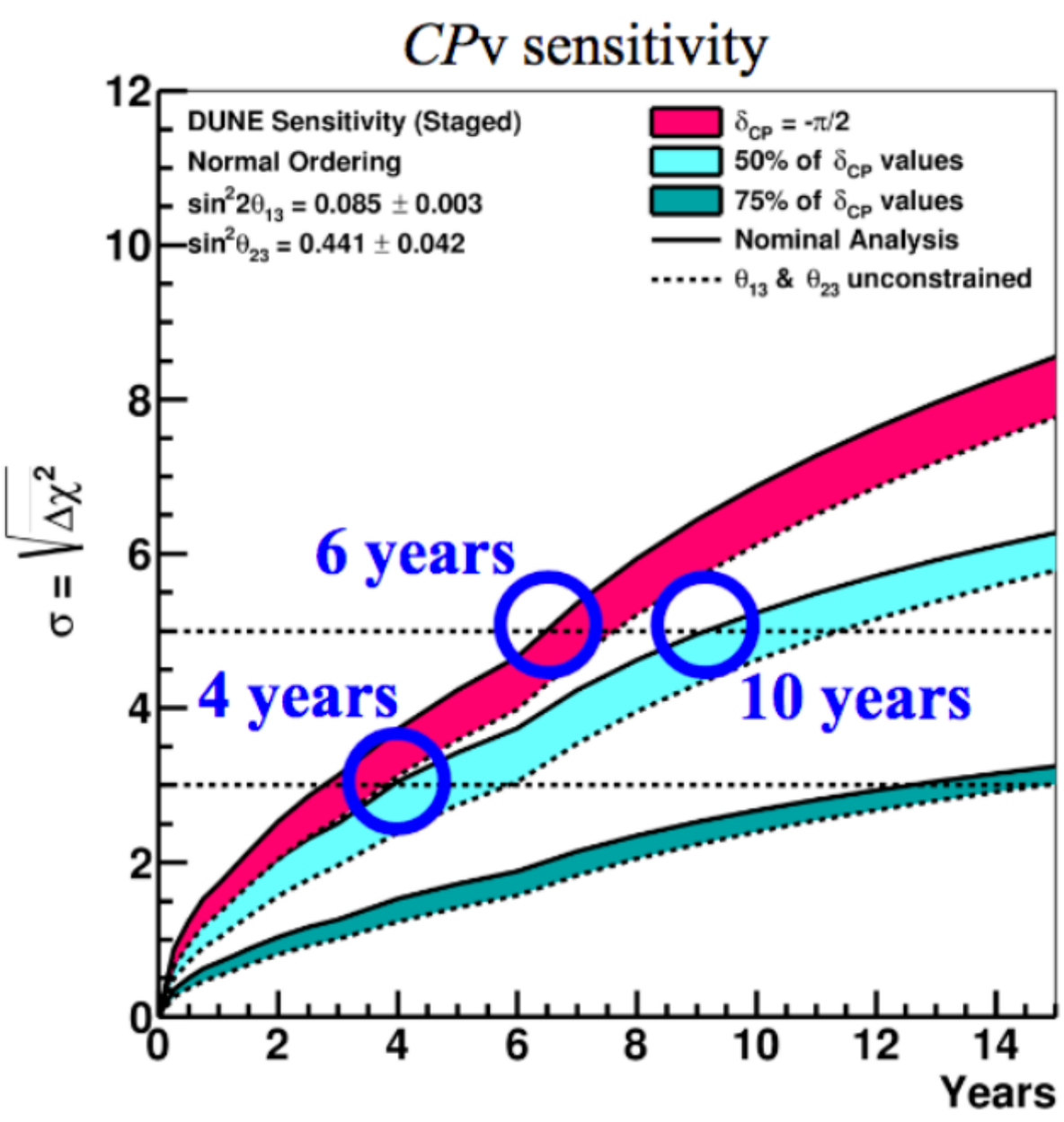




What we will learn from DUNE: CP Violation

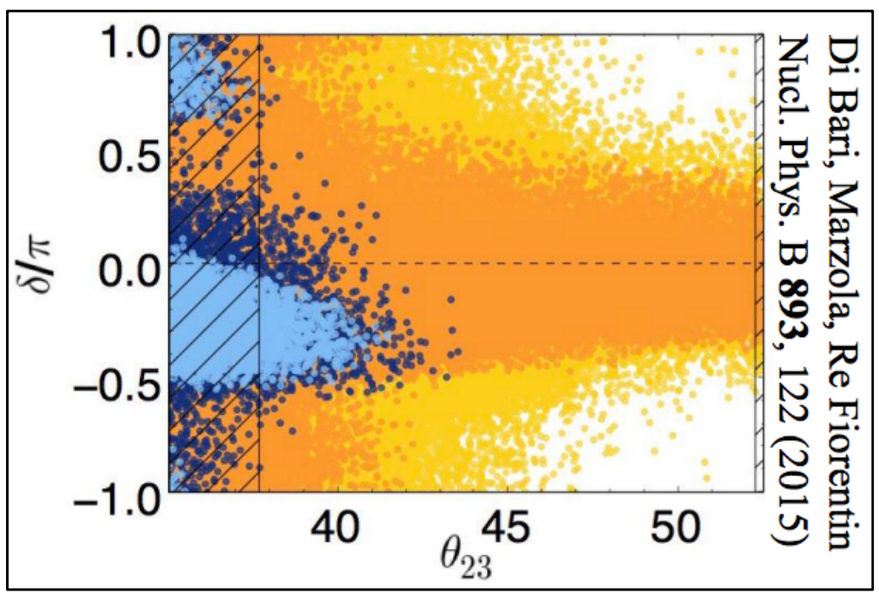
- 5σ at favorable δ within 7 years.
- 65% coverage at 3σ at that same point.



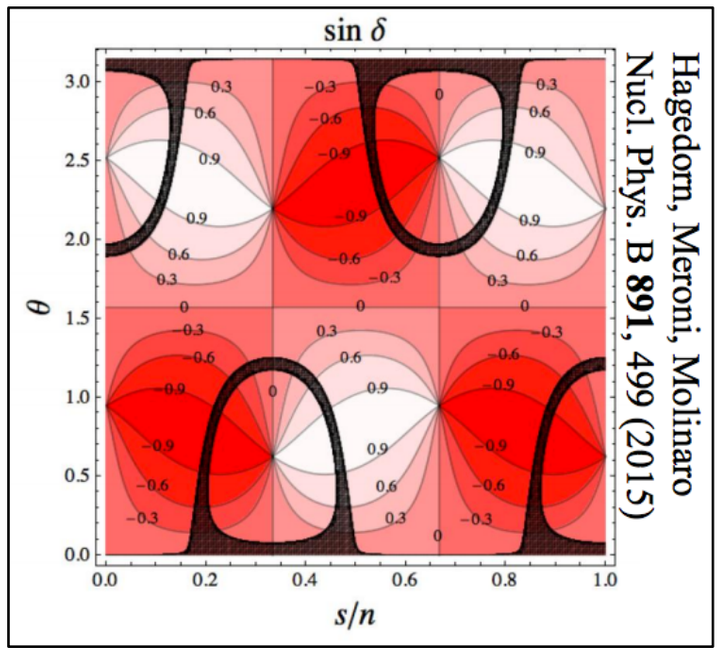


DUNE: Beyond Measuring Angles

- Beyond just measuring angles, the goal for DUNE is to address the theory of flavor.
- Making sufficiently precise measurements of the angles, octant, hierarchy can provide guidance on the underlying symmetries underneath flavor.
- Measuring the mixing via multiple channels can improve those constraints.
  - Take advantage of long baseline, high energy to look for ν_τ appearance, possibly at a different beam tune.



Di Bari, Marzola, Re Fiorentin
Nucl. Phys. B **893**, 122 (2015)



Hagedorn, Meroni, Molinaro
Nucl. Phys. B **891**, 499 (2015)

Pascoli and Zhou, JHEP **06**, 73 (2016)
Flavor symmetry $A_4 \times Z_2 \times Z_4$; flavon-induced connections between flavor mixing and CLFV, ***and…***

$$\sin\theta_{12} = \frac{1}{\sqrt{3}}\left(1 - 2|\epsilon_\varphi|\cos\theta_\varphi + 2\epsilon_\chi\right)$$

$$\sin\theta_{23} = \frac{1}{\sqrt{2}}\left(1 + |\epsilon_\varphi|\cos\theta_\varphi\right)$$

