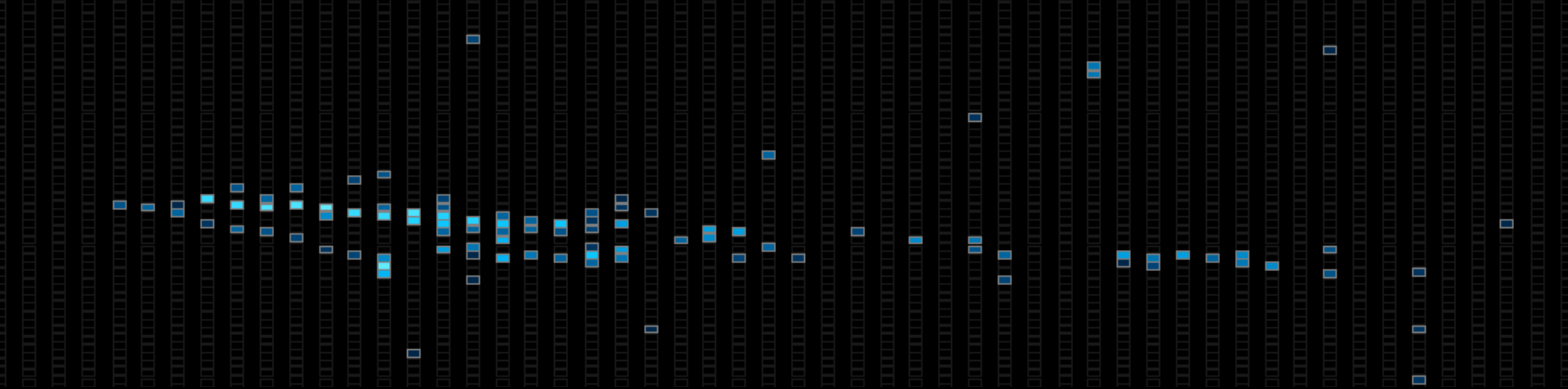


NOvA: Case for more protons

Mark Messier
Indiana University

Fermilab

Fermilab Physics Advisory Committee
10 November 2016

Outline

FY2016 Run Summary

I. Beam and Detector status

II. Physics results

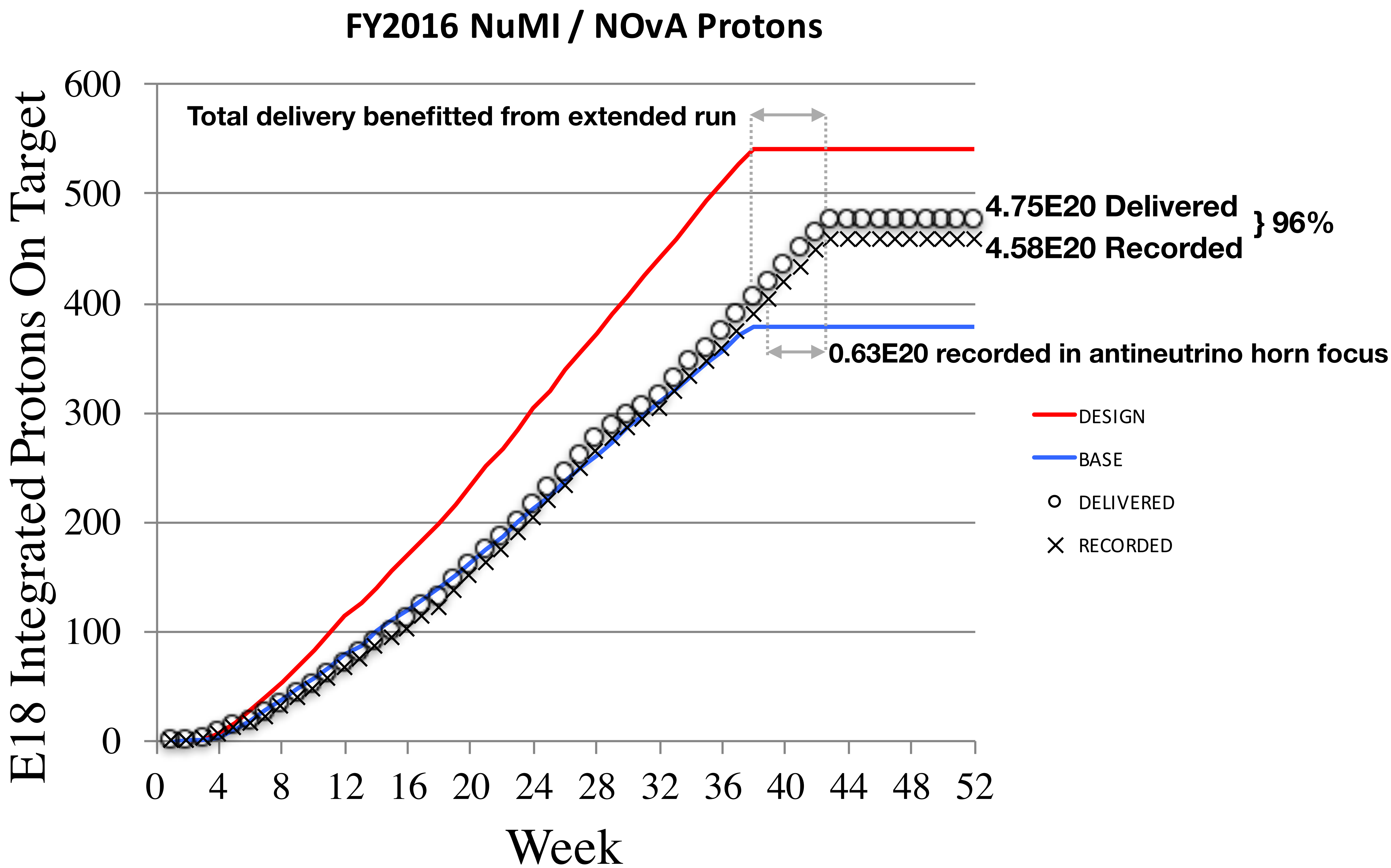
- ν_μ charged-current disappearance
- neutral-current disappearance
- ν_e charged-current appearance
- First look at antineutrinos

Looking ahead

III. Neutrino oscillations post Neutrino 2016

IV. NOvA Physics milestones and FY17 run plan

V. Looking further ahead

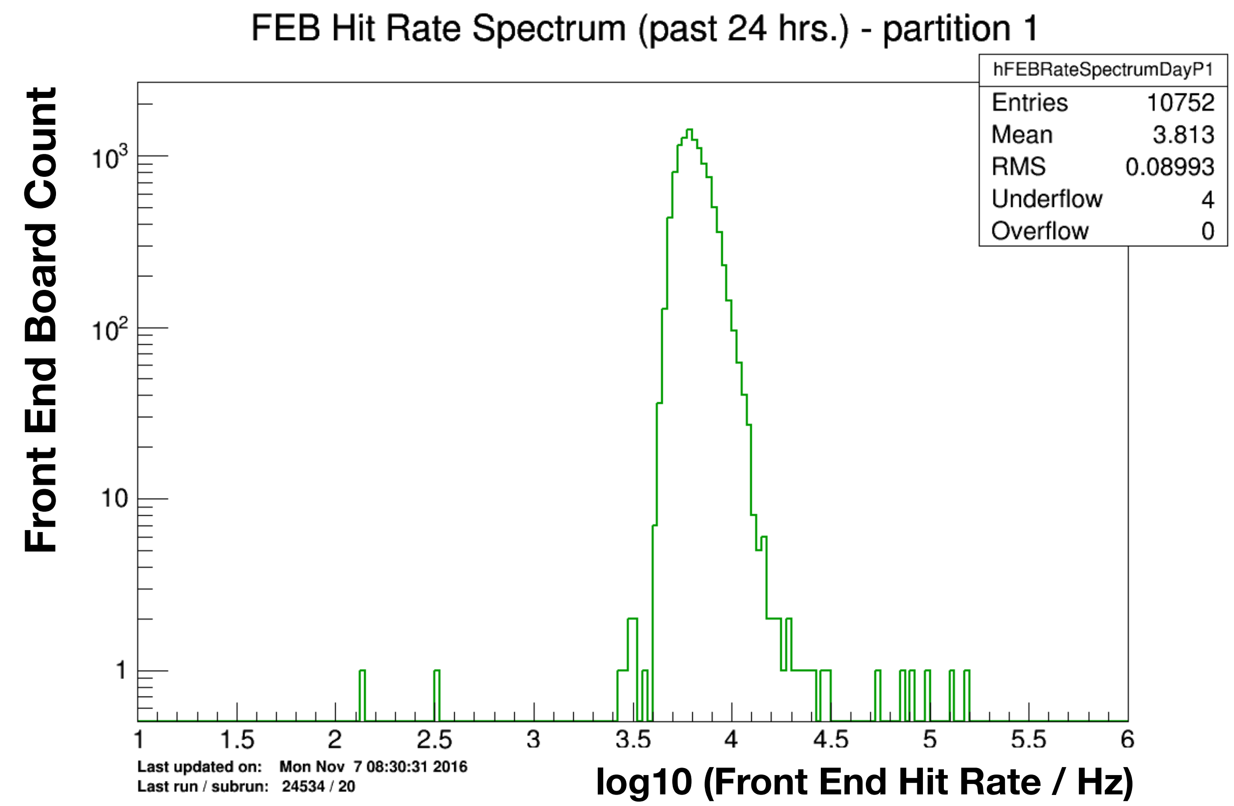


FY16 Beam Performance

- Last year saw routine delivery at 550 kW of proton power.
- Peak of 700 kW demonstrated last year.

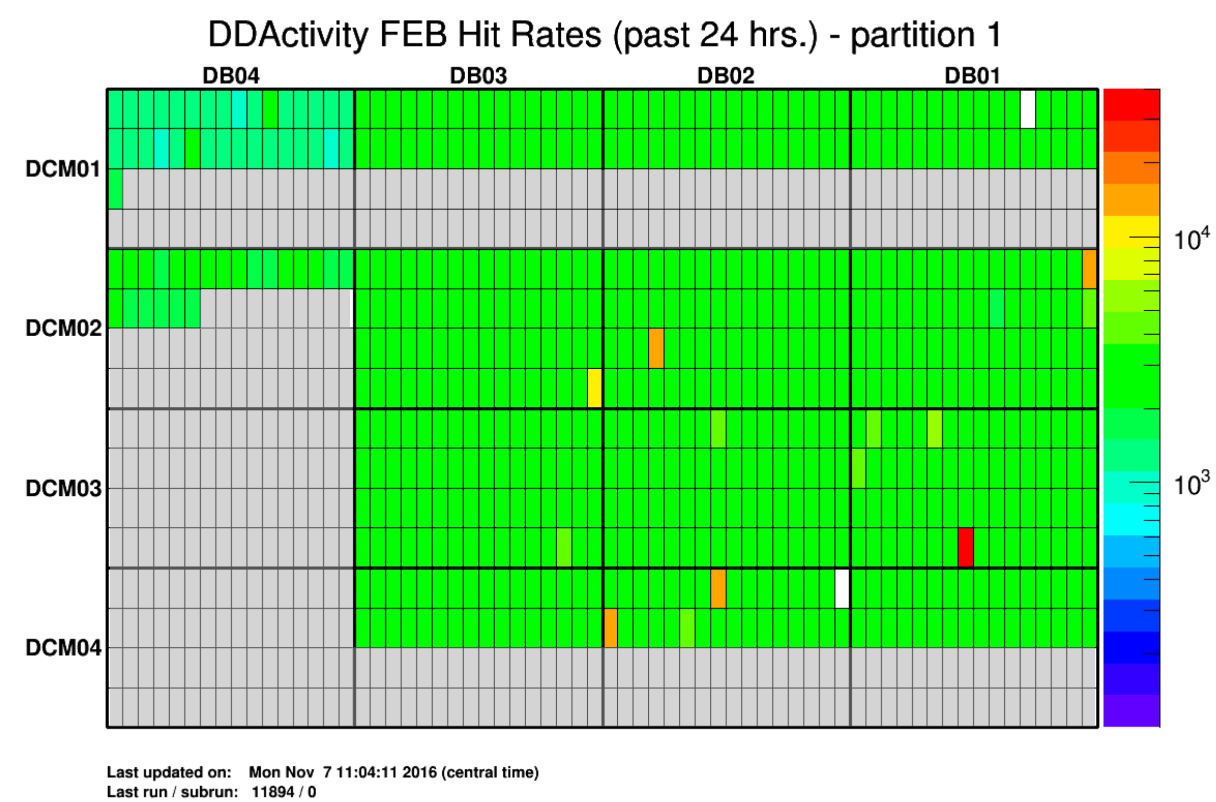
Far Detector

- 96% beam-weighted uptime in FY16
- 32 on-call incidents in 52 weeks
- 10745/10752 FEBs (99.9%) operating within normal parameters
- Average noise rate: 203 Hz / channel
- Added capability to read out continuously for 60+ seconds in case of supernova trigger



Near Detector

- 99% beam-weighted uptime in FY16 - includes weekly scheduled downtimes to train on call experts.
- 623/631 FEBs (98.7%) operating within normal parameters
- Average noise rate: 78 Hz / channel



NOvA FY16 Detector Operations

Offline software and computing

NOvA has aligned its offline computing model with SCD in a way we think is mutually beneficial

- We get access SCD's computing expertise and computing solutions
- SCD gets their solutions "battle tested" by an operating and demanding experiment

artdaq	DAQ & Engineering Consulting	Electronic Module Support	PREP Hardware?	Batch Job Management	User Jobs Monitoring	Gratia	Fermigrid	OSG Enabled	HEPCloud	Amazon	GUMS	VOMS		dcache/ enstore	Gridftp	AAF
	YES	YES	YES	In Production	In Production	In Production	In Production	In Production	Testing	Testing	In Production	In Production	Planning	In Production	In Production	

SAM Web	SAM4Users	IFDH	FTS	Software Framework (art)	Software Processing (larsoft)	ups/upd	Continuous Integration - Orchestration	Genie	geant4	IF Beam	Hardware DB	Conditions DB	Custom Databases	OPOS	POMS	CVMFS Repository
In Production	Testing	In Production	In Production	In Production	N/A	In Production	Planning	In Production	In Production	In Production	In Production	In Production	In Production	In Production	Testing	In Production

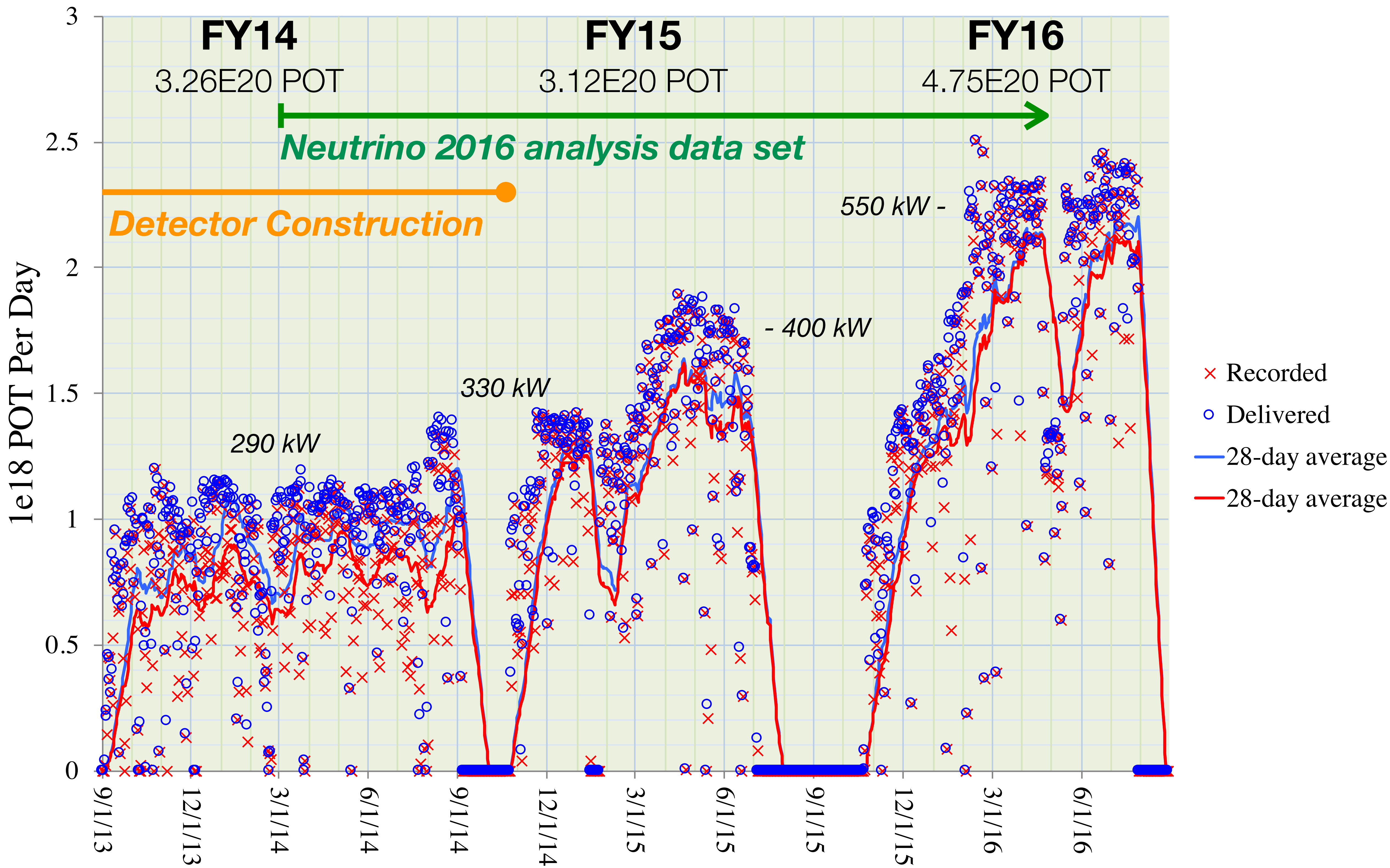
Managed Scientific Servers (incl. GPCF)	Control Room System Management	Continuous integration Infrastructure	Experiment Online System Management	Limited SLF Workstation and Scientific Test stand	Scientific Linux Distribution	Scientific Linux Engineering	System Administration and Engineering Consulting	Managed Scientific Workstations	Redmine	CVS	SVN	GIT	ECL	Shift Scheduler	Speakers Bureau	Projects
In Production	In Production	In Production	In Production	In Production	In Production			In Production	In Production		In Production		In Production	In Production		In Productio

DES Members	DES Publications	DES Speakers Bureau		NTP	DHCP	Site VPN	NAS	SAN	mysql	postgres		Apache HTTPD website hosting	Secure certificate (SSL)	Wordpress	Teamcenter	indico	doc dB
			In Production	In Production	In Production	In Production	In Production	In Production	No intention	In Production	In Production	In Production	n Productio	N/A	N/A		In Production

Chat	Maillists	Calendar	self service	walk in support	call in support	email support	User/Visitor Managemen t	ReadyTalk	Other Video conferenci ng	Federated Data Managem ent	High Throughpu t Analysis Facilities	Simulation	Framewor k
In Production	n Productio	Productio	In Production	In Production	In Production	In Production	In Production	n Productio	n Productio	xrootd	Deployed	yes	YES

