



Status of the NOvA Experiment

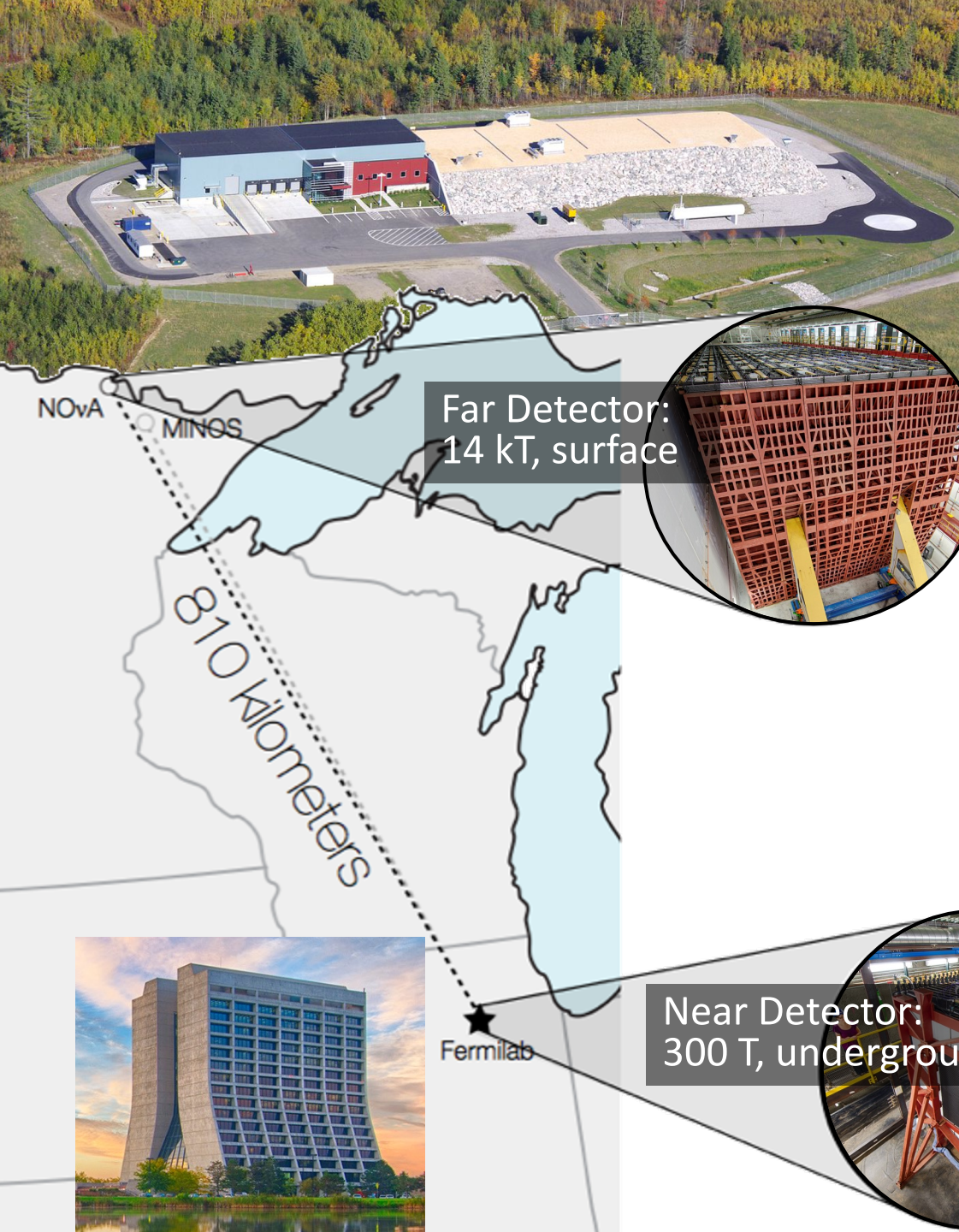
Alex Himmel, Tricia Vahle

Fermilab Physics Advisory Committee Meeting

November 16th, 2021

The NOvA Experiment

- Long-baseline neutrino oscillation experiment
 - 2 functionally identical, tracking calorimeter detectors
 - NuMI beam: ν_μ or $\bar{\nu}_\mu$
 - Off-axis, narrow beam
- Broad physics program:
 - 3-flavor oscillations
 - Exotic oscillations
 - Neutrino scattering
 - Astrophysics
 - BSM physics



NOvA Collaboration

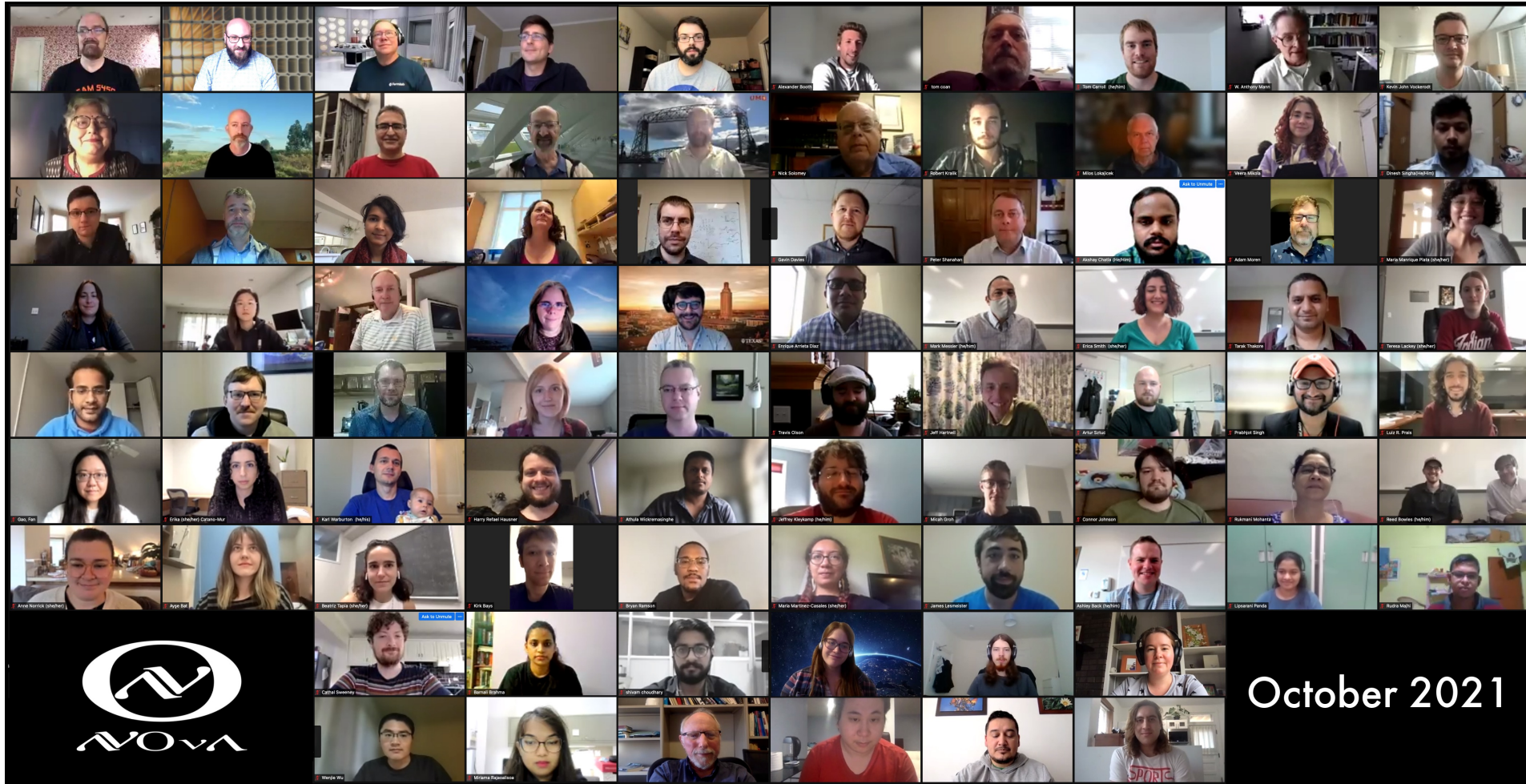
266 collaborators at 49 institutions across 8 countries