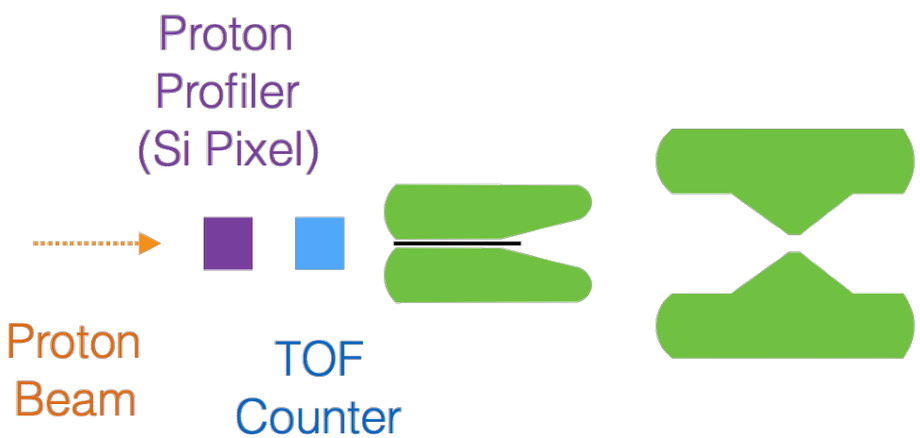
$$\sin\theta_{13} = \sqrt{2}|\epsilon_\varphi \sin\theta_\varphi|$$

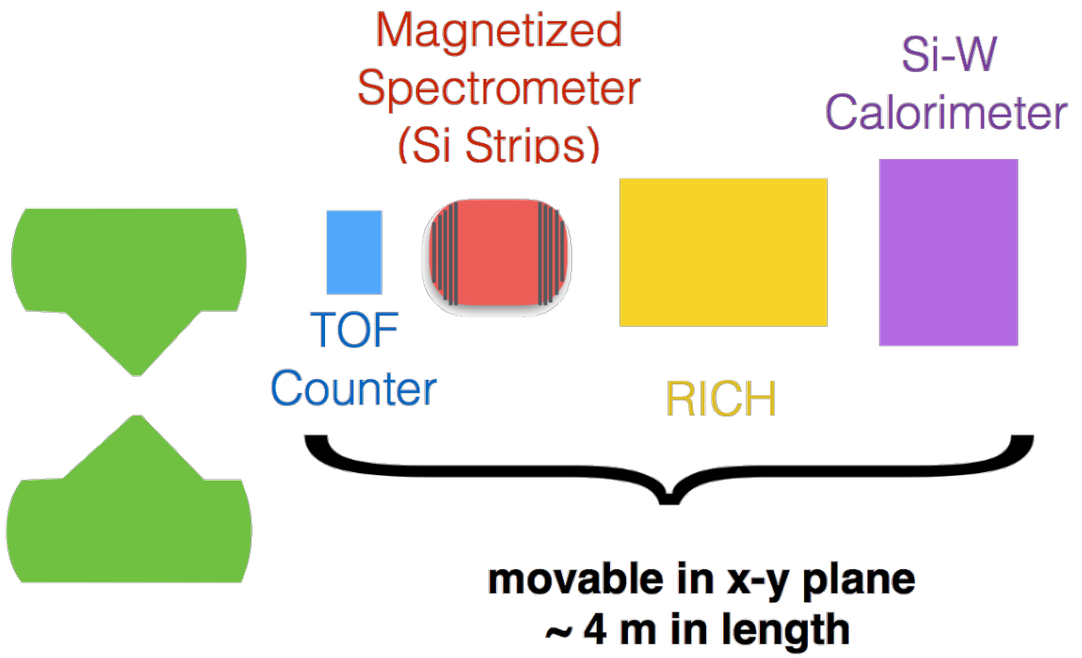
$$\delta = \begin{cases} 270^\circ - 2|\epsilon_\varphi|\sin\theta_\varphi\,, & \theta_\varphi > 0\,, \\ 90^\circ - 2|\epsilon_\varphi|\sin\theta_\varphi\,, & \theta_\varphi < 0\,, \end{cases}$$