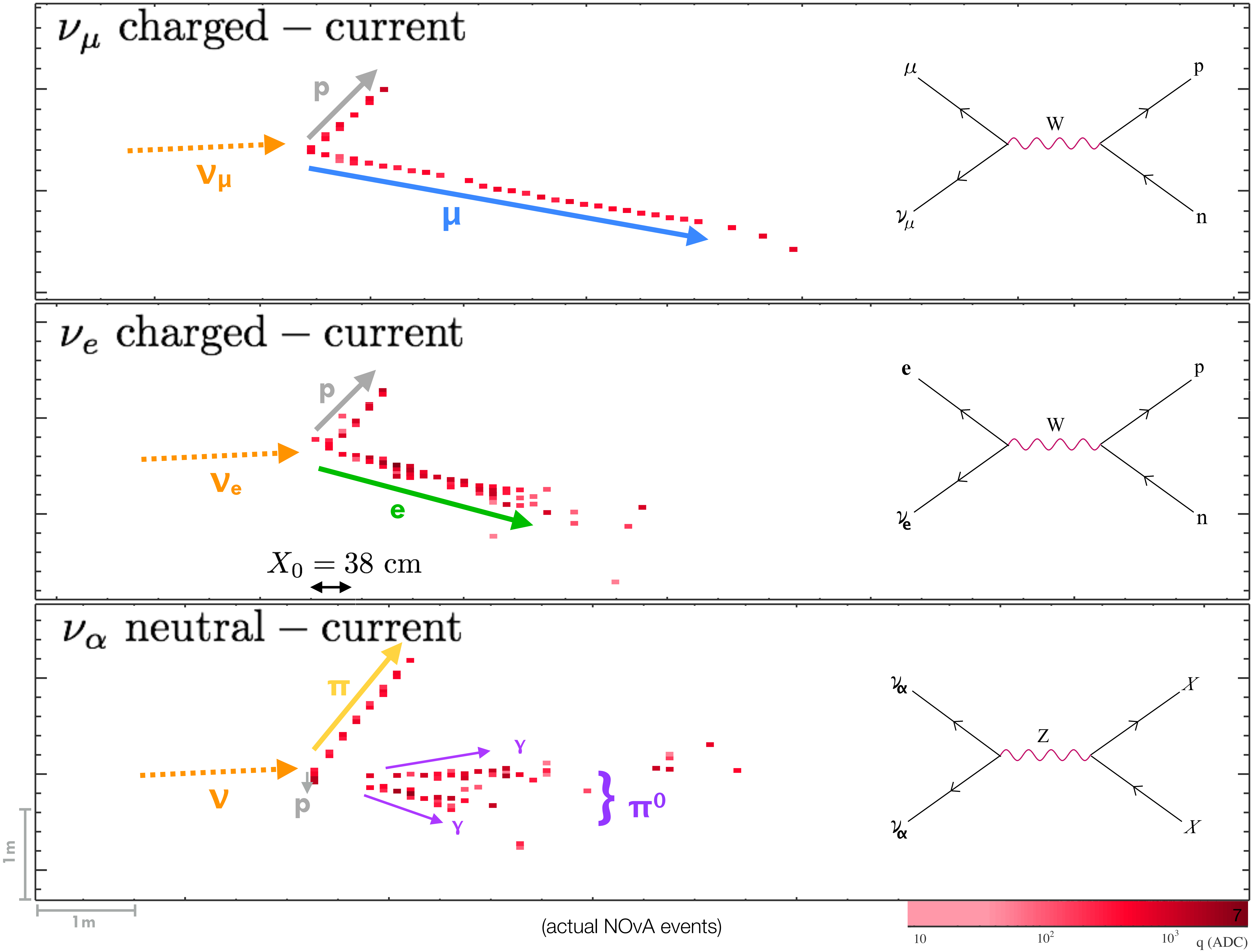
FNAL-supported packages, tools, and ***services in use by NOvA***

- Simulation tools: GENIE and GEANT4
- ART analysis framework
- Code management, build systems, distribution and documentation: SVN/SRT/CMake/UPS/Jenkins/CVMFS/Redmine
- Grid computing and OSG: **24 million CPU hours in FY16: 75% FNAL / 25% off-site**
- Large data storage and cataloging (SAM): **30 million files, ~3+ PB added in FY16**

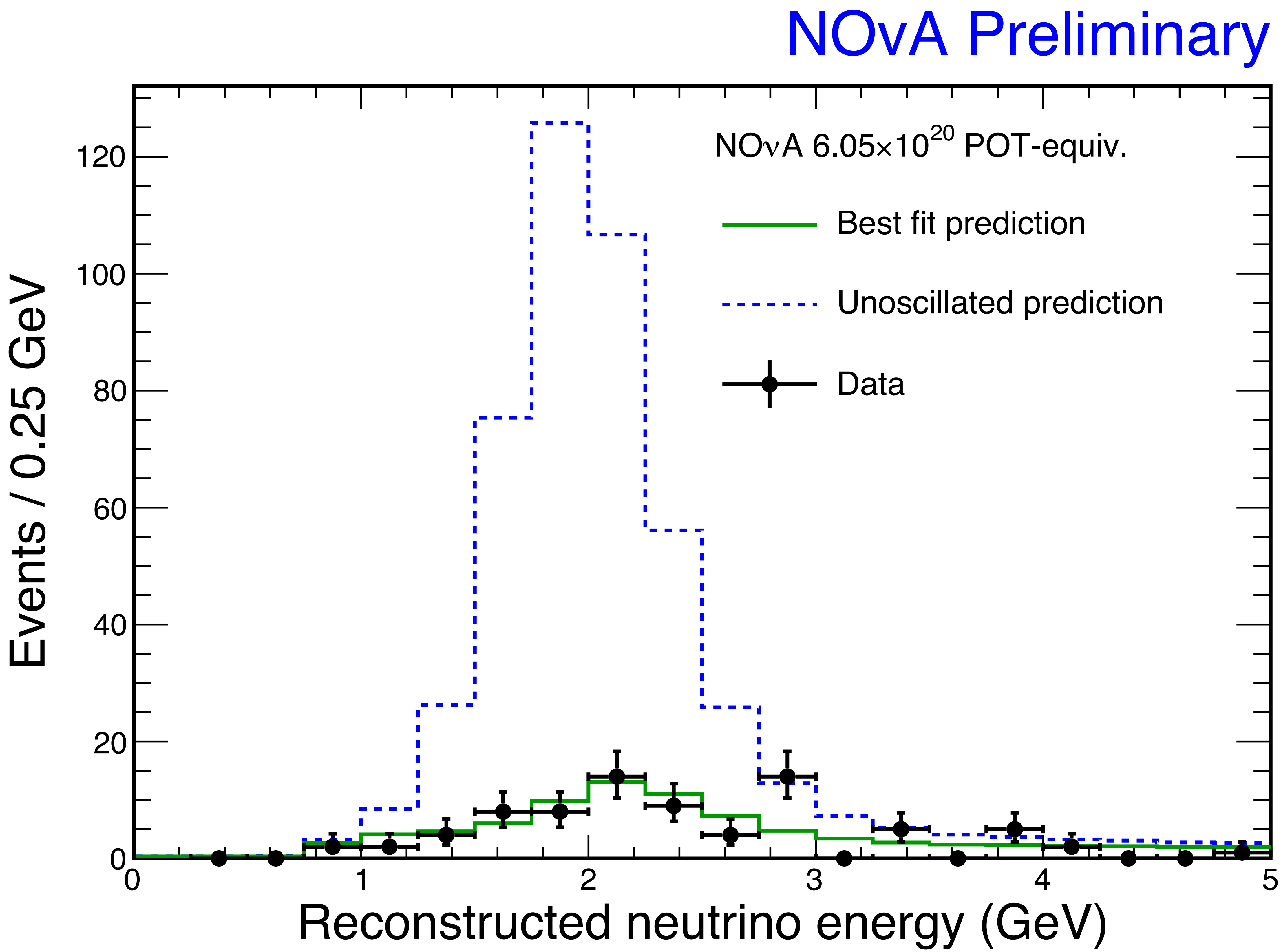


Beam Performance

- Last year saw routine delivery at 550 kW of proton power.
- Peak of 700 kW demonstrated last year.
- Expect routine operations at 630 kW (700 kW-10%) in early calendar 2017

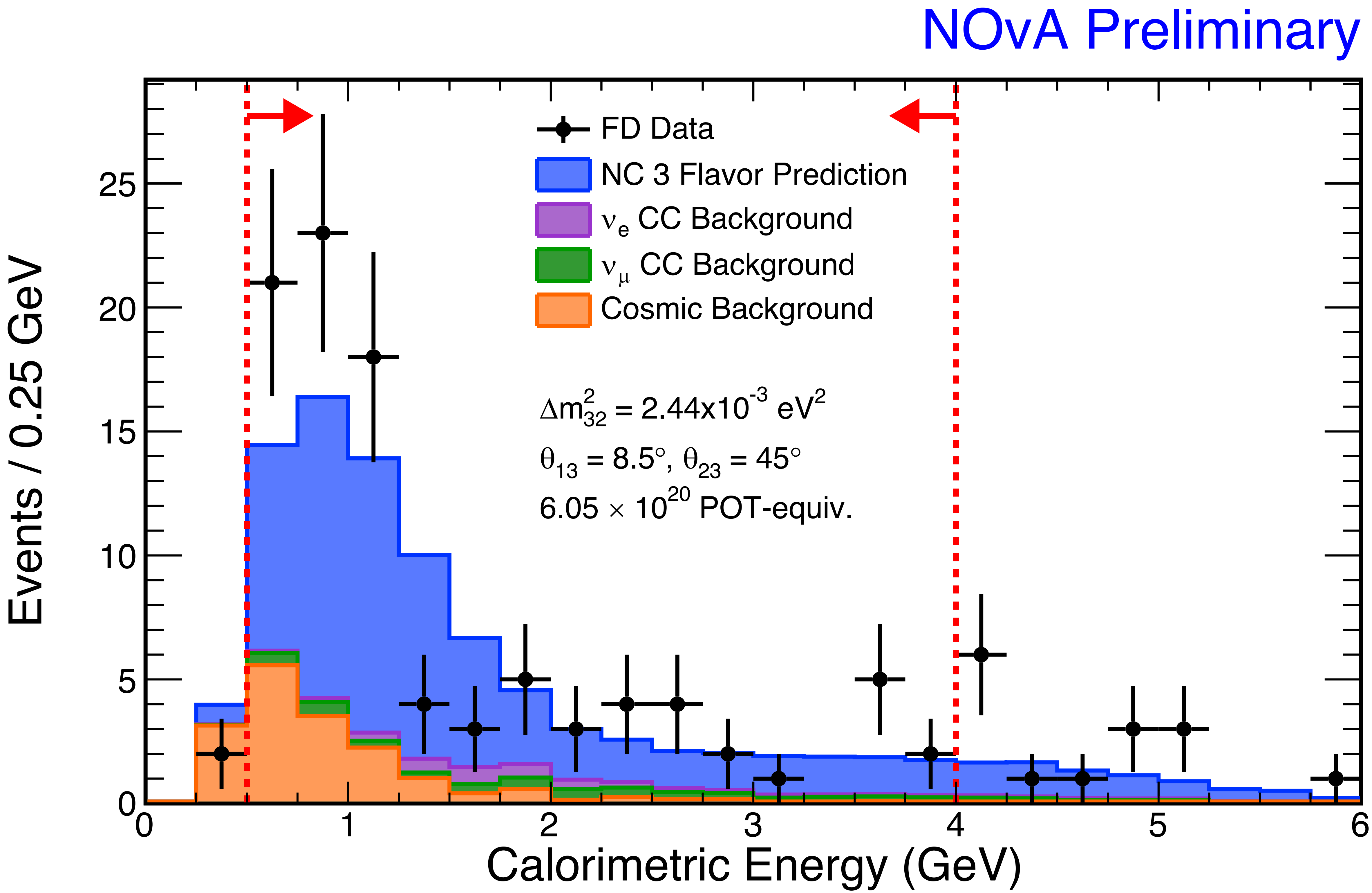


(actual NOvA events)



NOvA Far detector muon neutrino spectrum

473 events expected before oscillations
78 events observed



First look at Neutral-Current Events at Far Detector

NC events are a way to count the total neutrino flux which should be unaffected by standard oscillations.