25 Remote Control Rooms across the globe

NOvA Collaboration

266 collaborators at 49 institutions across 8 countries



49 PhD theses and 12 Masters theses

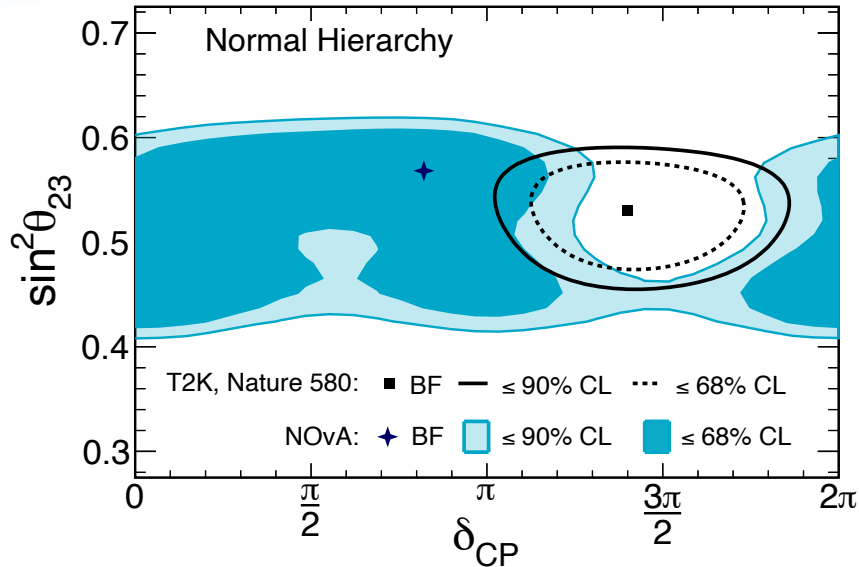
14 new PhDs since last May!

PAC Charge

- We ask the committee to **review the status** of the NOvA experiment and to comment on the **expected sensitivity** for neutrino oscillations and neutrino mass hierarchy as a function of the PoT. The PAC will also be asked to review the status of the **combination of the NOvA and T2K results** as well as the status of the two recommendations made at the July 2020 PAC meeting:
 - The Laboratory should continue to **prioritize operations and computing resources** required for the NOvA collaboration to produce its oscillation results on the full planned dataset before the planned long shutdown for LBNF. Maintaining and even increasing the strength of the NOvA collaboration to exploit this data should be a high priority.
 - The Collaboration should consider ways to engage scientists outside the collaboration who may be able to bring new effort to **analysis of the NOvA data for studies of neutrino interactions or BSM physics topics.**

Recent Results from NOvA

NOvA Preliminary



2021 NOvA Papers

3-flavor Oscillations
submitted to *Phys. Rev. D*

ν_μ CC Inclusive Cross Section
submitted to *Phys. Rev. D*

Long-baseline sterile neutrino
search in antineutrinos
Phys. Rev. Letters

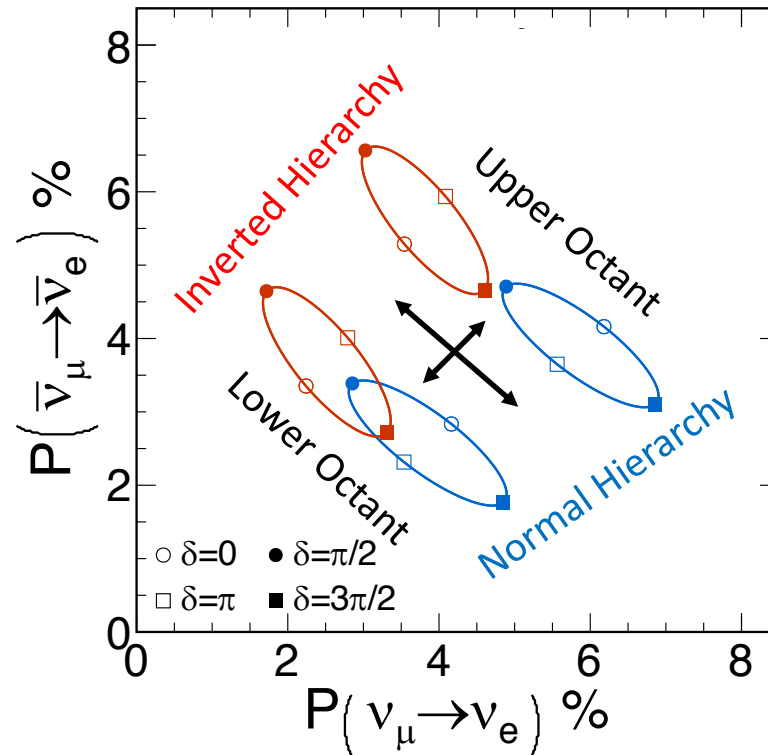
Search for LIGO coincidences
Phys. Rev. D