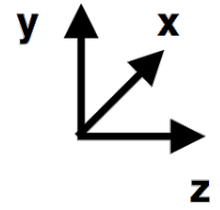
$$\epsilon_\varphi = |\epsilon_\varphi| e^{i\theta_\varphi}$$

$$\delta \approx \begin{cases} 270^\circ - \sqrt{2}\theta_{13}\,, & \theta_\varphi > 0\,, \\ 90^\circ + \sqrt{2}\theta_{13}\,, & \theta_\varphi < 0\,. \end{cases}$$

Proposal LBNF Spectrometer: Reducing Beam Uncertainties:

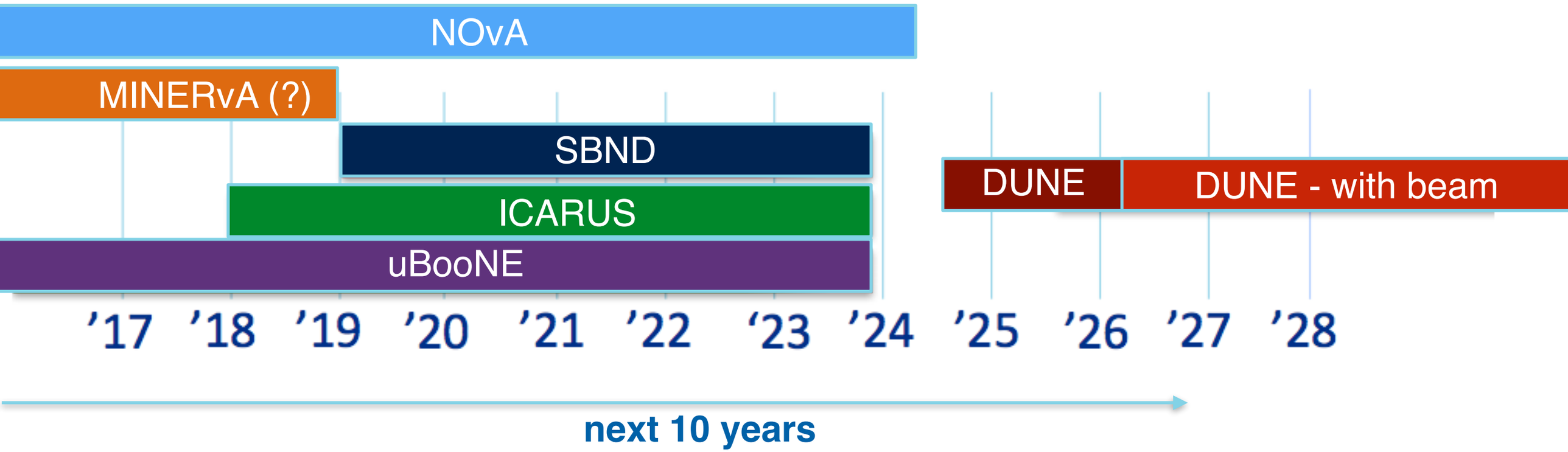






- DUNE will require unprecedented control of systematic uncertainties for a neutrino oscillation experiment.
- One large component: the neutrino flux.
- Spectrometer: measure the actual focused flux to high precision.
  - Requires a replica LBNF setup, made up of spare target, horns.
- Could take advantage of an upgraded test beam facility.

Looking forward next the 10 years and beyond



- The lab program for the next 10 years is quite set and DUNE will run for ~10 years
- Not shown, R+D work for DUNE and beam complex improvements, Spectrometer

Looking forward

- Where do we want to go after DUNE?
  - Depends on if questions DUNE set out to answer have been answered,
  - SBN ruling out sterile neutrinos will make it clearer how likely that will be

- What will be the unanswered questions at the end of DUNE?
  - Assuming no sterile neutrinos or other non-standard interactions we **will know** the **Mass Hierarchy, likely know the CP phase, and $\sin^2\theta_{23}$** if far enough away from maximal
  - **We will still not know if neutrino are Majorana or Dirac**
  - **We will not know masses of the three neutrino states**

- What do we want to do with Booster neutrino beam and detectors and after SBN?
  - Nothing
  - Precision nu_s measurements
  - Precision cross section measurements
  - Look for dark matter with beam dump, eta
  - other??