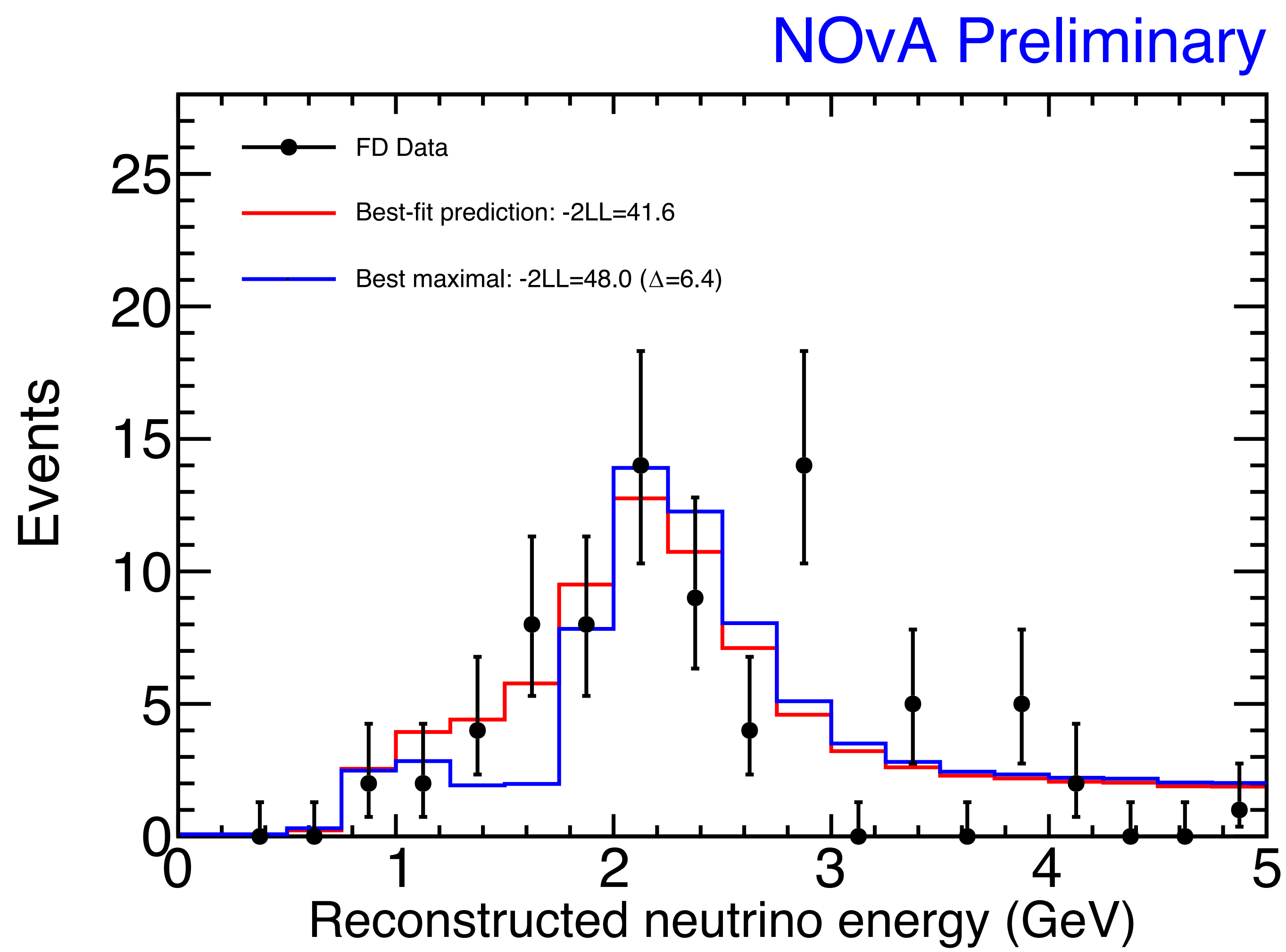
Expect: 61 events signal

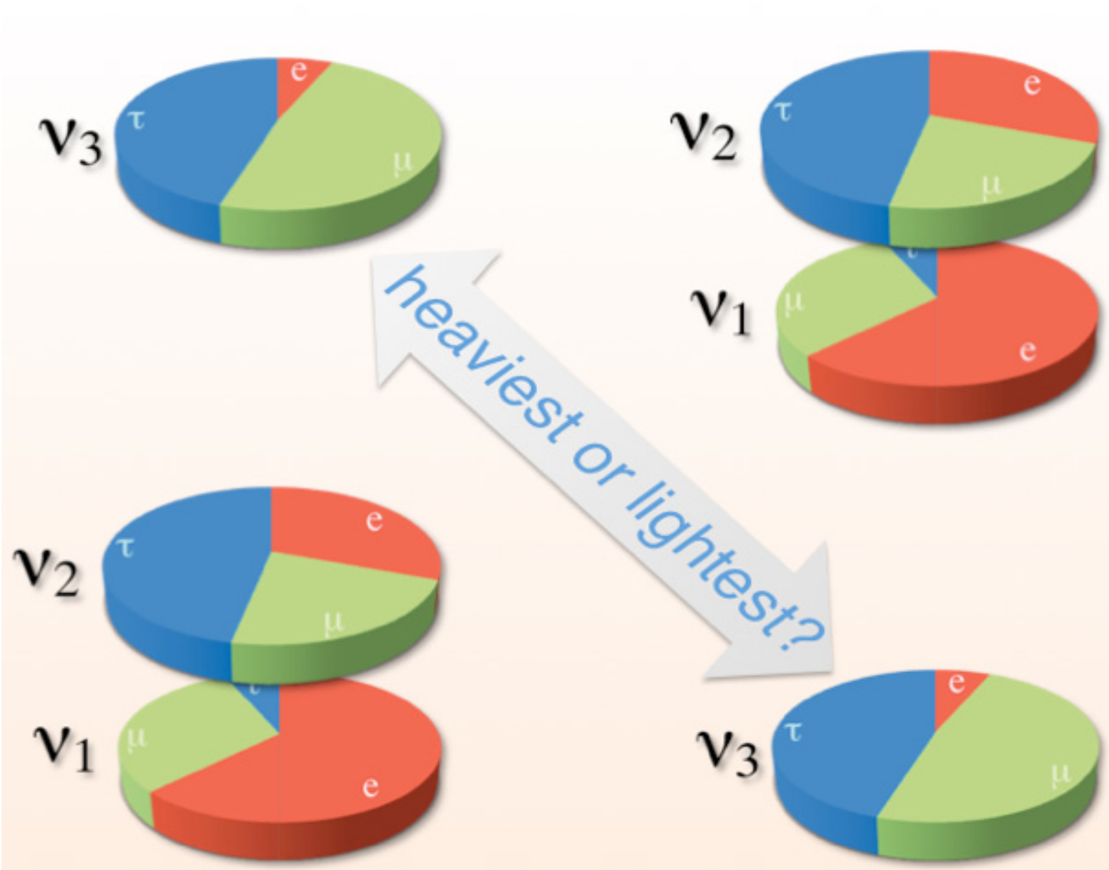
Measure: 72 events

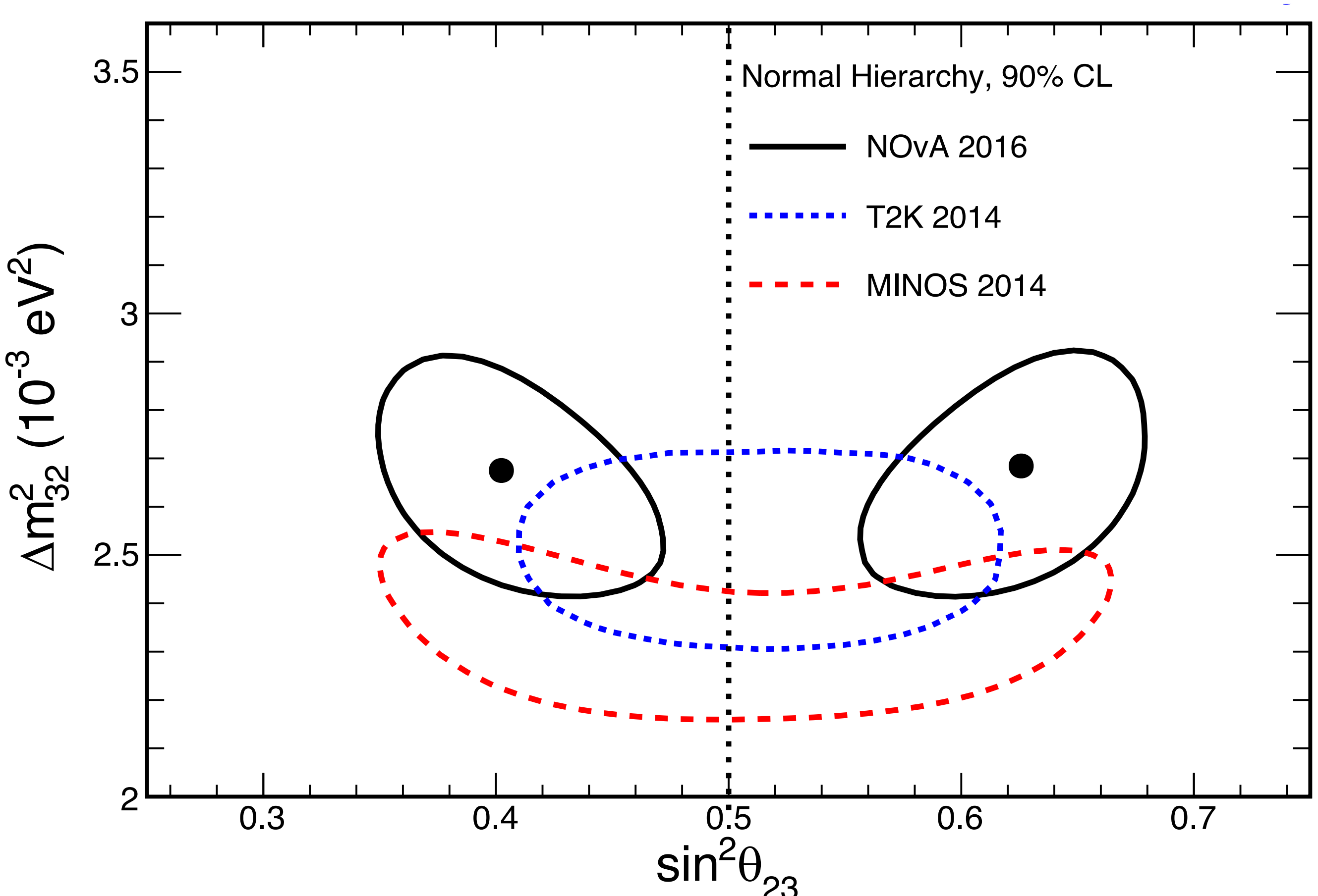
NOvA
ν_μ Disappearance

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3} \mathrm{eV}$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})$$

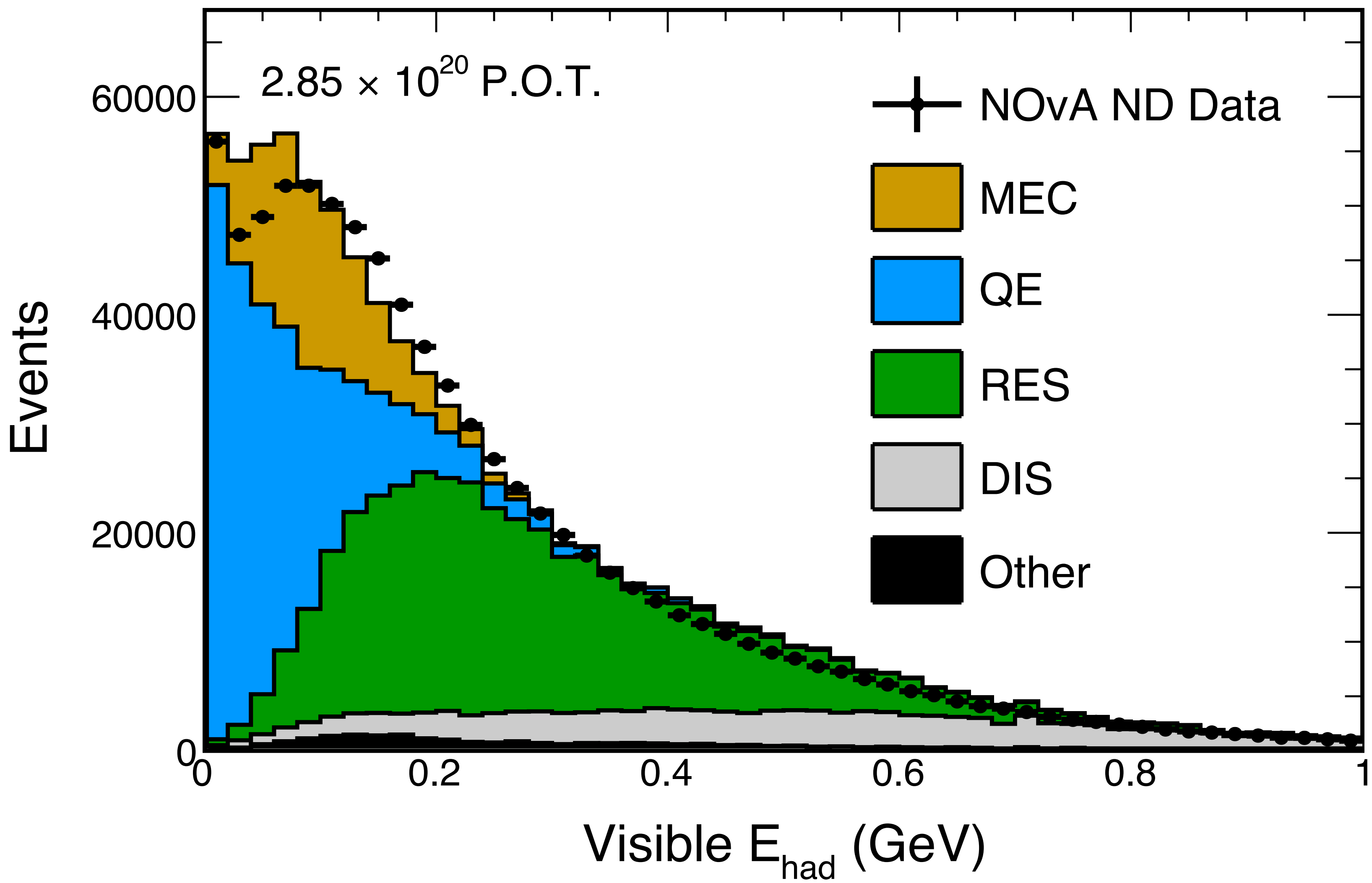
Excludes maximal mixing at 2.5σ



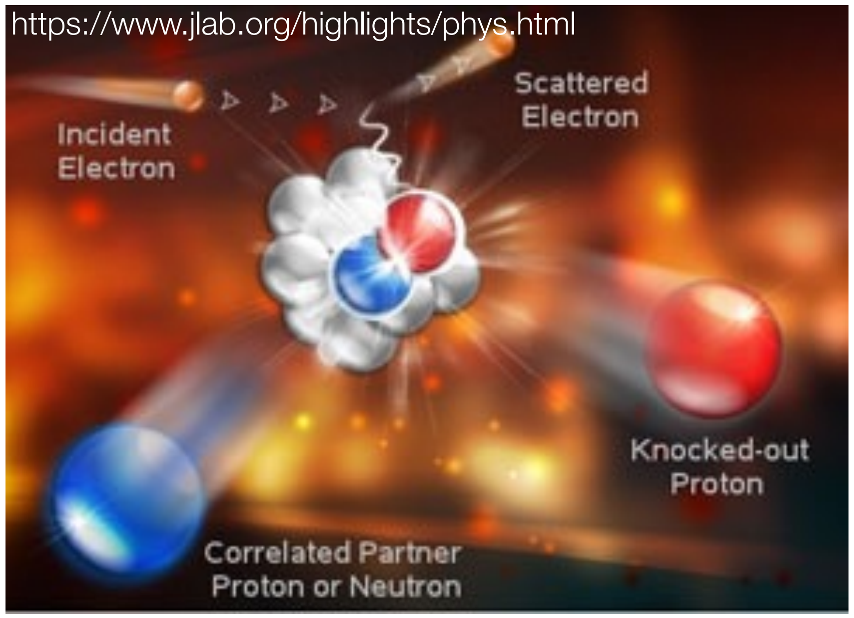




NOvA Preliminary



Empirical model of Meson Exchange Current coded into GENIE inspired by JLAB electron scattering measurements and guided by MINERvA data



[1] P.A. Rodrigues et al. (MINERvA), PRL 116 (2016) 071802 (arXiv:1511.05944)
[2] S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57, and,
T. Katori, AIP Conf. Proc. 1663, 030001 (2015)
[3] P.A. Rodrigues et al. (MINERvA), arXiv: 1601.01888

In first analysis this was a leading systematic for mixing angle measurement: Contributed to a 4% uncertainty on absolute energy scale

Now leading systematics are:
2.2% from muon energy scale
2.0% from calibration
2.0% relative near/far energy scale

Major update from first analysis to second analysis was an improvement in our understanding of generator-level hadronic energy distribution

MACHINE ANALYSIS OF BUBBLE CHAMBER PICTURES

P. V. C. Hough

The University of Michigan, Ann Arbor, Mich.

Fig. 1a A typical hydrogen bubble chamber photograph (Berkeley) with 1.1 BeV/c negative pions incident, showing an associated production.

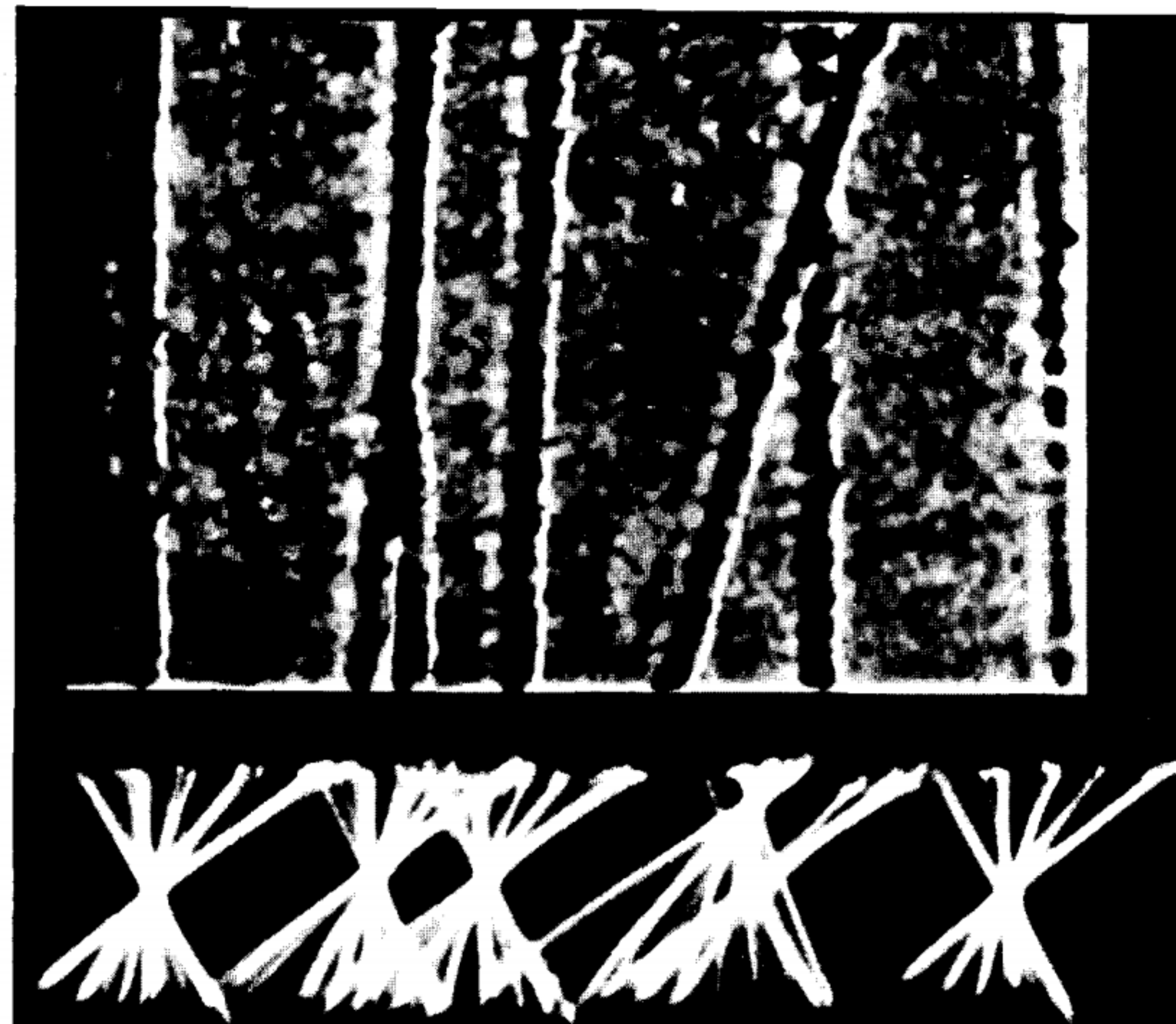
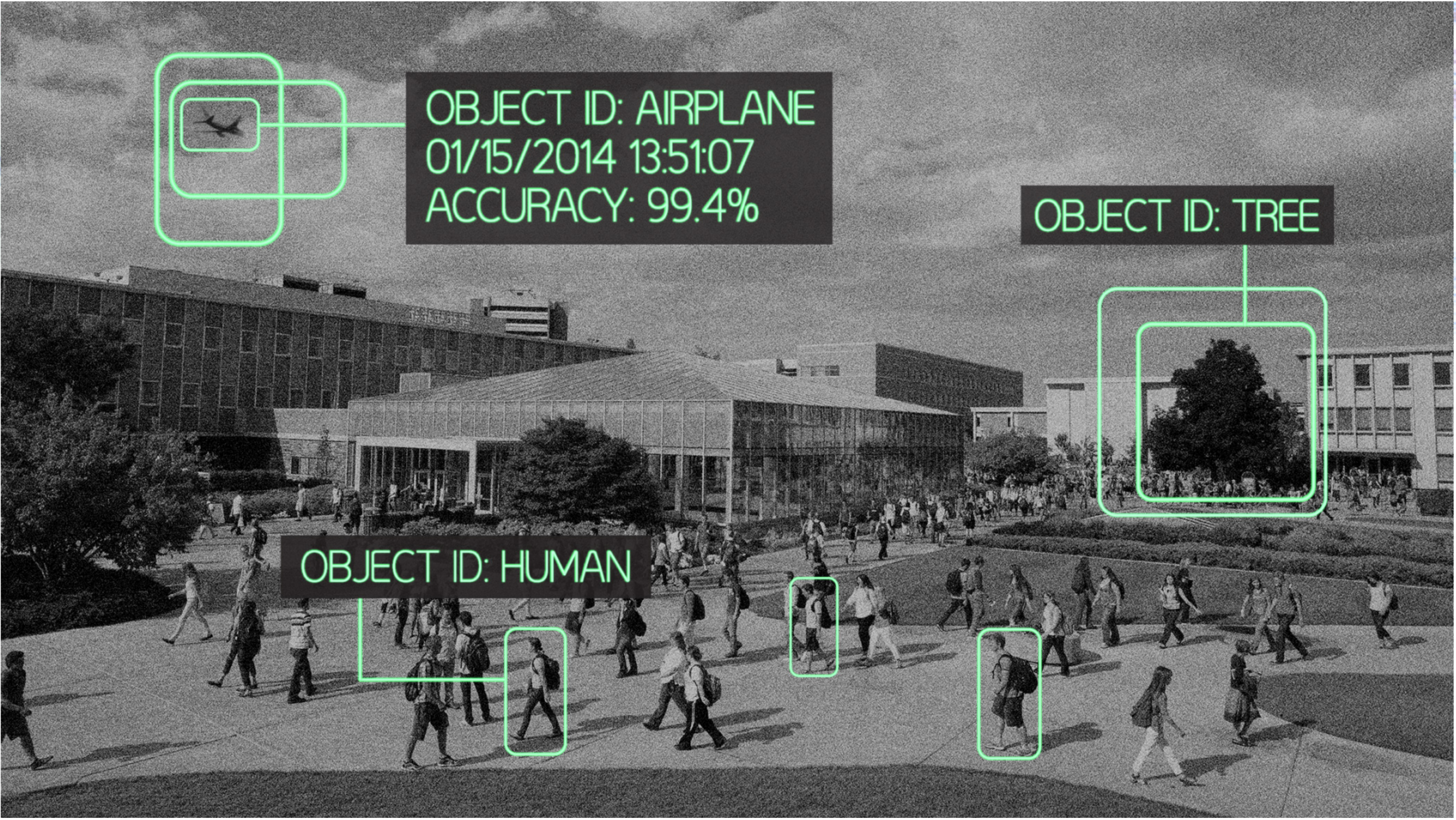


Fig. 3 A framelet giving a reasonably complex bubble pattern. The electronically-drawn transform appears at the bottom.