Multi-muon seasonal variations
at the Far Detector
Phys. Rev. D

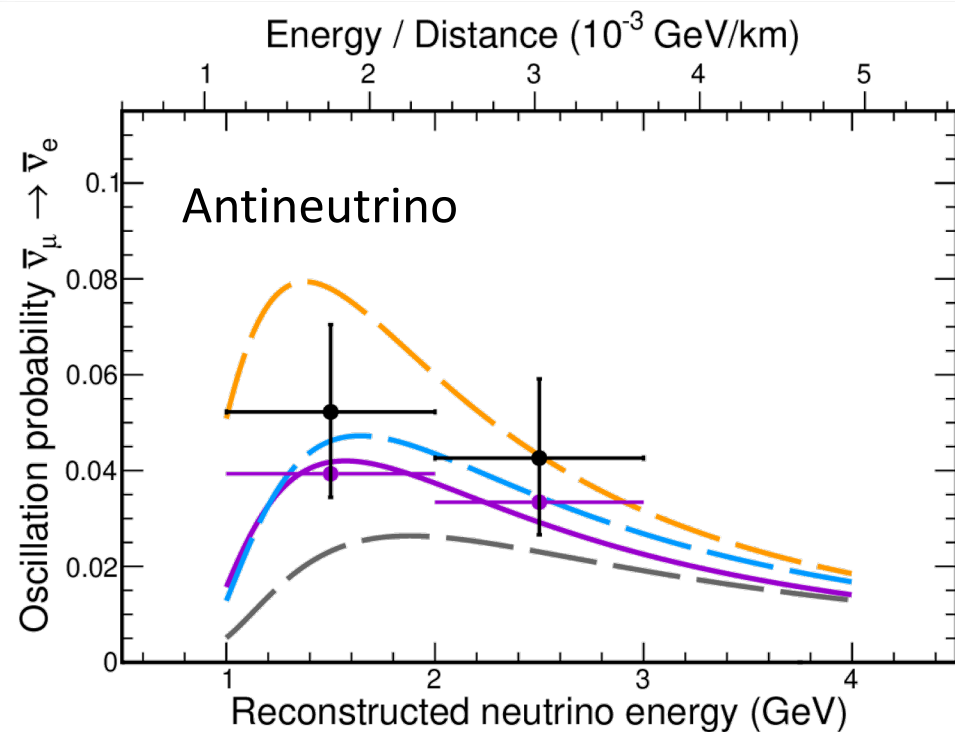
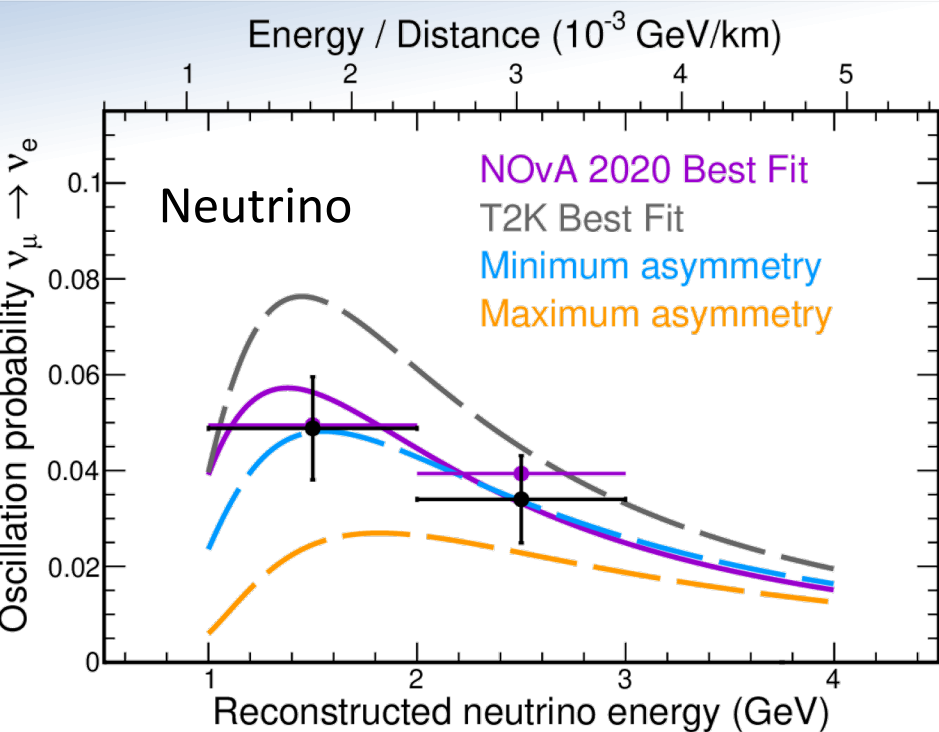
Search for Magnetic Monopoles
Phys. Rev. D

- Latest results presented NEUTRINO 2020.
 - Oscillation tension with T2K generated significant community interest.
 - Also presented 2 new inclusive cross section measurements.
- 16 total collaboration papers
 - 5 in PRL, 9 in PRD
 - Most cited: 264, 5 others > 100
- Beginning our 3rd year of test beam running.