Working with others: Cosmic Frontier

Place holder

Working with others: Theory

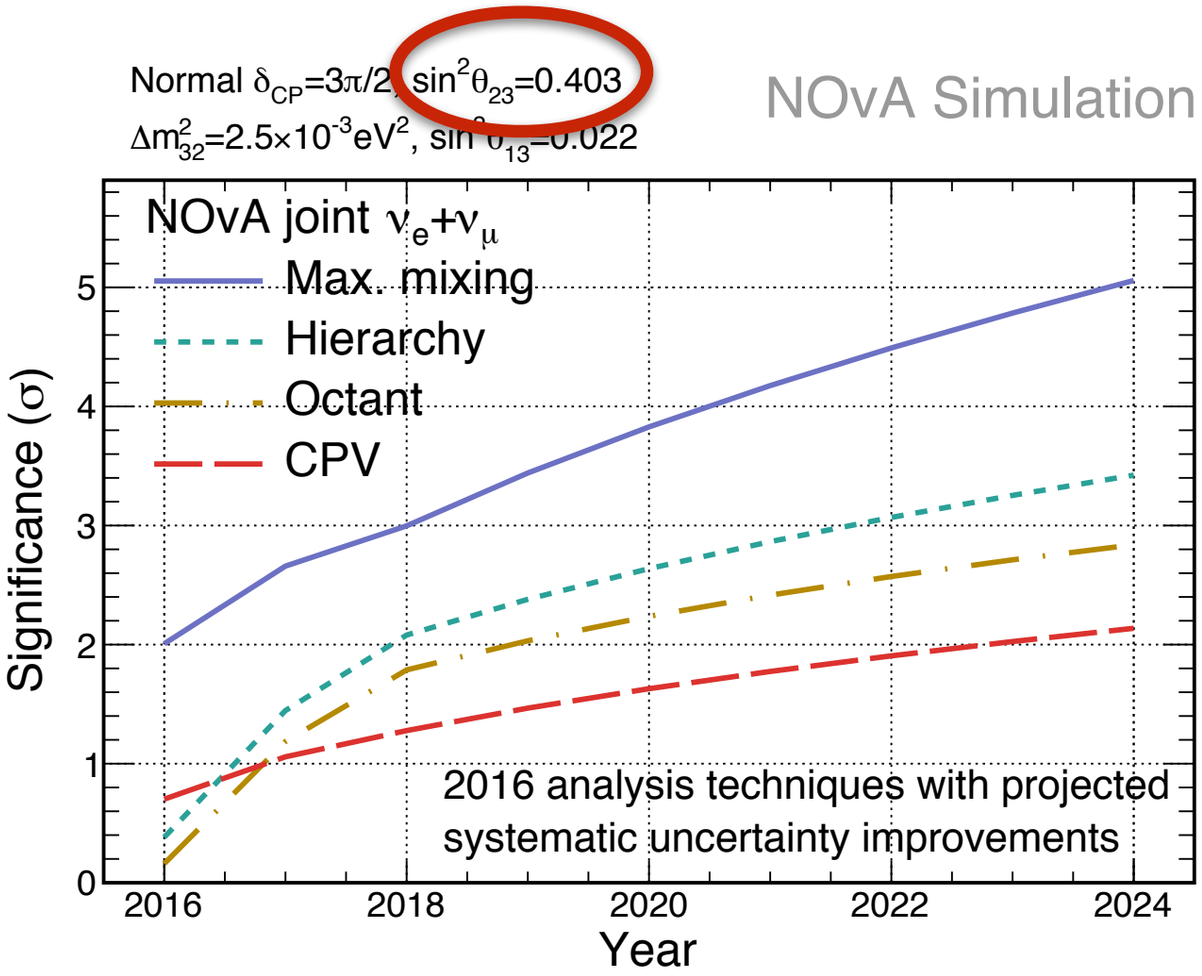
What are the most important questions to our theory colleagues?