Proc. Int. Conf. High Energy Accelerators and Instrumentation, 1959

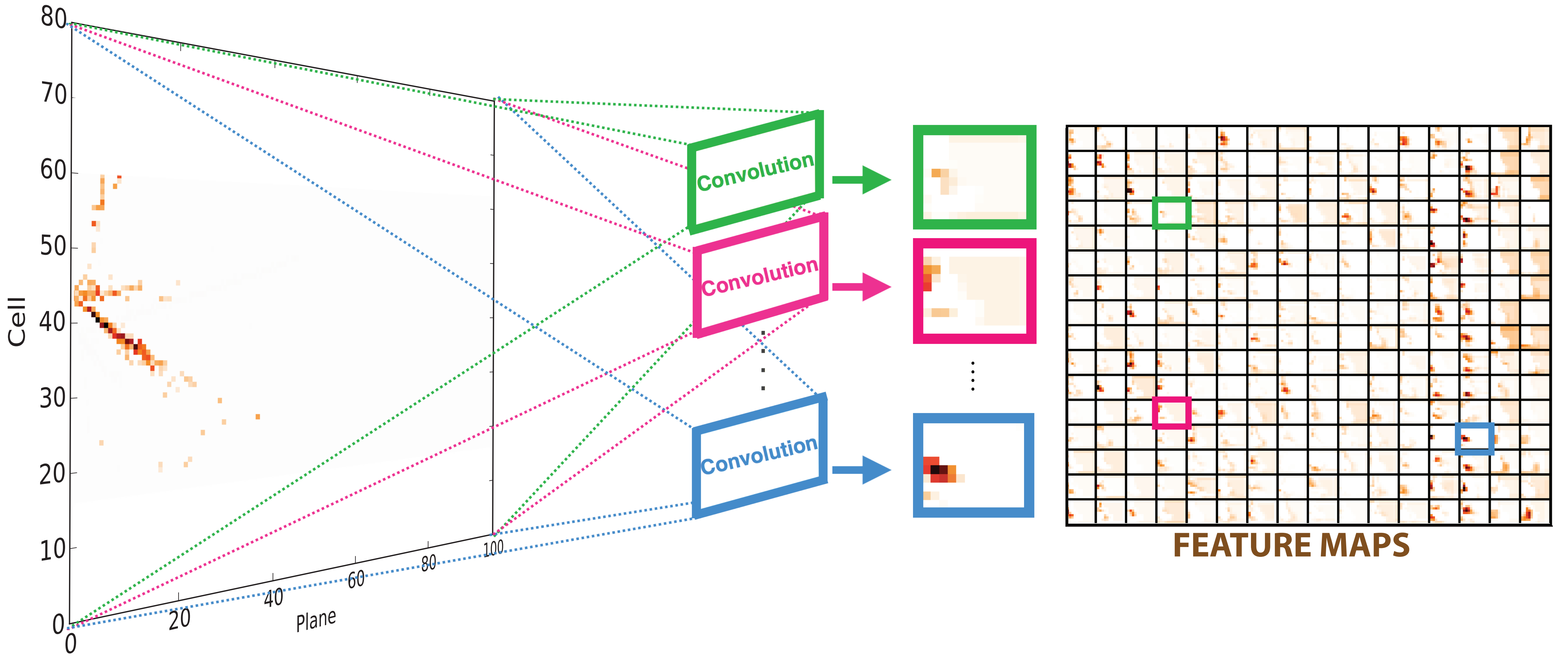


ν_e Event Identification in NOvA

Borrow ideas from Computer Vision:
Convolutional Neural Networks and Deep Learning

Application to NOvA events: A.~Aurisano et al., *A Convolutional Neural Network Neutrino Event Classifier*, JINST **11**, no. 09, P09001 (2016)

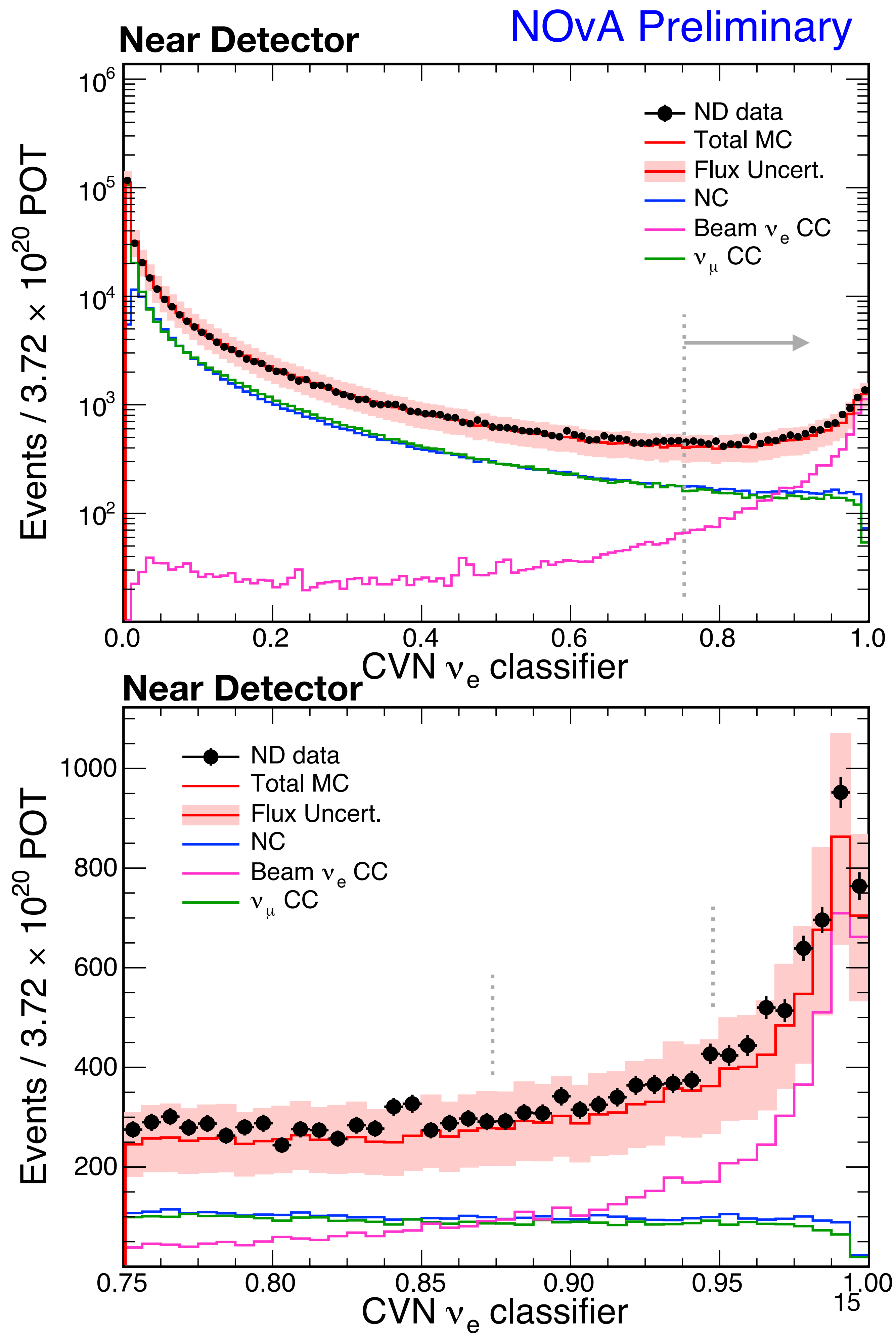
ν_e Identification in NOvA

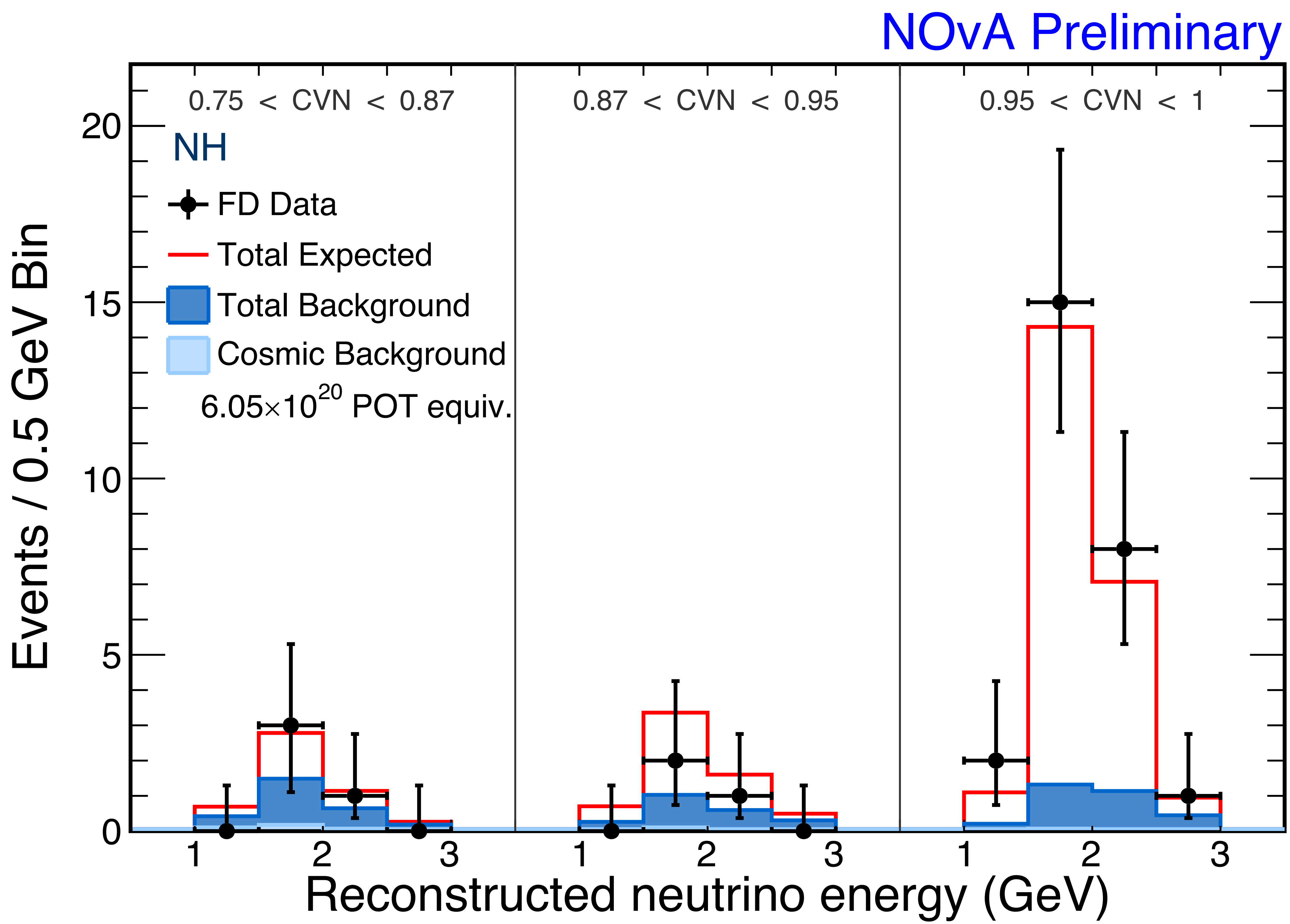


ELECTRON NEUTRINO

CVN Identifier on Near Detector Data

- CVN selects 73% of pre-selected electron-neutrino charged current events
- Produces a 76% pure sample of electron-neutrino CC events
- Improved S/N equivalent to 30% more exposure over techniques used in our first analysis

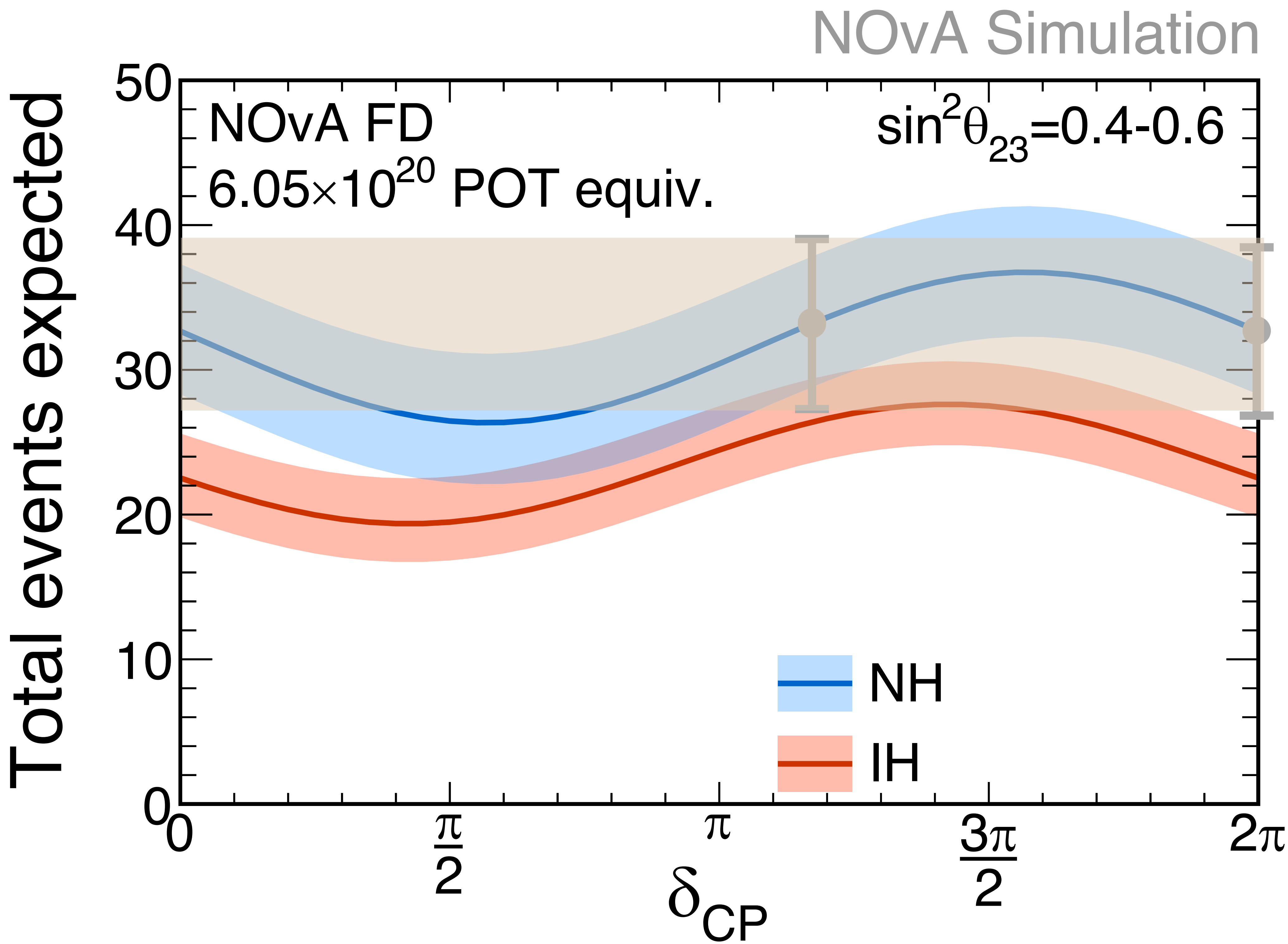




NOvA Electron Neutrino Appearance

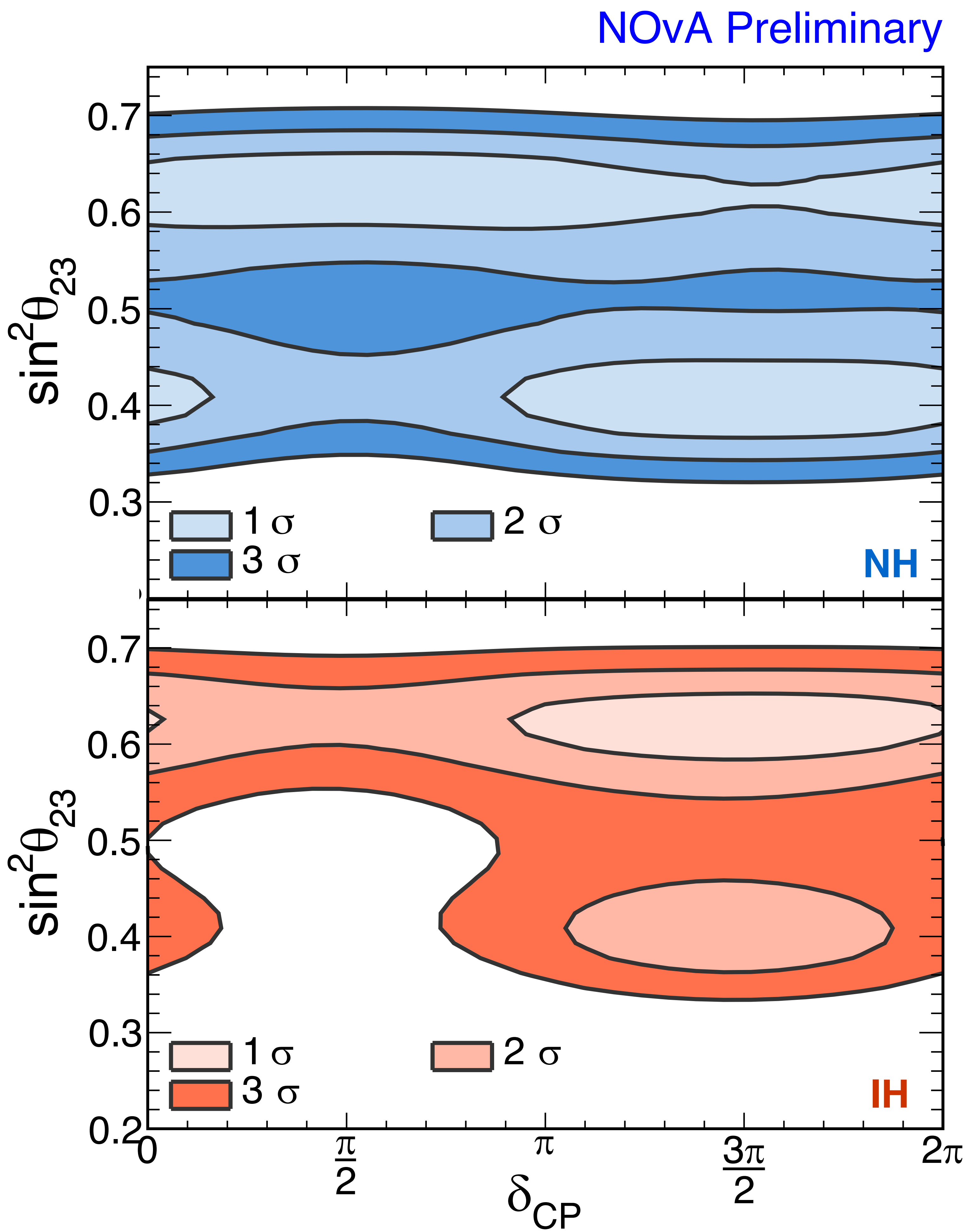
Observe 33 events at far detector
Expect 8 events of background
±5% error on signal
±10% on background