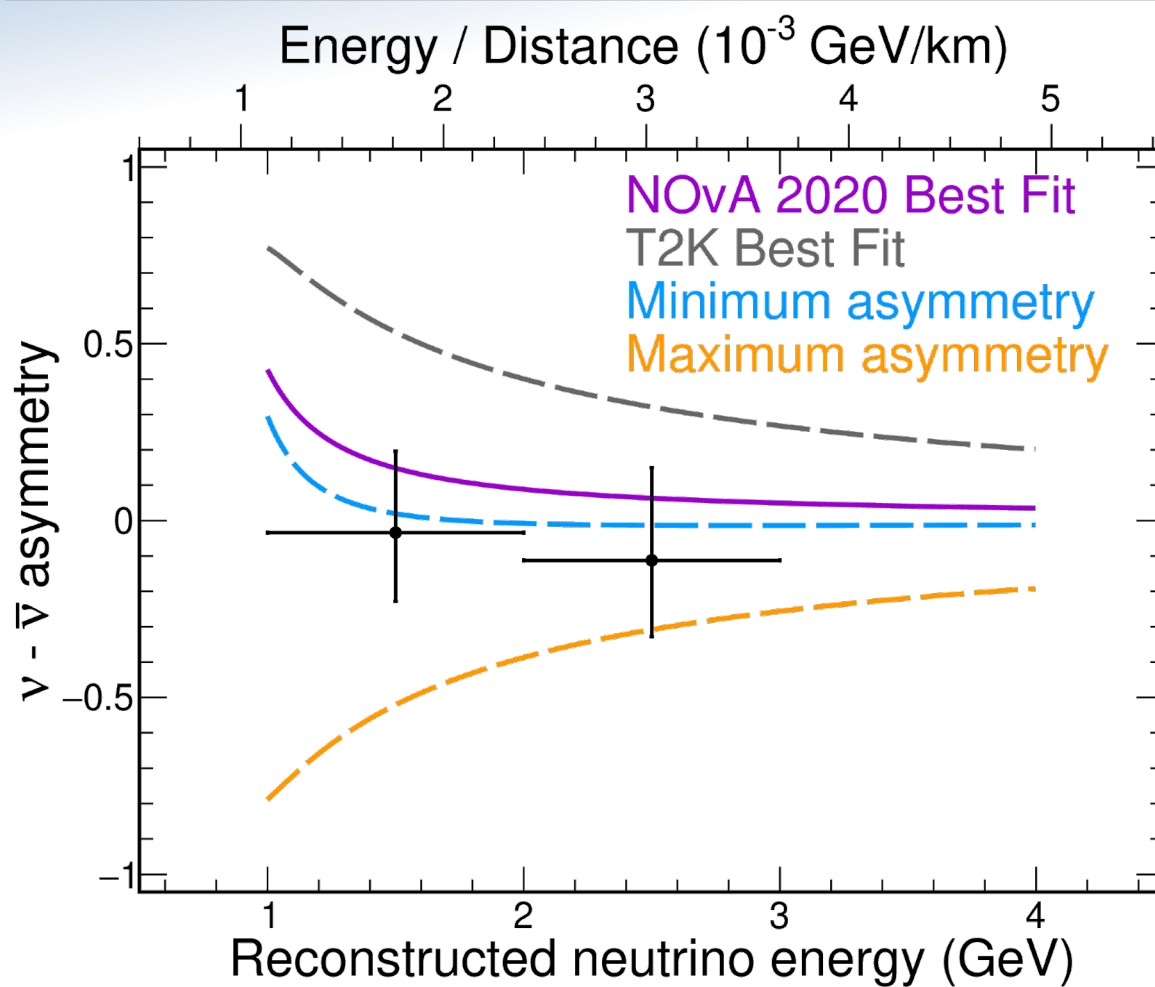
Measuring Asymmetry



- Mass ordering and δ_{CP} are both primarily observable through the *asymmetry* between ν_e and anti- ν_e appearance probabilities.
 - Since they can “interfere” constructively or destructively, our sensitivity depends on the true values in nature.
- Since this is a critical observable, we have developed a way to show it directly.



- First ingredient is oscillation probabilities
 - Compared to several reference probabilities.
 - Background-subtracted assuming best fit oscillations.
 - Statistical uncertainties are dominant.
- Shown in 2 bins, 1-2 GeV and 2-3 GeV.
 - The energies where NOvA is most sensitive to the asymmetry
 - Wide bins so uncertainties are well-behaved



- Our 2020 results are consistent with no asymmetry, and disfavor large asymmetries in either direction.
- Translates into statements about hierarchy- δ_{CP} combinations.
 - Disfavor extremes: (NO, $\delta=3\pi/2$) and (IO, $\delta=\pi/2$)
 - Cannot make strong statements about ordering or δ separately.

Near Future: Strategic Planning

- Last spring and summer, we undertook a strategic planning exercise.
 - Since the beginning, 3-flavor oscillations received priority access to collaboration resources like production processing.
 - We recognized that as the “doubling time” increases, now is the moment to prioritize a broader range of physics and pay off “technical debt”
- Production for non-3-flavor analyses
 - Nearing the end of a year-long production campaign focusing on the needs of cross section measurements.
 - First results next summer.
 - Exploring new production models to handle tape-limited processing of specialized trigger samples for non-oscillation physics
 - ex: monopoles, dark matter, etc.
- Entering a “year of upgrades”
 - Allow time and space to develop more fundamental improvements not possible with annual production cycles
 - Take the time now to invest in system improvements which will sustain us in the future
 - ex: automatic “keep-up” calibration