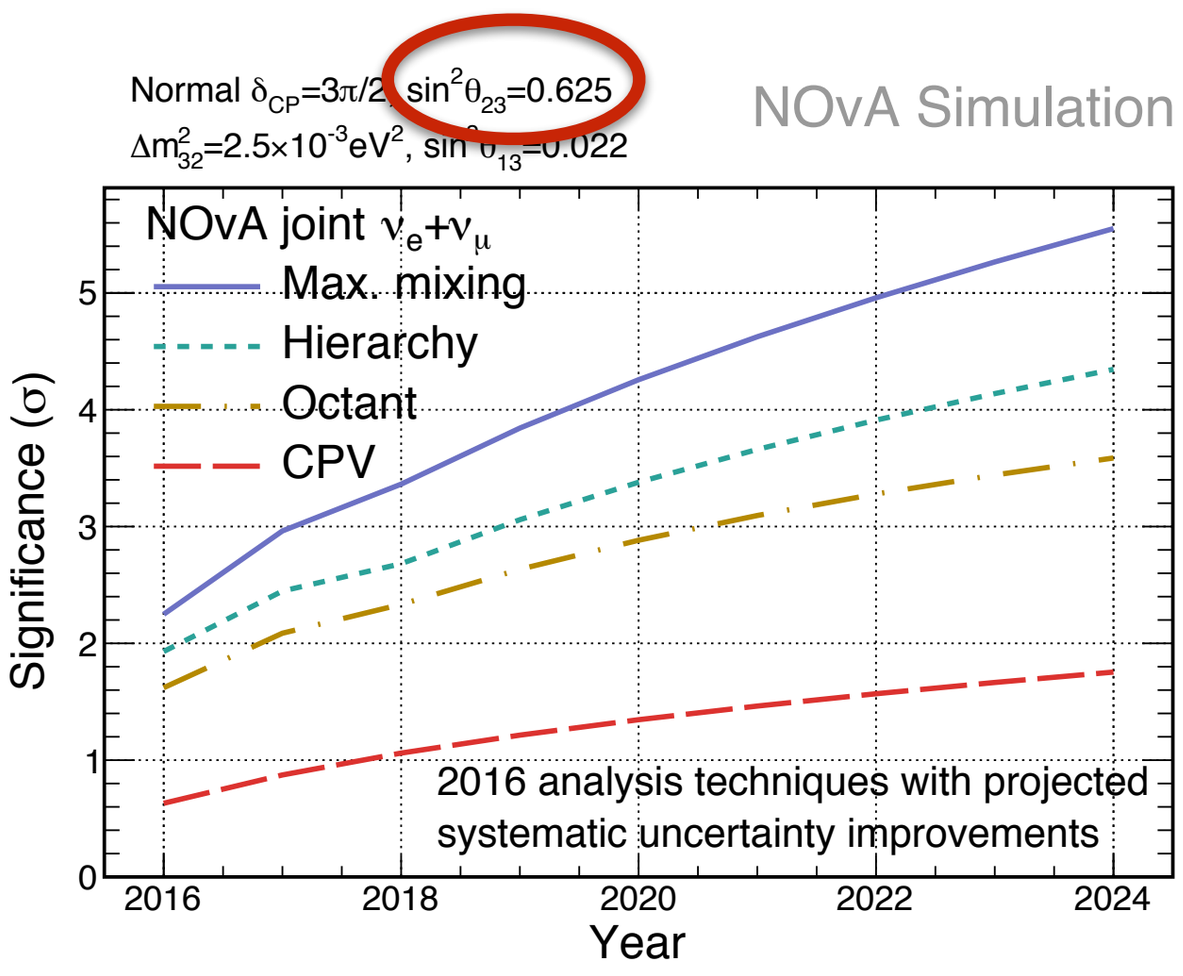
- Determining the octant is important for model building. Is there a symmetry there or not?
- For values of theta_23 close to maximal this might not happen at DUNE
- Important to test the three flavor paradigm, taus are problematic even at DUNE

- DUNE will require unprecedented control of systematic uncertainties for a neutrino oscillation experiment.
- Important to work with Nuclear/interaction theorists to produce best simulation of neutrino interactions and to understand fully the uncertainties arriving from this

Backup

NOvA reach dependence on oscillation parameters





3 sigma on hierarchy change from 2019 to 2022

Short Baseline Neutrino Timeline (Dec 2016)

MicroBooNE

CRT Top Design & Fabrication & Installation

Lar Fill | Commission | Operate

ICARUS

Cryogenics

CRT & OB

ICARUS TPC 1 & Cold Vessel

TPC 2

Ship

Lar Fill | Commission | Operate

Not all activities shown

SBND

TPC Assembly

Detector Installation

CRT and Overburden

LAr Filling & Commissioning

2Q 2016 | 3Q 2016 | 4Q 2016 | 1Q 2017 | 2Q 2017 | 3Q 2017 | 4Q 2017 | 1Q 2018 | 2Q 2018 | 3Q 2018 | 4Q 2018 | 1Q 2019 | 2Q 2019