NOvA Electron Neutrino Appearance

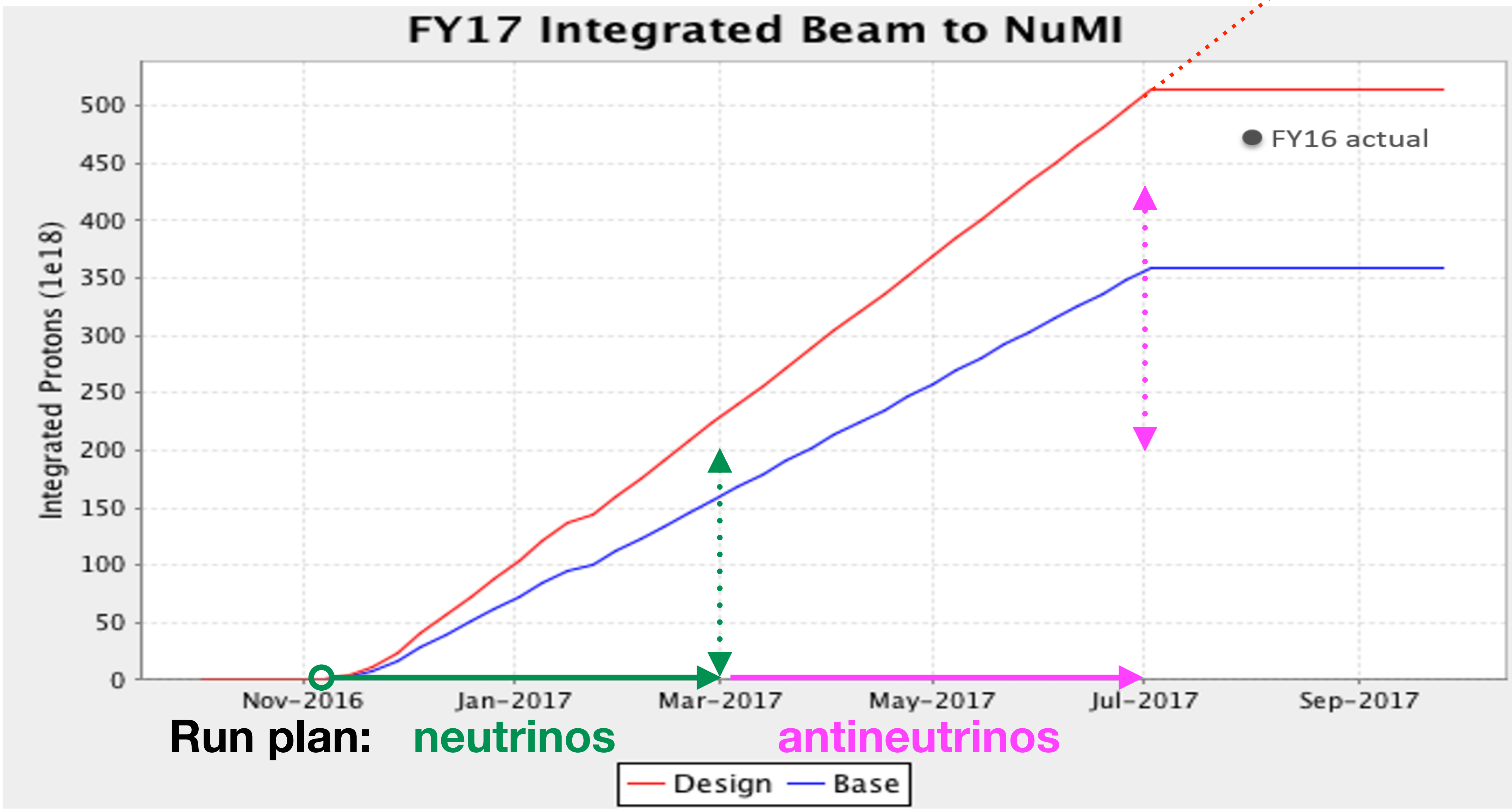


Electron Neutrino Appearance

- Rule out lower octant, inverted hierarchy at >3σ
- Resolution of remaining ambiguities requires antineutrino running
- Recorded 0.5E20 POT in antineutrinos at end of run. Will collect 3E20 POT in neutrinos and 3E30 POT in antineutrinos next year
- Current data sample is 1/6th of total planned running.



6E20 POT = 1 TDR Year

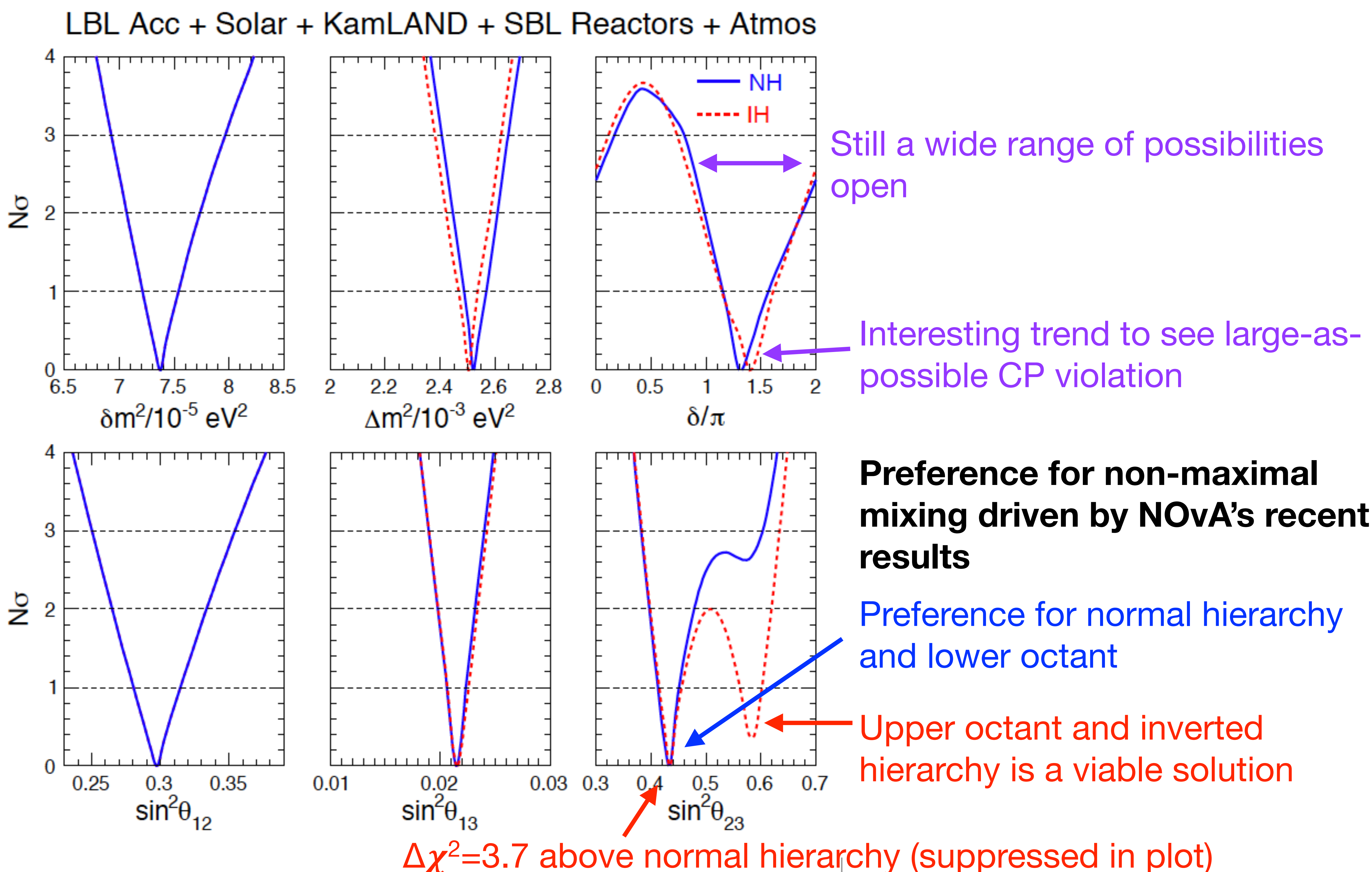


Projected FY17 Beam Delivery

Assumes 83% uptime
32 weeks of running
10% of time line to Switch Yard

NOvA Run Plan

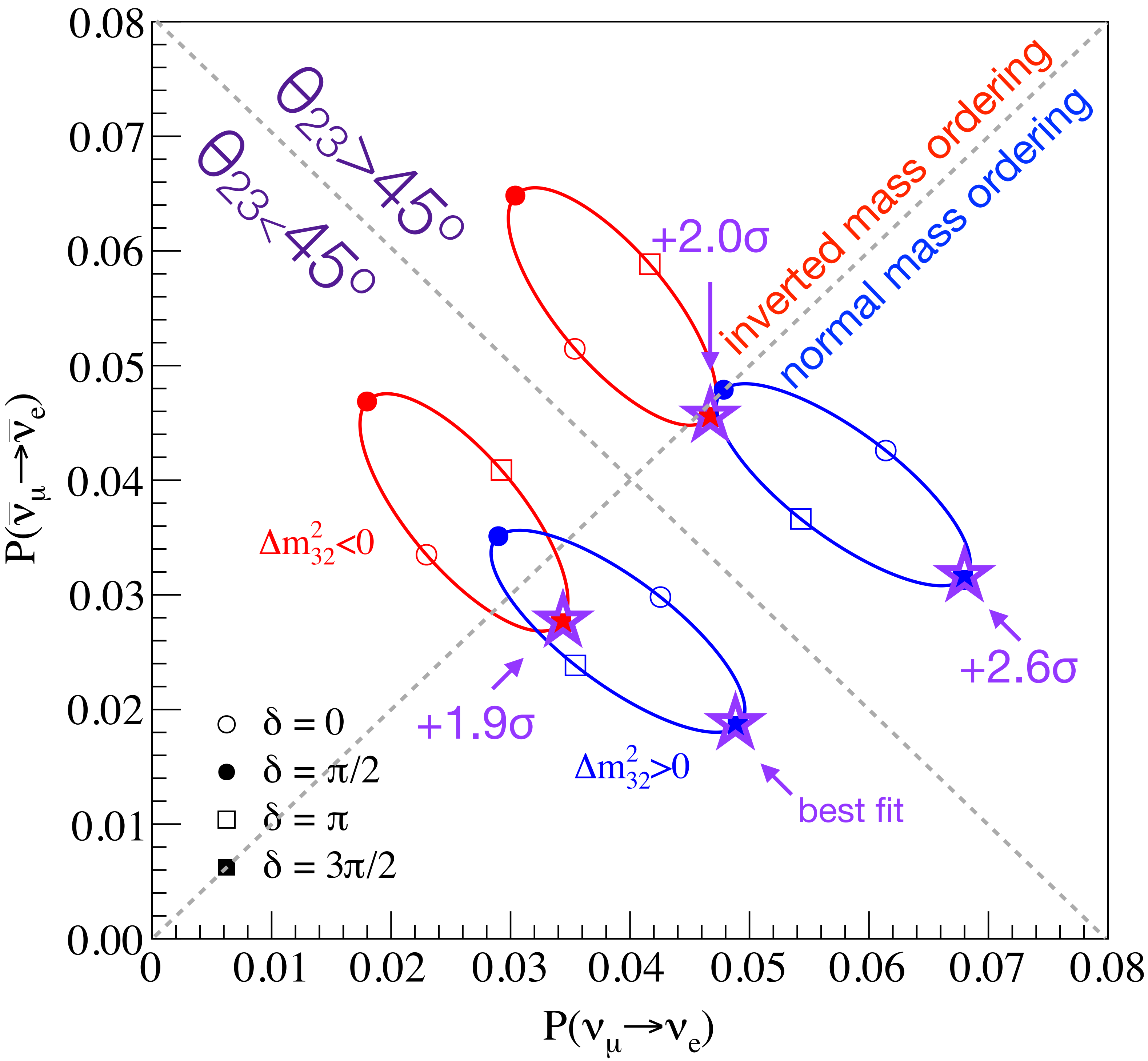
- Our ν_μ data favors non-maximal θ_{23} with 2.5σ significance. Implications:
    1. Opportunity to exclude maximal mixing with high confidence: Favors additional neutrino running.
    2. Opportunity to resolve the θ_{23} octant. Requires antineutrino running if θ_{23} is in lower octant
    3. If θ_{23} is in lower octant antineutrino running is required to resolve hierarchy.
- Our run plan seeks to take advantage of these opportunities and to clarify the situation as quickly as possible
    - **FY17**: **3E20 POT additional neutrino data** to clarify the ν_μ situation. Is θ_{23} really non-maximal? Can we push the significance beyond 3σ?
    - **FY17**: **3E20POT in antineutrinos** helps us achieve the optimal balance between neutrinos and antineutrinos for what appears to be the most likely scenario following Neutrino2016 (normal hierarchy, lower octant). 0.6E20POT collected in antineutrinos in FY16 optimizes our use of analysis time.
    - **FY18:** Run more antineutrinos



Post Neutrino2016 "global picture"

Francesco Capozzi (Lisi et al.) reporting at NOW2016

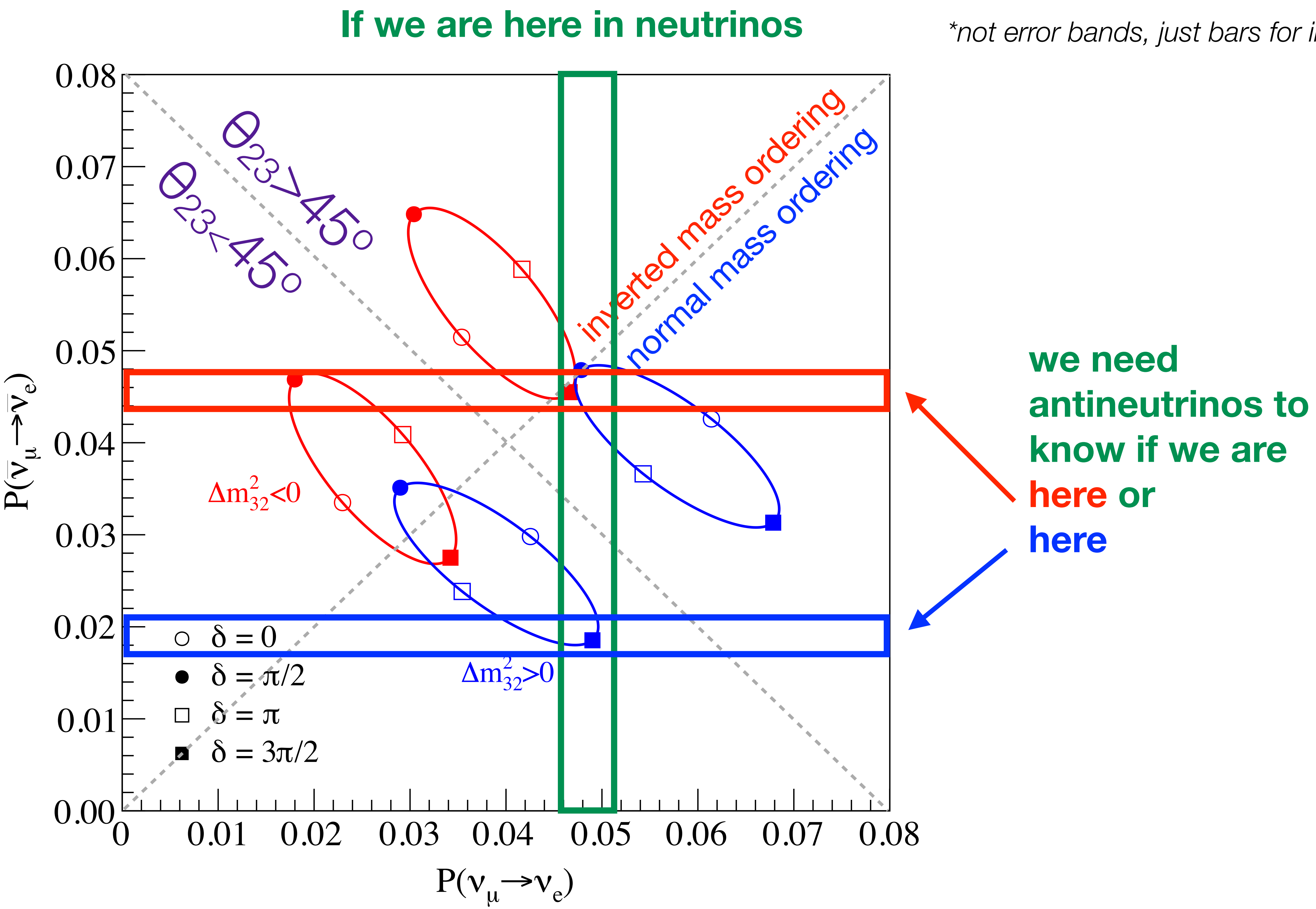
Taking that global fit at face value



Need for antineutrinos:

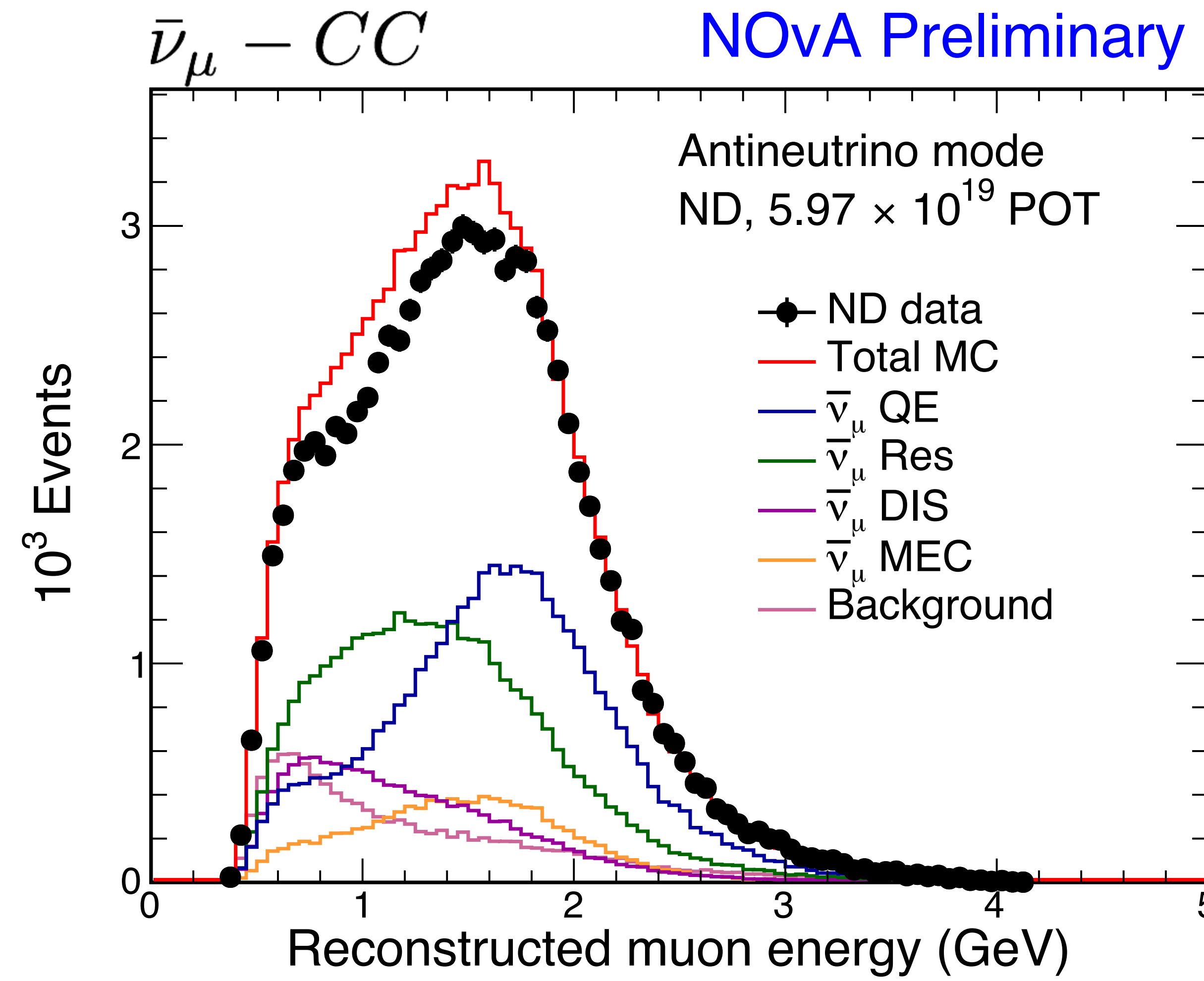
If we are in lower octant, normal hierarchy, antineutrinos are required.