NOvA's Extended Run

Office of the CRO January 2021

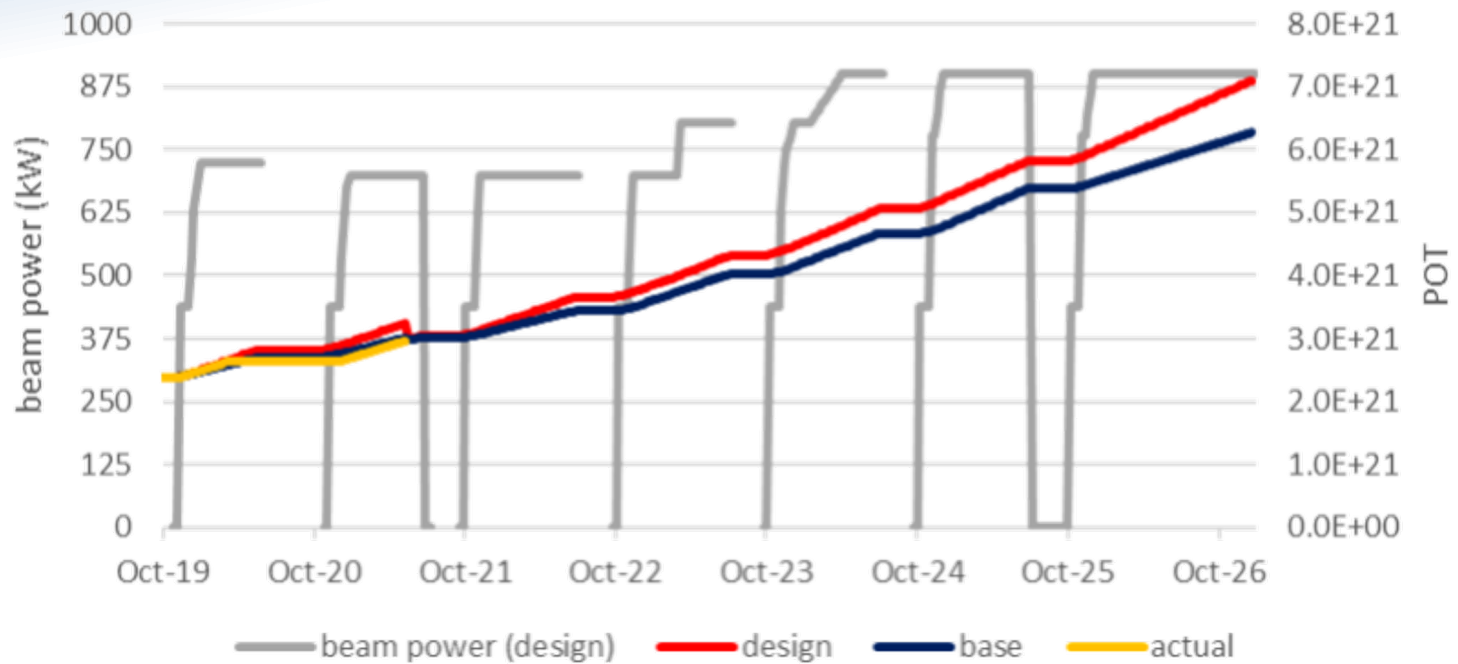
DRAFT LONG-RANGE PLAN

		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	
LBNF /	SANFORD				DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	v
PIP II	FNAL				LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	
Neutrino	MI	MINERvA	MINERvA	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	LONG SHUTDOWN				μ
		NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA					
BNB	B	lBooN	lBooN	BooN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	LONG SHUTDOWN				p
		CARUS	CARUS	CARUS	CARUS	CARUS	CARUS	CARUS	CARUS	CARUS					
		SBND	SBND	SBND	SBND	SBND	SBND	SBND	SBND	SBND					
Muon Complex		g-2	g-2	g-2	g-2	g-2	g-2	g-2	g-2	g-2	LONG SHUTDOWN				μ
		Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e					
SY 120	MT	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	LONG SHUTDOWN				p
	MC	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF					
	NM4	OPEN	SpinQ	SpinQ	SpinQ	SpinQ	SpinQ	OPEN	OPEN	OPEN					
LINAC	MTA				ITA	ITA	ITA	ITA	ITA	ITA	LONG SHUTDOWN				p
		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	



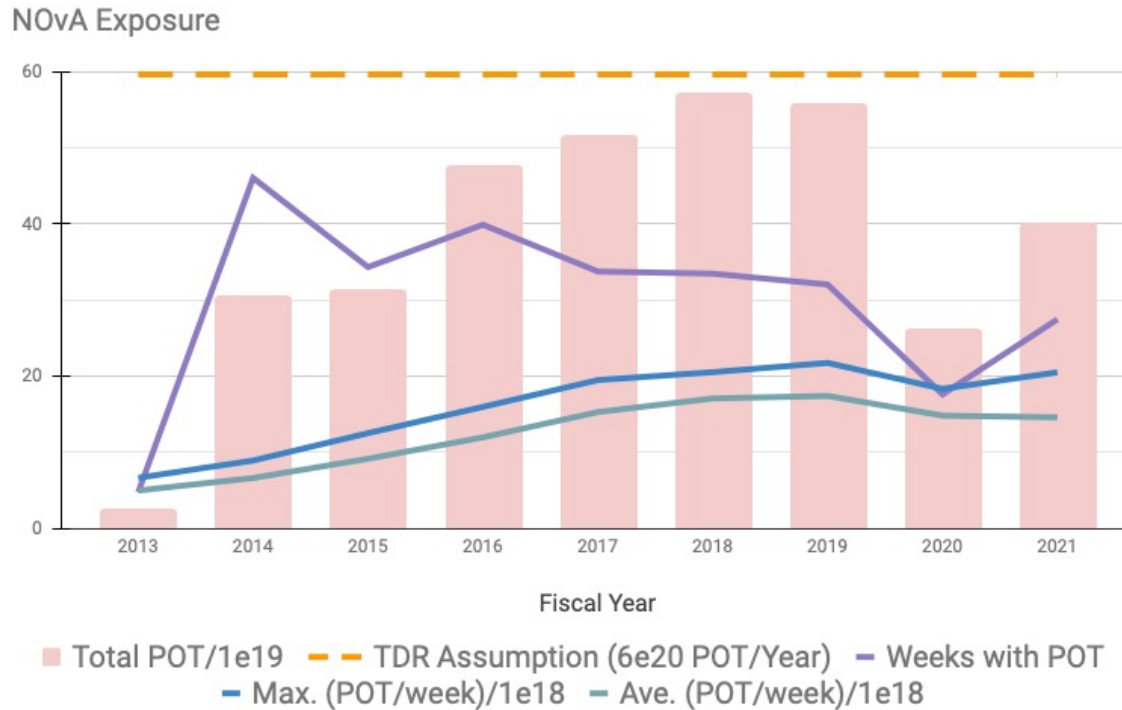
- NOvA is now planning to run until the long shutdown for LBNF
 - Scheduled for Q2, FY27.
 - Original run plan ended in FY24.
- The extended run takes advantage of PIP-II beam upgrades planned for LBNF.
- This change in scope creates additional operations and computing needs.

NOvA



- Projections prepared by the accelerator division in June.
- Increase in power to ~900 kW by FY23.
 - PIP-II upgrades bringing increased pulse intensity
 - Enabled by new MW-capable targets and horns
 - Faster cycle time after the g-2 run ends.
- Using 54/63/72e20 POT as pessimistic/optimistic references.
 - Latest results: 29e20
 - Total recorded: 33e20