May 2017

Timeline – Calendar year

Winter2019

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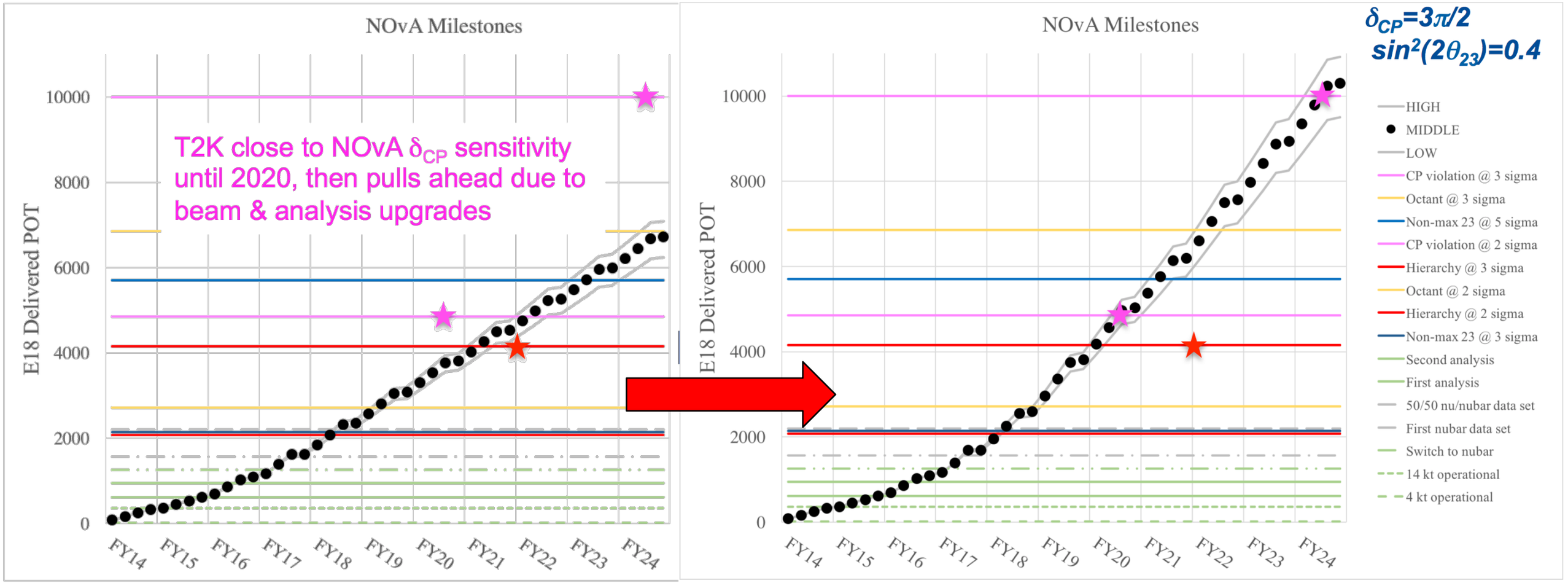
DUNE: Neutrinos and more

- Supernova neutrinos
  - DUNE at 10 kpc: ~3000 ve events over 10 seconds
  - Potential for diffuse supernova discovery and ~20% rate measurement
- Nucleon decay
  - A general prediction of grand unified theories.
  - LArTPC technology particularly shines for complex p decay modes with final state kaons, a favored by SUSY GUTs.
  - DUNE is expected to improve existing limits by one order of magnitude with 40 kton detecto after 20 years.
- Light sterile neutrinos
- Non-standard interactions
- Dark matter and more…
- Plus millions of interactions in the Near Detector for exploring v-nucleus scattering: final state interactions, nuclear structure, MEC/2p2h channels, ...

What we could learn from NOvA: Extended Reach



- NOvA can remain competitive with T2K and beat ORCA/JUNO to the mass hierarchy, but upgrades are required.
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  - New target design which extends into horn 1.
- Caveat: What is possible depends on what the true parameters are.