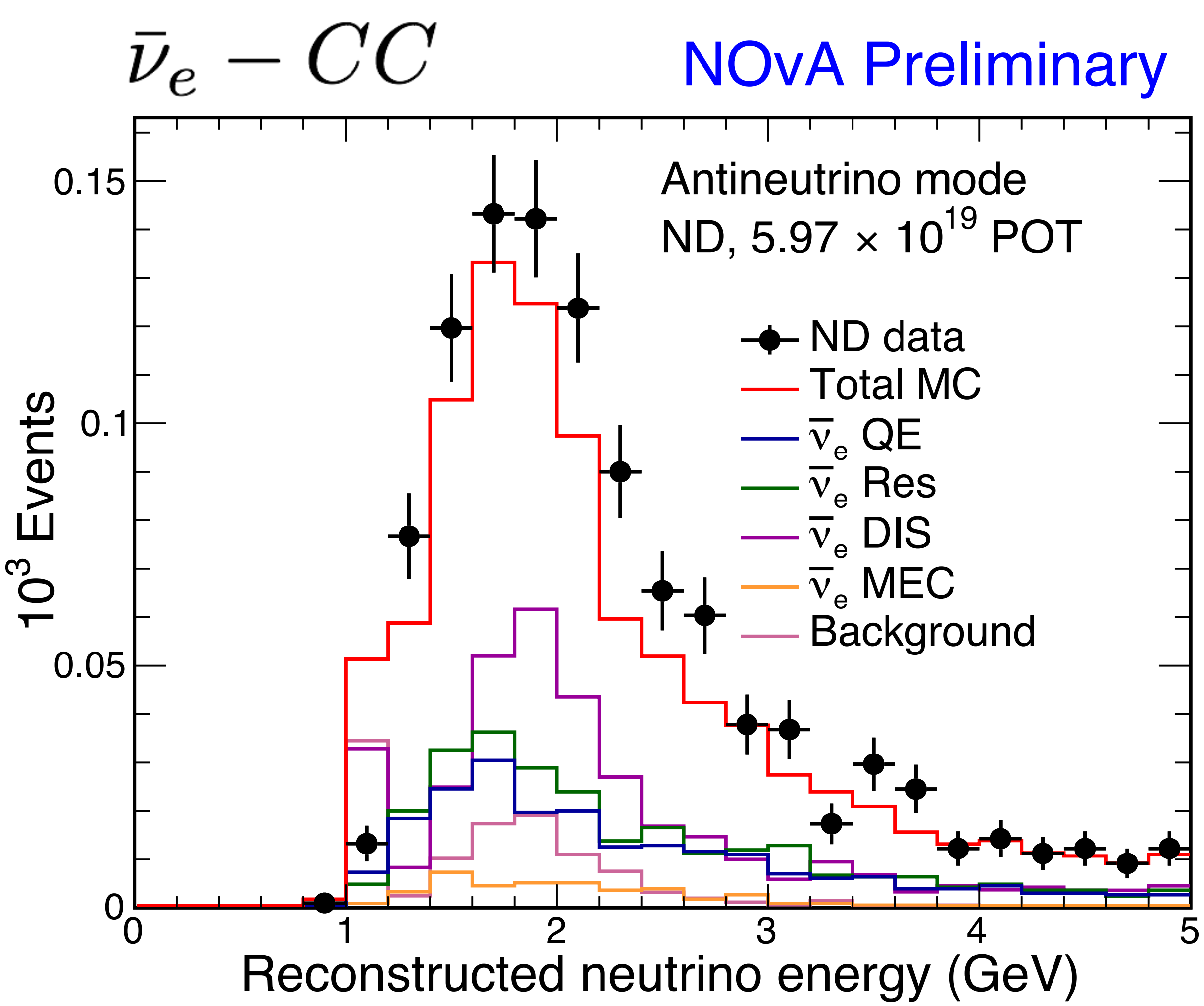
**not error bands, just bars for illustration*

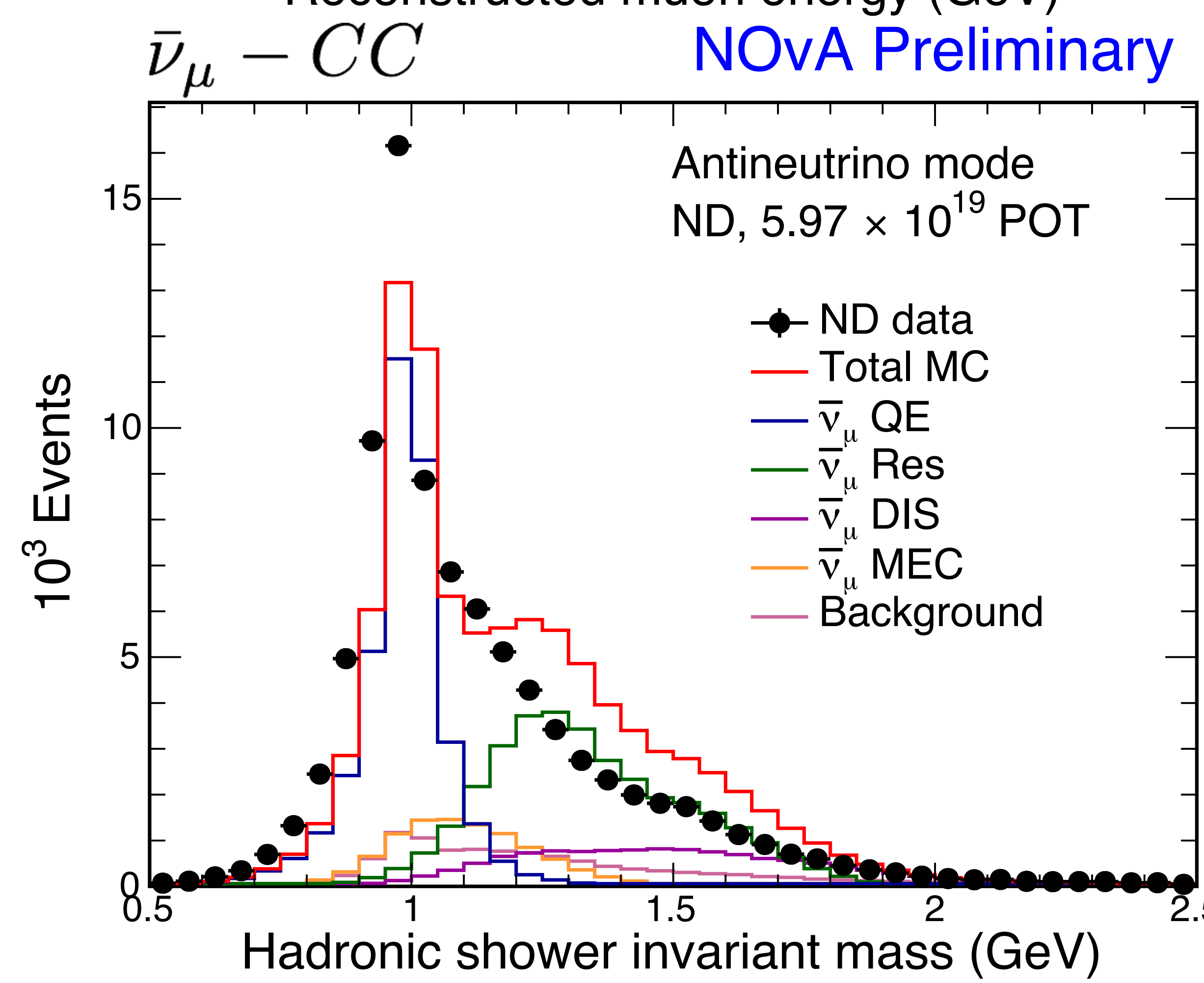


First look at 0.6E20 POT taken in antineutrinos

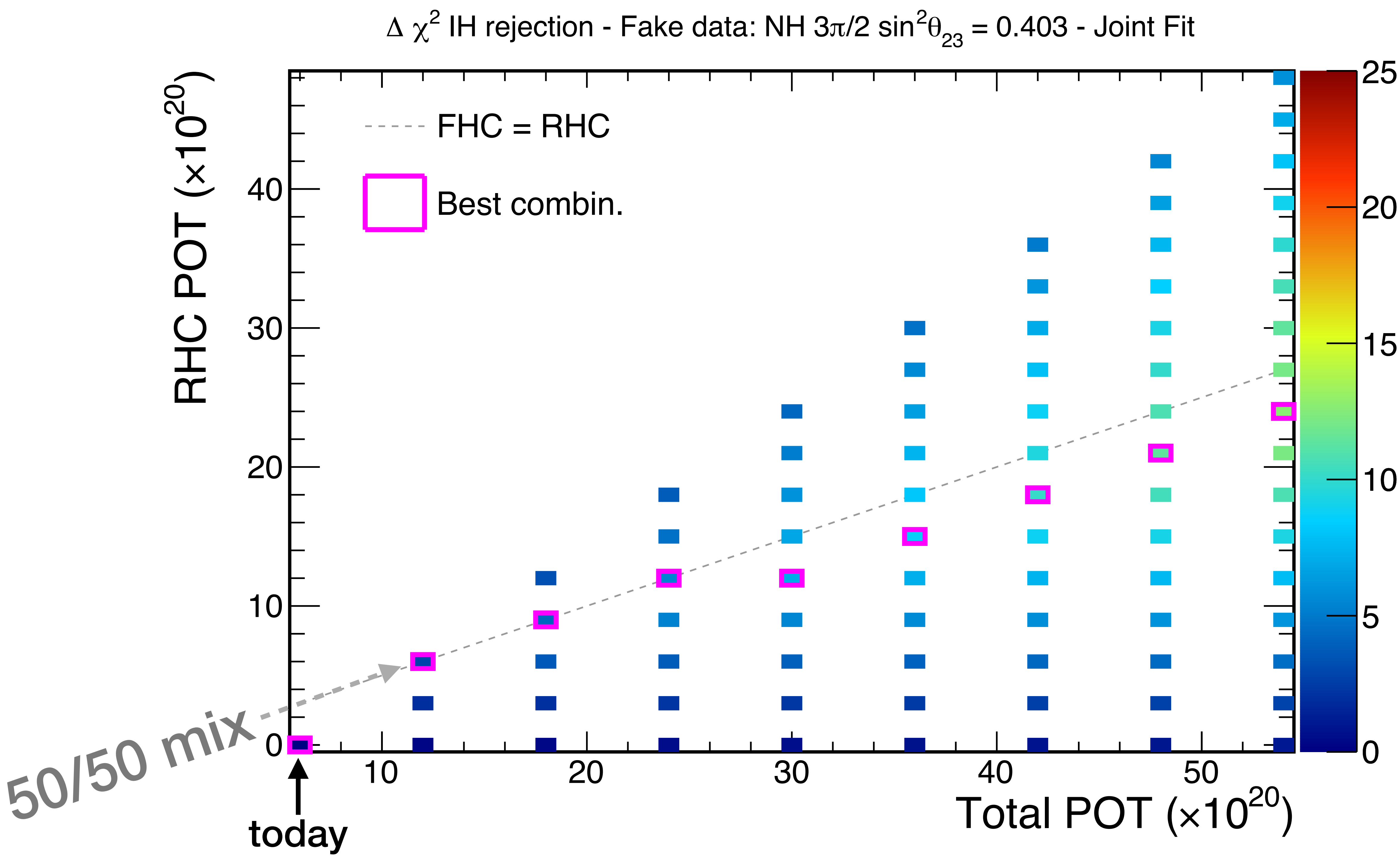
- We spent most of July 2016 in antineutrino mode
- Goal was to accumulate a sizable data in the near detector to jump start analysis work for the longer antineutrino run to begin in mid 2017
- A few sample distributions for electron-neutrino events (below) and muon neutrinos (right) show that while many things are in reasonable agreement, many things (mostly cross-sections) will need to be tuned up — in progress.



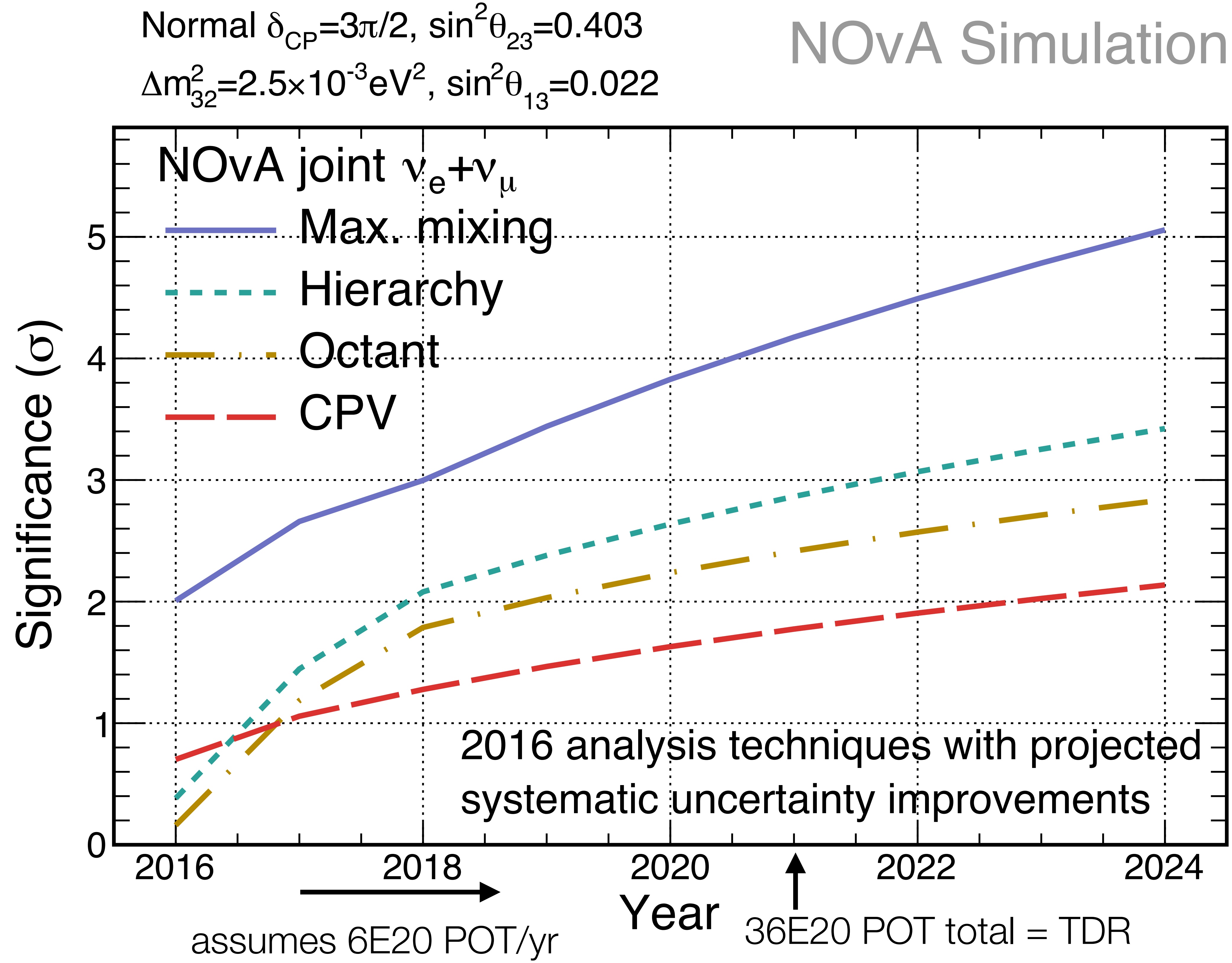




An optimal neutrino / antineutrino mix
Normal hierarchy / lower octant



year-by-year a 50/50 allocation of protons is very close to optimal



Projected NOvA physics reach

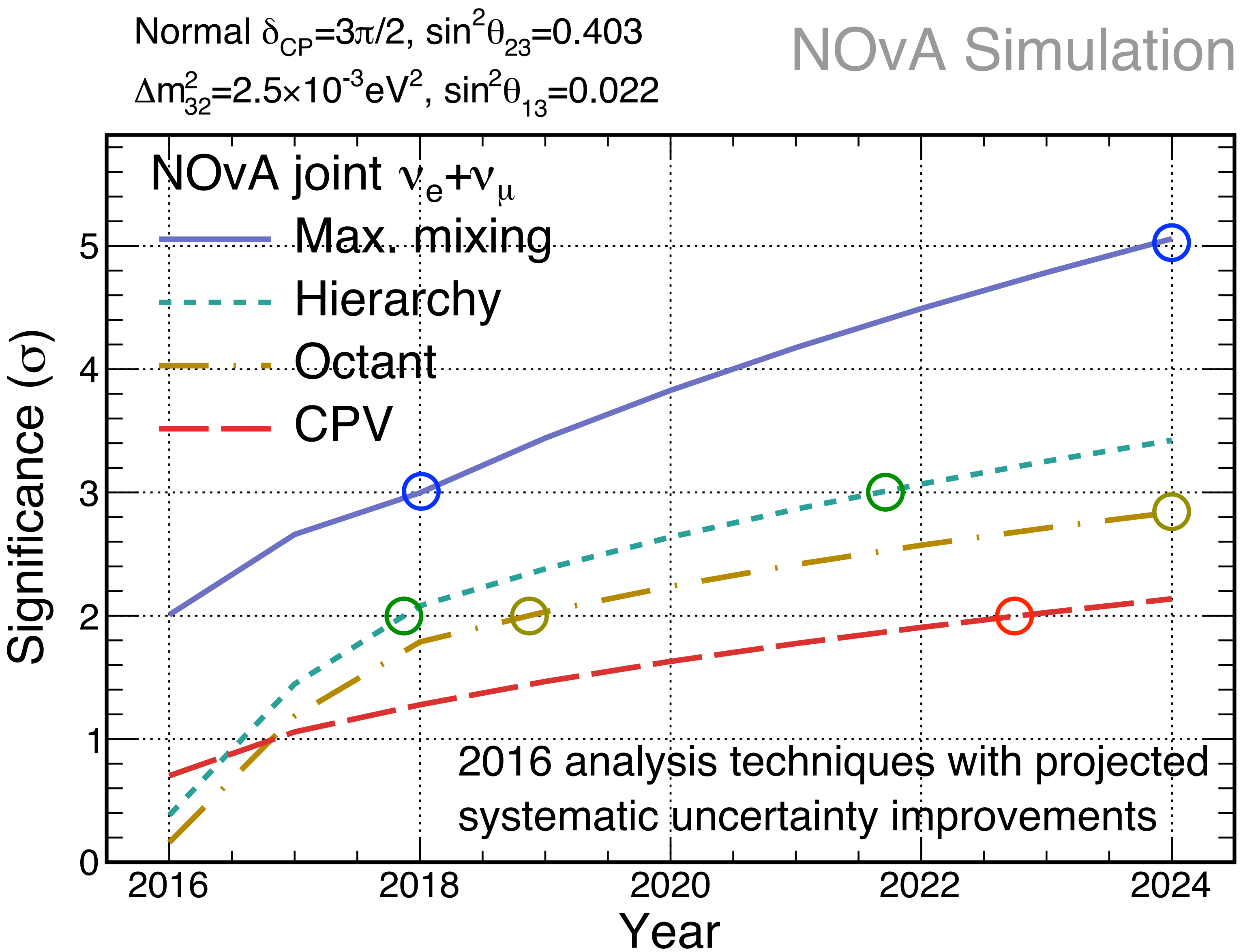
50/50 run plan for normal hierarchy lower octant