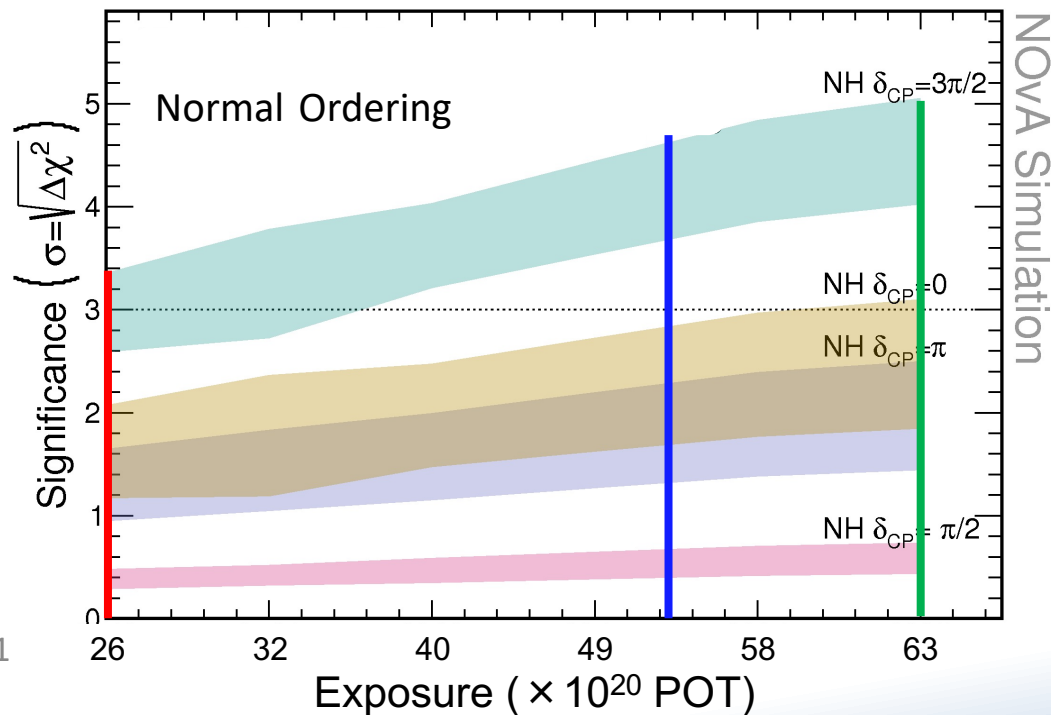
Accelerator Performance



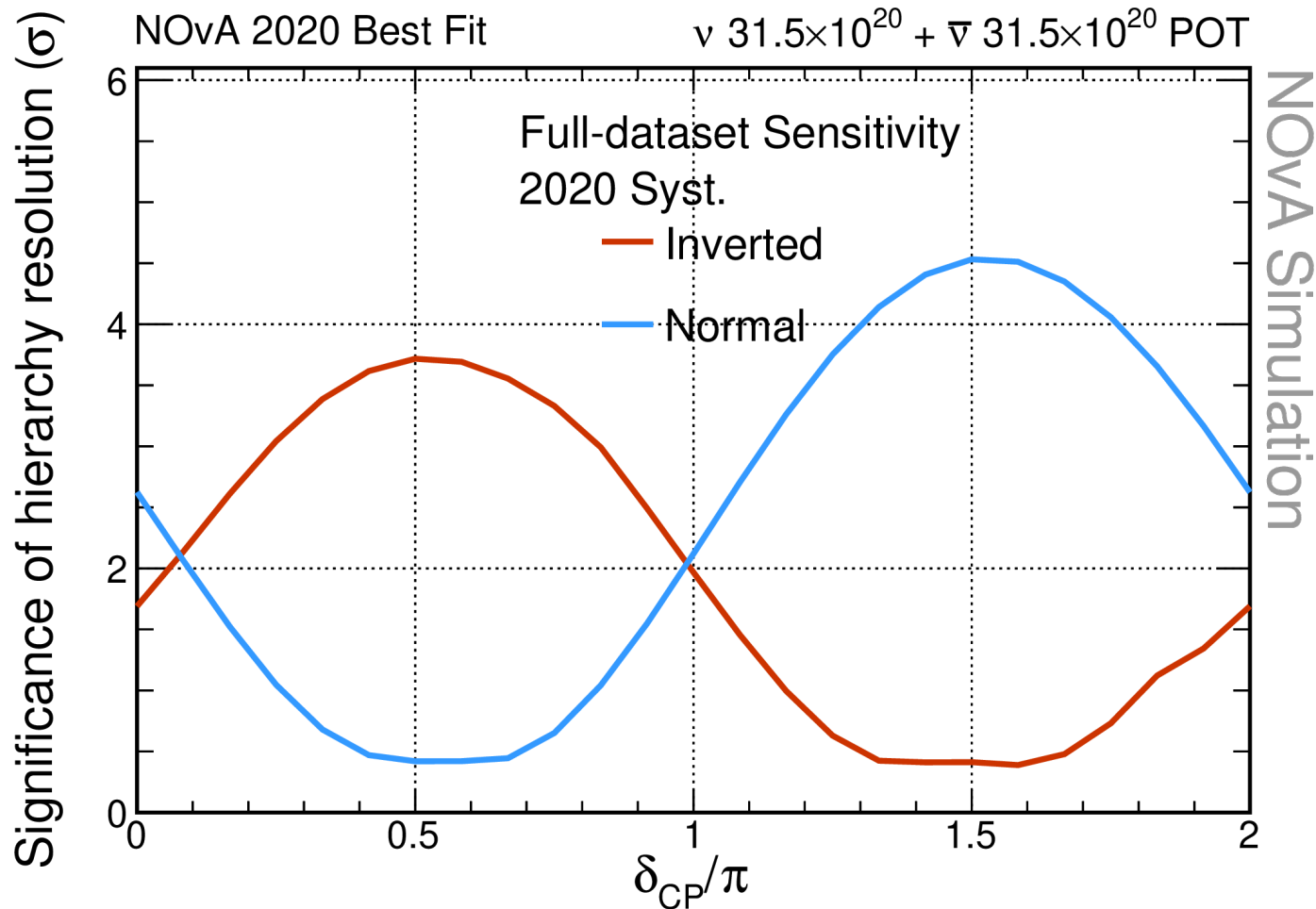
- Our best year for POT delivered was 2018.
 - Fall off since then driven primarily by the number of weeks the accelerator operated.
- We recognize the hard work from AD to continuously increase peak power to NuMI
 - But we need long, steady runs to realize those gains in total exposure
- FY22 is off to a *great* start, we're already at >800 kW operations.
 - 850 kW power record in October.
 - Likely a record year if we run the full 41 weeks.

Future Sensitivity: Asymmetry & Hierarchy

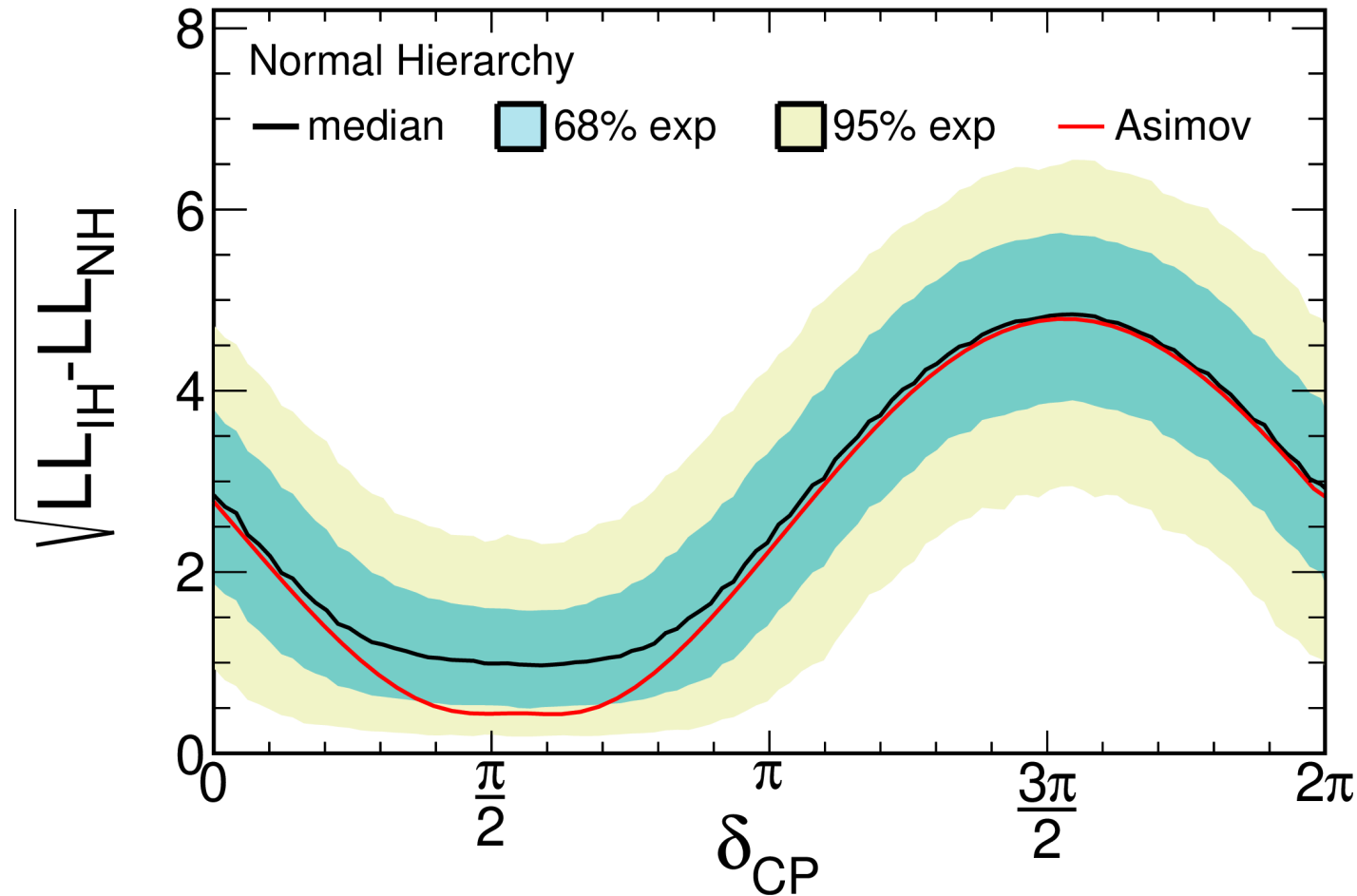
- Asymmetry error will improve significantly with exposure:
 - **Current:** 0.21
 - **54e20 POT:** 0.16 (25% improvement)
 - **63e20 POT:** 0.15 (30% improvement)
 - **72e20 POT:** 0.14 (35% improvement)
- But hierarchy discovery depends strongly on true parameters



Future Sensitivity: Hierarchy



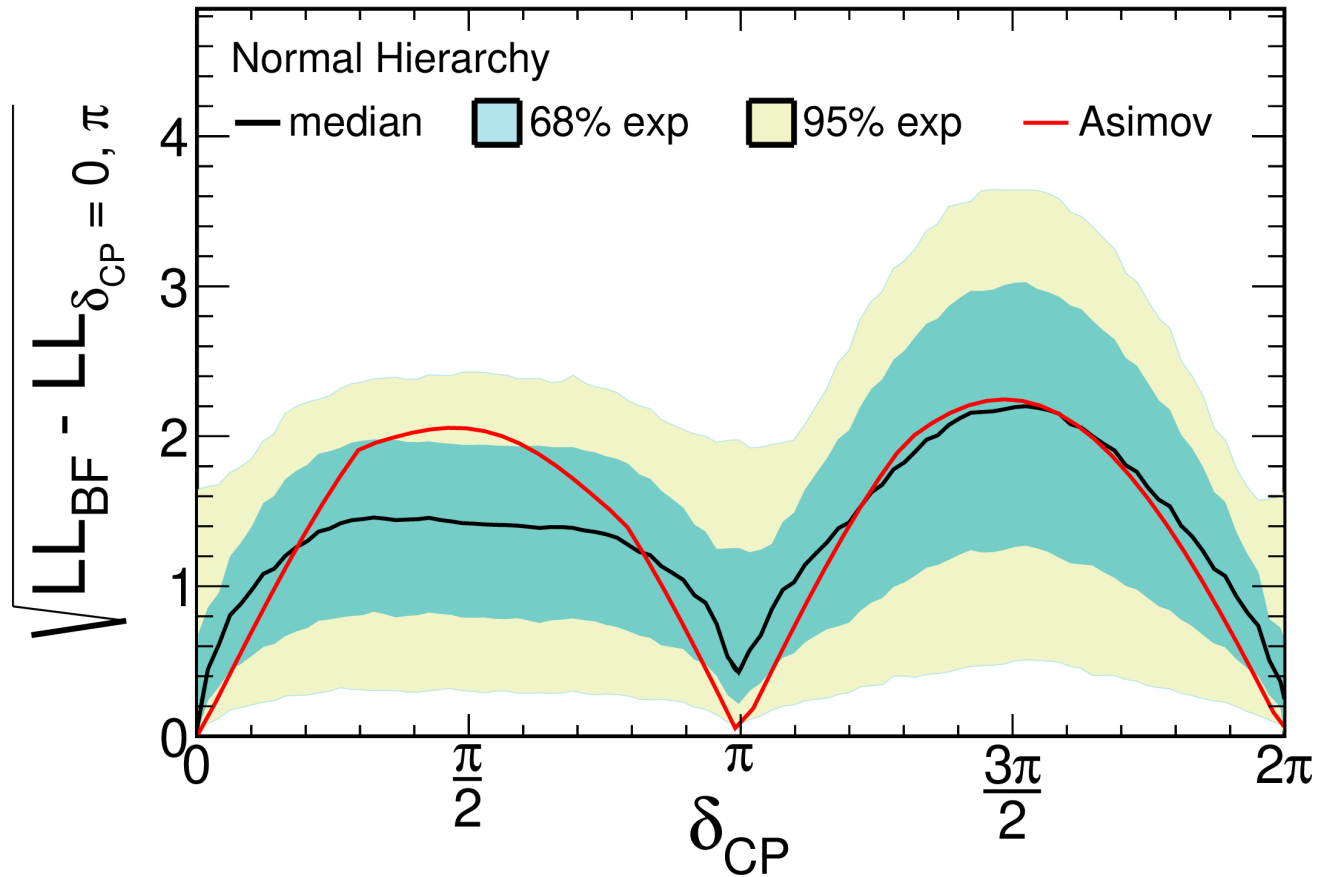
- You can see the variation vs. true δ and hierarchy more clearly here, focusing just on 63e20 POT.
 - Based on NEUTRINO2020 techniques and systematics.