Assumes uncertainties are reduced to

- νe: 2% signal / 5% background
- νμ: 2% muon energy scale, 3% hadronic energy, very small NC backgrounds

NOvA Physics Milestones

- The most likely scenario emerging from Neutrino2016 presents Fermilab with the opportunity to lead in neutrino science.
- NOvA has an opportunity for breakthroughs on all its major physics goals



θ_{23}

2018: >3σ exclusion of maximal θ_{23}

2019: >2σ octant determination

2024: >5σ exclusion of maximal θ_{23}*

2024: ~3σ octant determination*

Mass Hierarchy

2018: >2σ determination

2022: >3σ determination*

CP violation (sinδ≠0)

2023: >2σ observation of CPV*

***** *opportunities enabled by higher than TDR proton delivery***

Mass Hierarchy: JUNO

JUNO Experiment

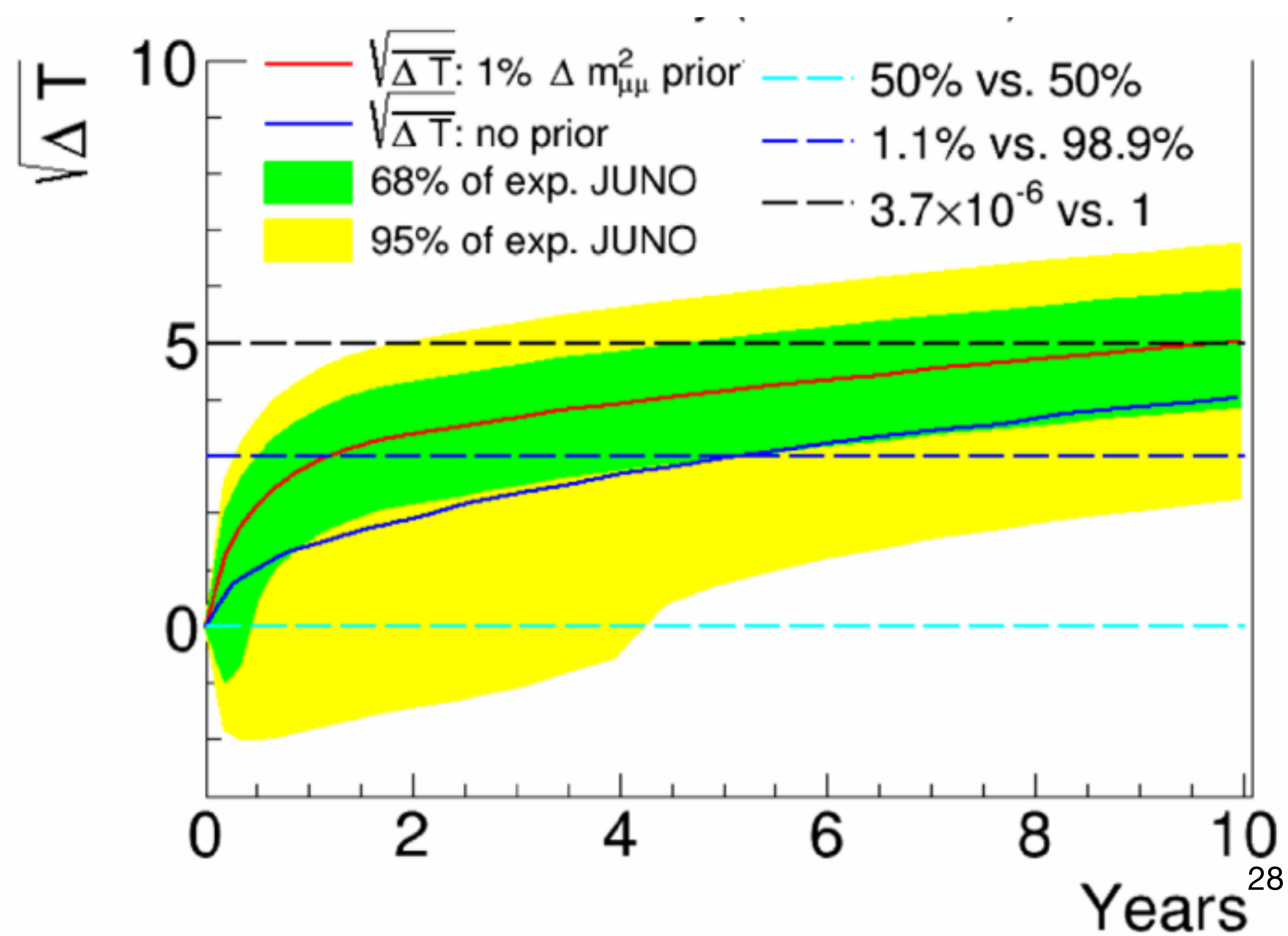
- 20 kt liquid scintillator
- 20+ GW
- L=50 km

Schedule

- Civil construction: 2013-2017
- Detector construction & installation 2016-2019
- Filling and data taking: 2020

Mass hierarchy reach

- 3σ in 2 to 5 years: 2022-25
- 5σ in 10 years: 2030



Mass Hierarchy: ORCA

ORCA / KM3NET Experiment

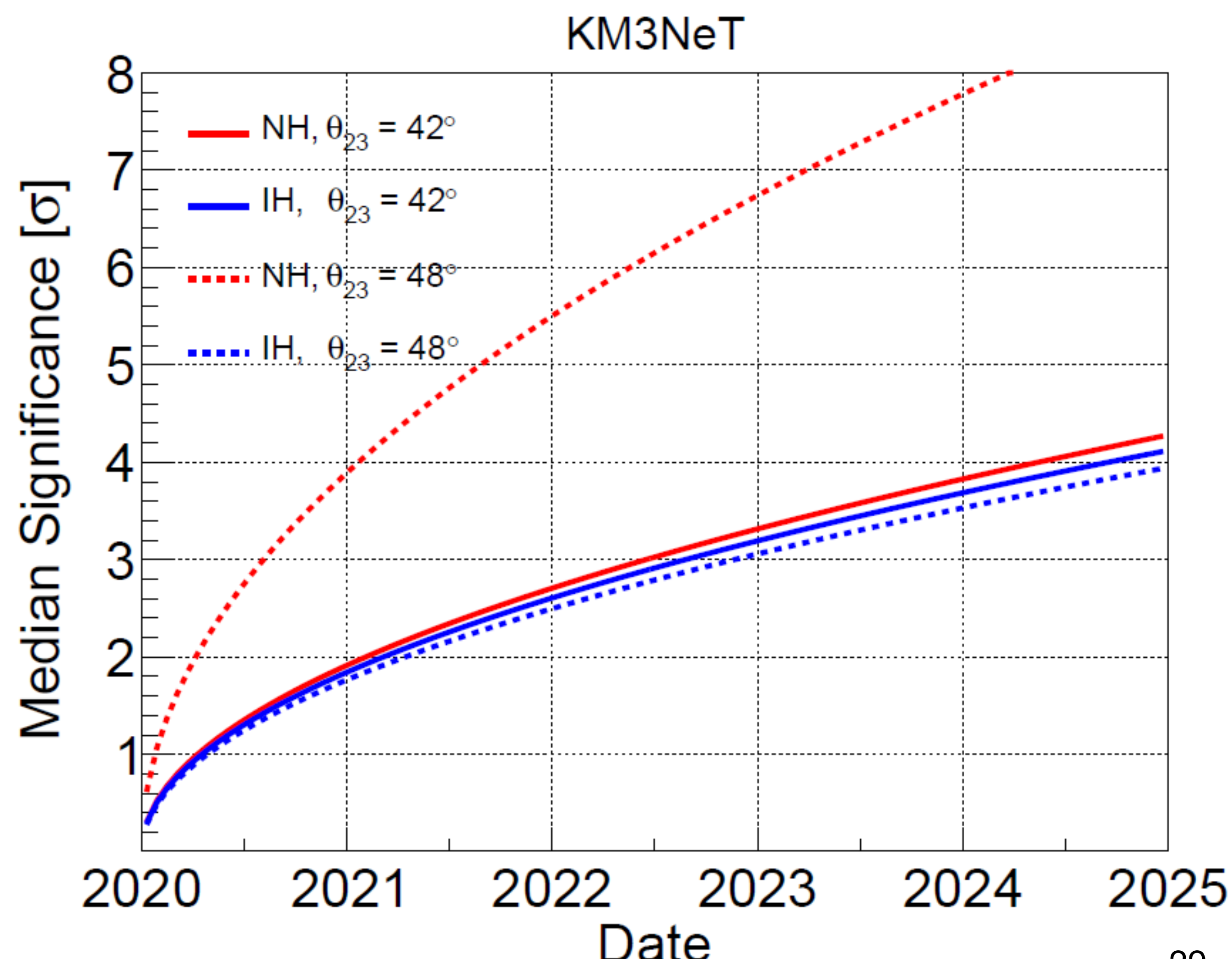
- 1.8 Mton of instrumented sea water
- Search for resonance in Earth core in atmospheric neutrinos

Schedule

- Construction through 2020

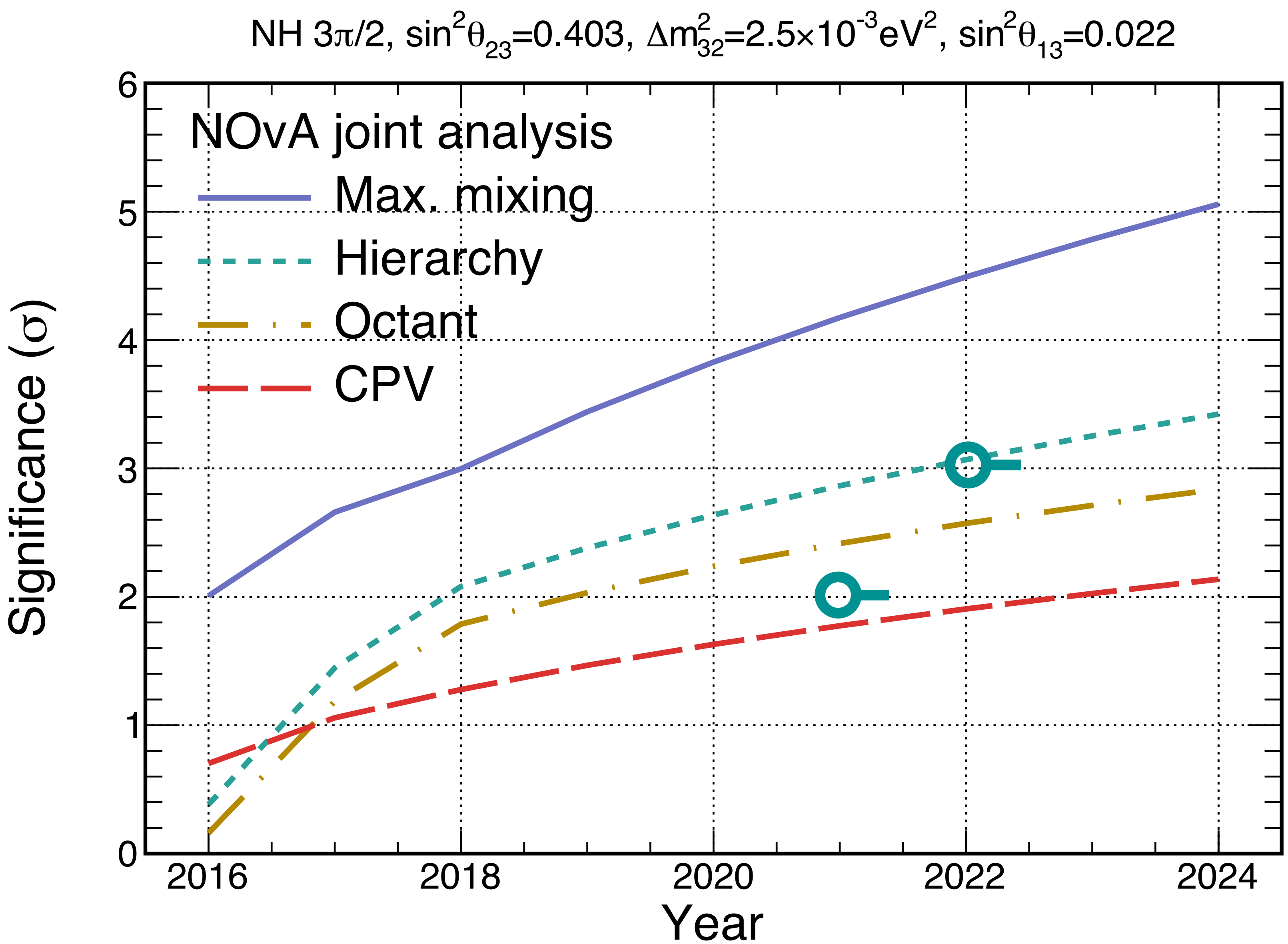
Mass hierarchy reach

- 3σ in 3 years ~2023, maybe faster
- 5σ possible faster



Competition

This opportunity is not unique to Fermilab. There are several projects hoping to capitalize on this opportunity.



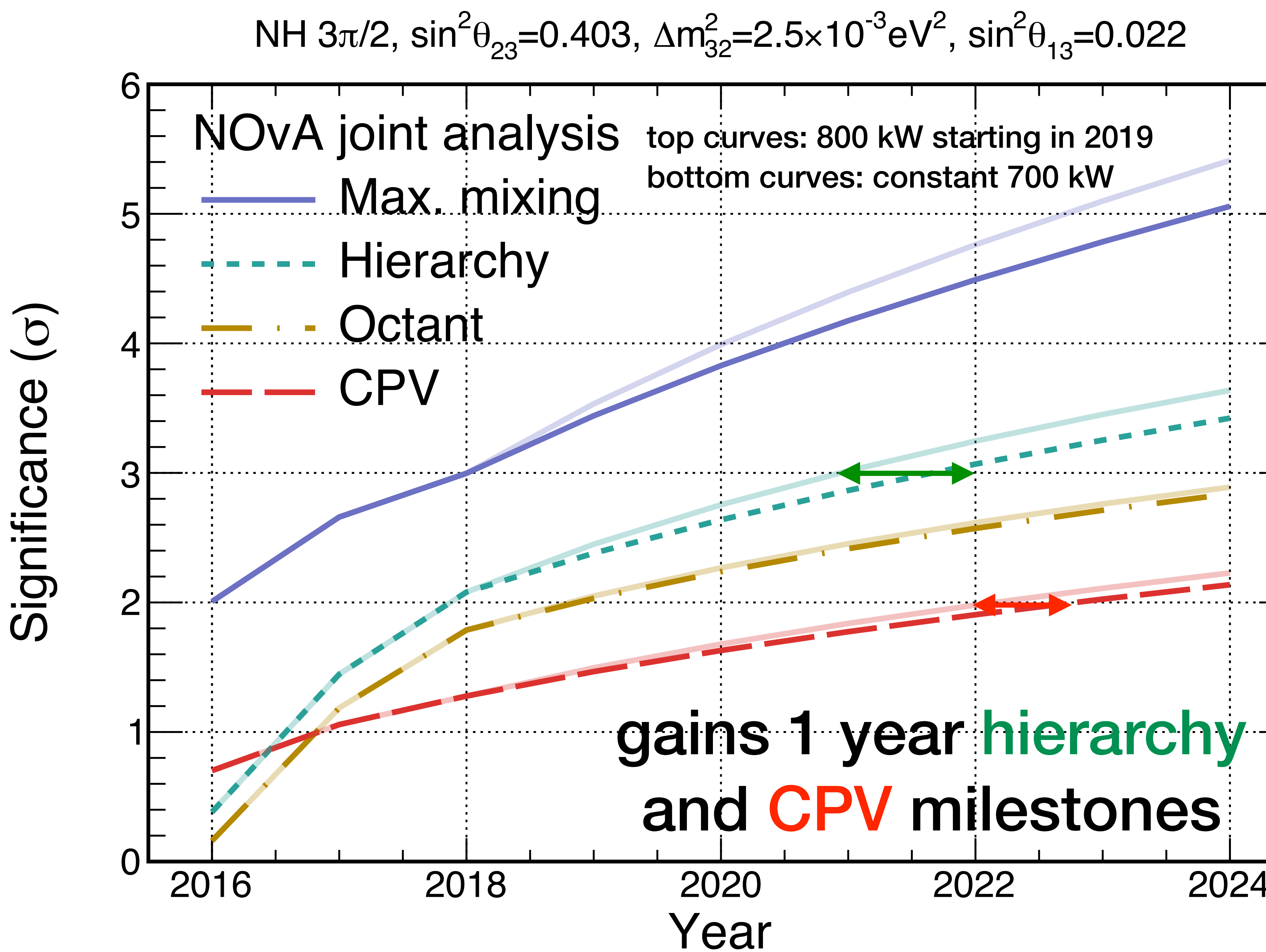
Both **JUNO** and **ORCA** have construction underway.
Nearly identical schedules for mass hierarchy reach:

- 2σ as early as 2021
- 3σ as early as 2022

A Super-K + T2K combination gives roughly 2σ

Other competition from, global fits, and cosmology fits.

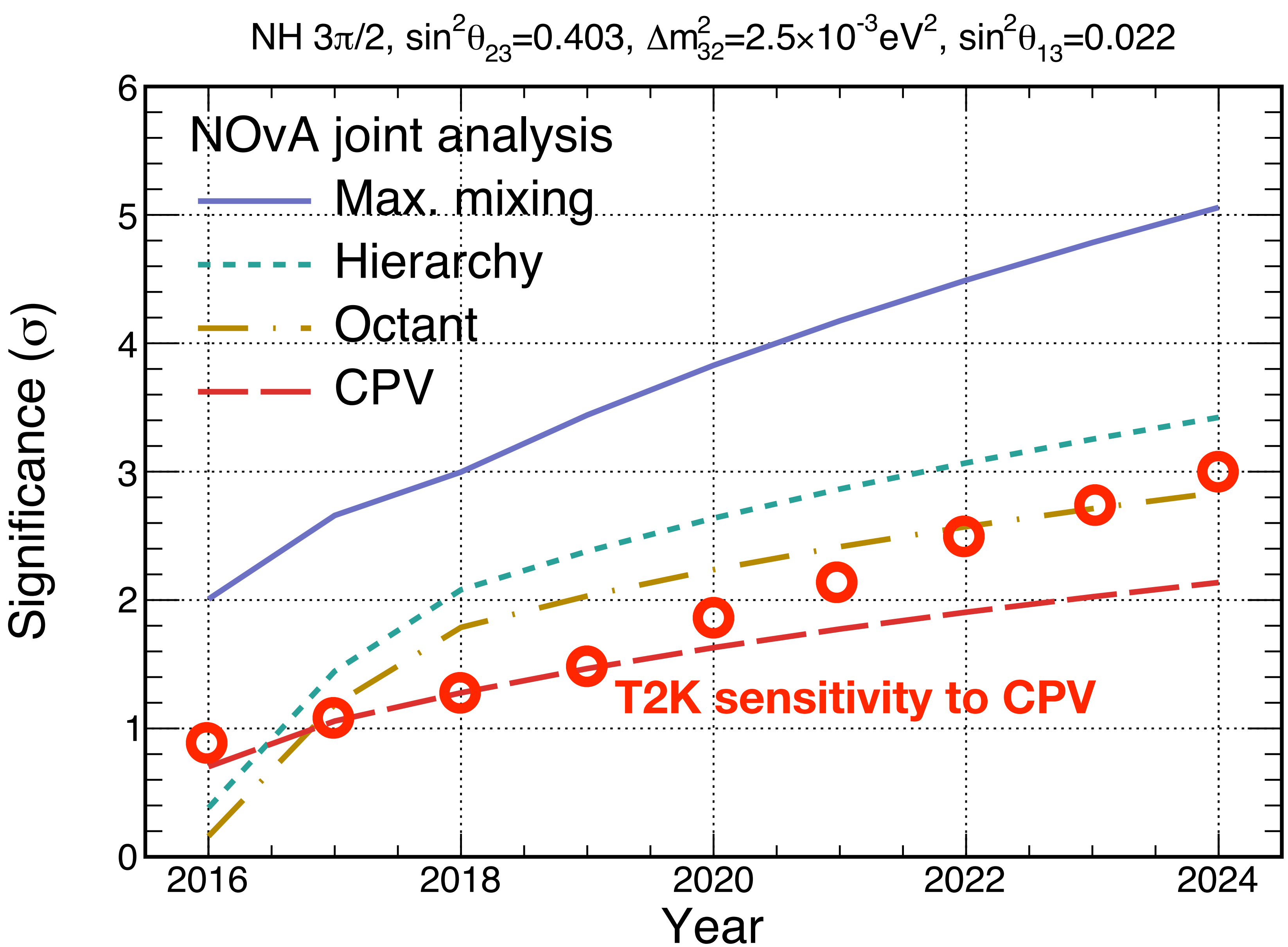
Assume NOvA beam delivery goes from 6E20 to 7E20 / year starting in 2019



Competition

T2K has proposed an extended run to get 3σ sigma evidence for CPV

(arXiv:1607.08004v1 [hep-ex] 27 Jul 2016)



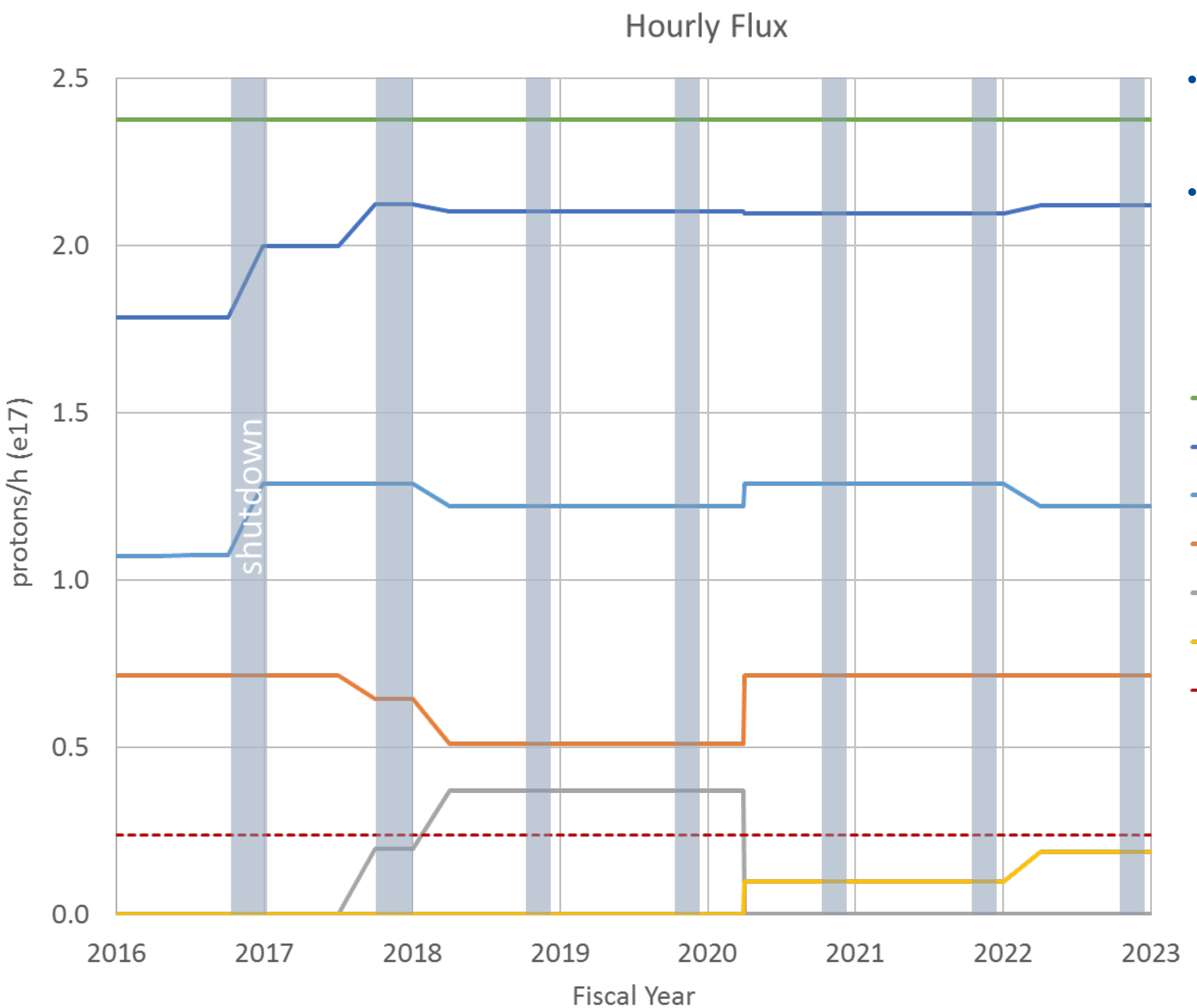
Until 2020 NOvA running flat-out and T2K have same CPV reach.

T2K beam power ramps from current 420 kW to 770 kW by 2020 (surpassing NuMI power) and then to 1.1+ MW by 2023. Assumes 5 months / year beam allocation for T2K

This plus analysis improvements drives the CPV reach of T2K to 3 sigma in 2024.

Projections Summary

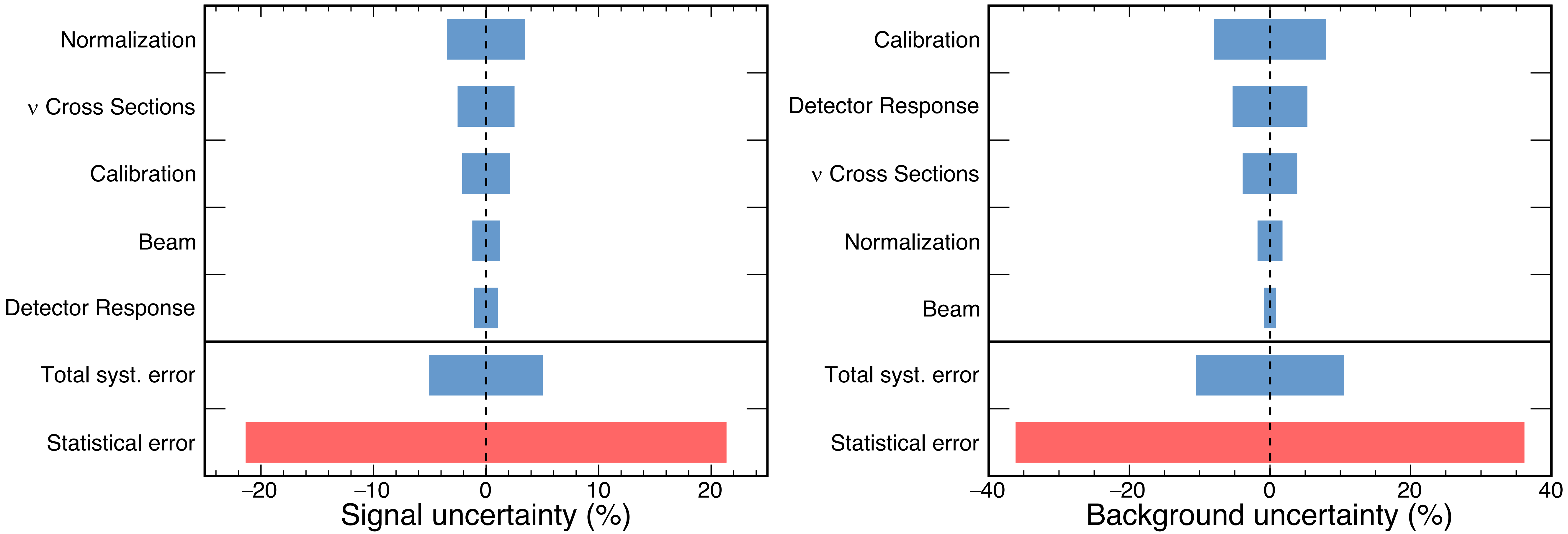
- Over the next decade Fermilab has an opportunity to lead the world in neutrino measurements
    - Non-maximal θ_{23}
    - θ_{23} octant
    - Neutrino mass hierarchy
    - CP violation
- To realize this we continue to
    - Operate the detectors at high efficiency
    - Push analysis to increase efficiency, reduce backgrounds, and reduce systematics
    - Push on beam delivery
- Beam delivery continues to ramp toward TDR design parameters 6E20 POT/yr.
- NOvA can achieve these milestones before 2024:
    - 5 sigma exclusion of maximal 23 mixing
    - 3 sigma resolution of octant
    - 3 sigma mass hierarchy determination
    - 2 sigma CPV sensitivity
- Higher rate of beam delivery can advance milestones by 1 year which may be important to maintain NOvA and Fermilab's leading role in these measurements in the 2020's



- Does not take into account uptime efficiencies, etc
- Assumes 4.4E12 ppp to BNB (last week 4.7E12)

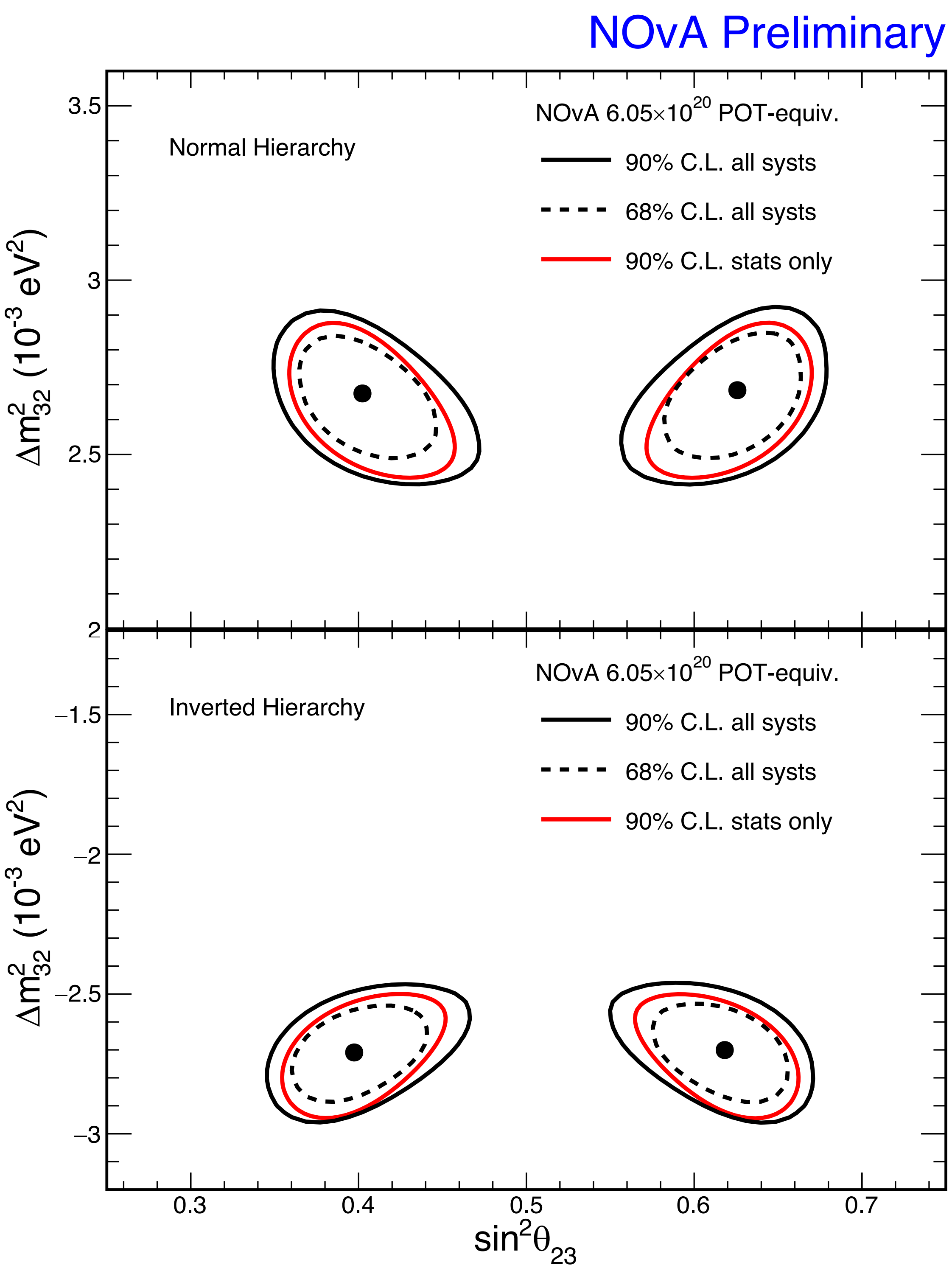
Proton flux evolution

Mary Convery
3 March 2016 PMG



Electron neutrino systematic uncertainties

left: Signal uncertainties
right: Background uncertainties



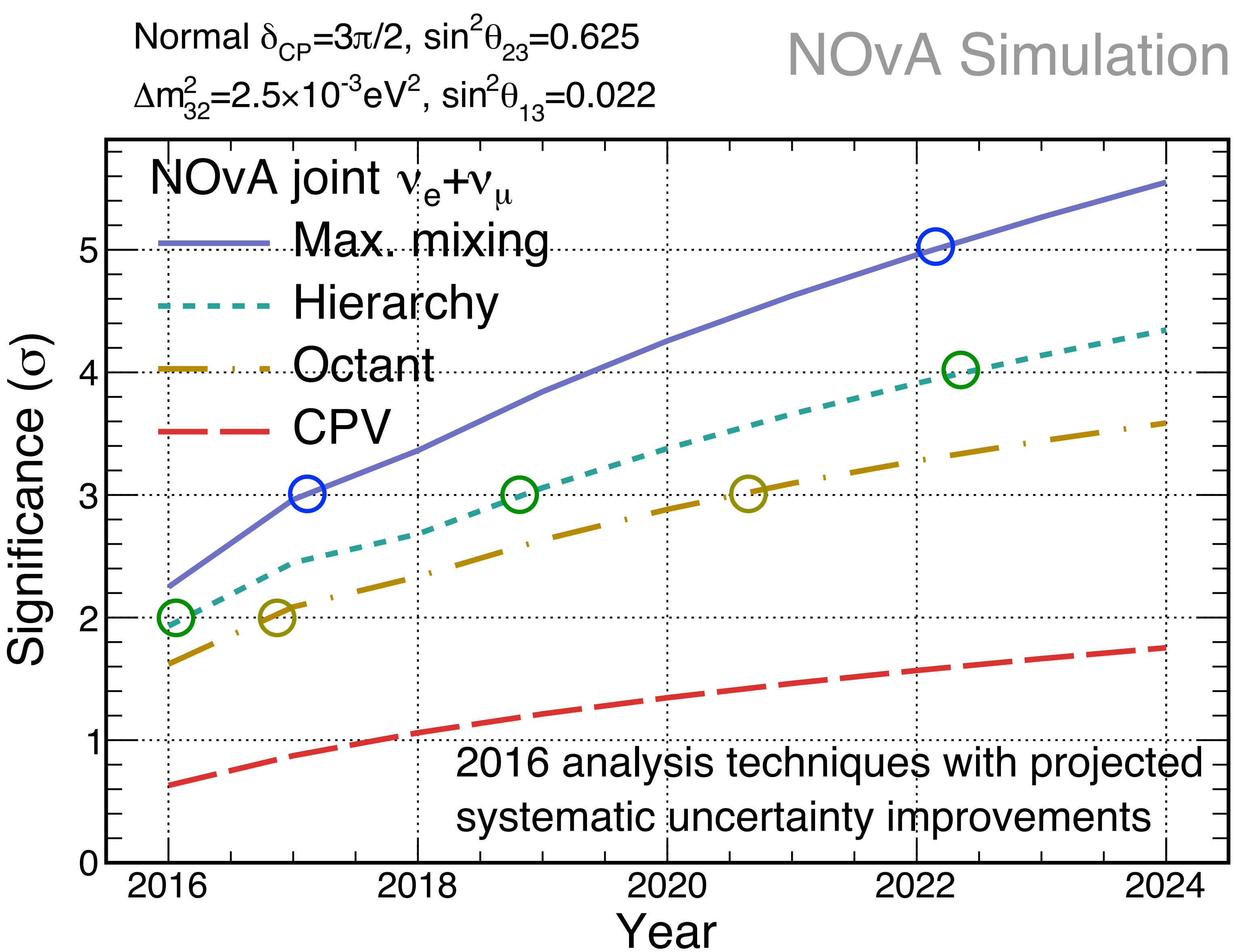
Systematic	Effect on $\sin^2(\theta_{23})$	Effect on Δm^2_{32}
Normalisation	± 1.0%	± 0.2 %
Muon E scale	± 2.2%	± 0.8 %
Calibration	± 2.0 %	± 0.2 %
Relative E scale	± 2.0 %	± 0.9 %
Cross sections + FSI	± 0.6 %	± 0.5 %
Osc. parameters	± 0.7 %	± 1.5 %
Beam backgrounds	± 0.9 %	± 0.5 %
Scintillation model	± 0.7 %	± 0.1 %
All systematics	**± 3.4 %**	**± 2.4 %**
Stat. Uncertainty	**± 4.1 %**	**± 3.5 %**

Muon neutrino systematic uncertainties

left: Impact of systematics on current contours
right: Table of systematic impacts on mixing and mass splitting

NOvA Physics Milestones

- Recompute milestones for best fit parameters in upper octant



Start from 2016 exposure and extrapolate forward at design proton intensity. Assumes some improvement in systematic uncertainties over current analysis.

θ_{23}

2017: >3σ exclusion of maximal θ_{23}

2017: >2σ octant determination

2022: >5σ exclusion of maximal θ_{23}*

2021: ~3σ octant determination*

Mass Hierarchy

2018: >2σ determination

2019: >3σ determination*

2022: >4σ determination

CP violation (sinδ≠0)

2023: 1.8σ CPV sensitivity

**** opportunities enabled by higher than TDR proton delivery***