- Small datasets mean luck will matter (and every proton counts!)
 - Statistical errors only, systematics would be computationally prohibitive, but impact is not large even at $63e20$ POT.

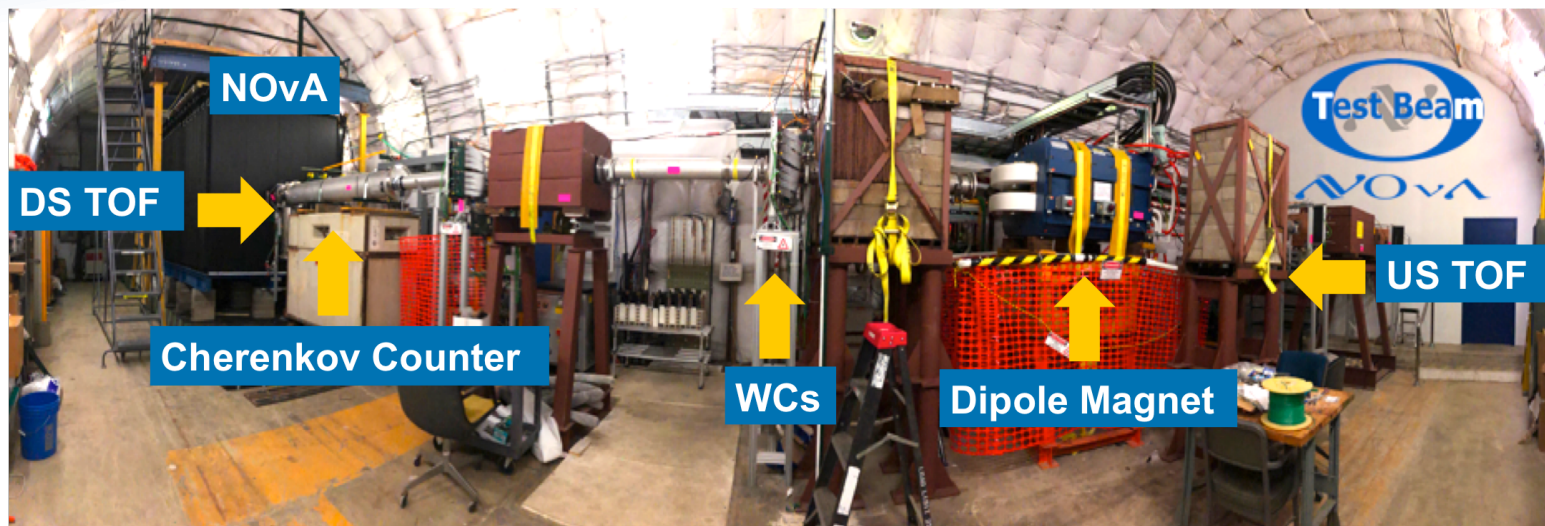
NOvA Future Sensitivity: CP Violation

NOvA Preliminary

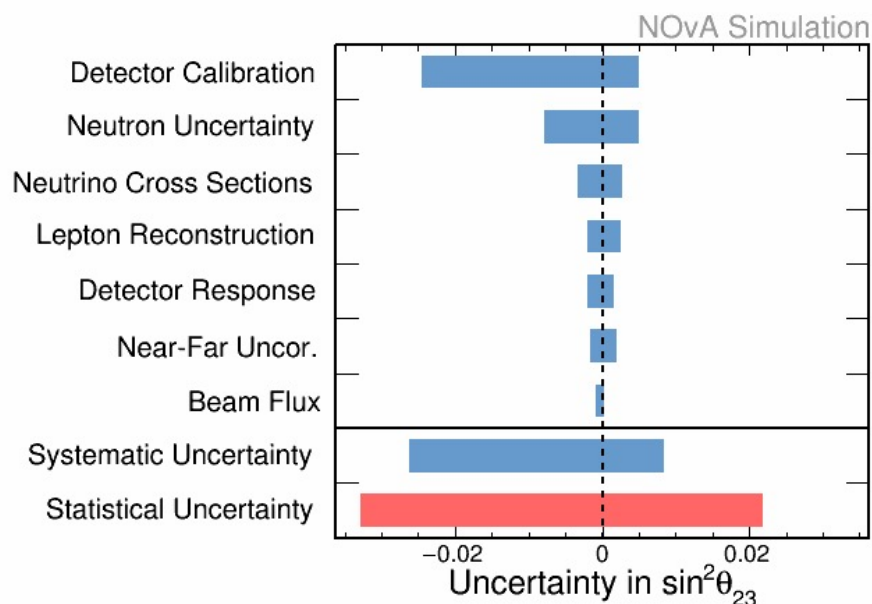


- Measuring CP -violation is tough, so luck matters even more
- A key opportunity for complementarity between NOvA and T2K:
 - Different baselines help break the degeneracy with hierarchy.

Supporting an Extended Run: Test beam



- Detector response and energy calibration dominant systematics on Δm^2 and $\sin^2\theta_{23}$ — addressed by test beam program
- Going into our 3rd year, experiment in the best shape yet:
 - Mitigated high-rate issue in electronics though beam tune, shielding, and firmware.
 - 5x more data in year 2 than year 1, expect even better for year 3.
 - Topped up under-filled cells.
- Test beam analysis group formed.



Supporting an Extended Run: Operations

- Personnel:
 - We are updating the role of our “Operations Manager.”
 - The senior Fermilab collaborators with relevant experience are picking up new responsibilities outside NOvA.
 - We will likely need help from the Neutrino Division to cover some of the responsibilities of this role.
 - SCD support for our DAQ software has been, and must remain, strong.
 - As the system gets older, we are at increasing risk that something “breaks” due to changes in network, security, hardware, etc.
 - If a key component breaks, forestalling a major downtime may require an all-hands-on-deck effort with 1-3 computing professionals from SCD.
- Hardware:
 - Continue regular refreshing of DAQ hardware as components age.
 - Primarily replacement of aging computers
 - A wider range of equipment may need replacing as time goes on
 - Cooling at our Far Detector in Ash River may need investment
 - Over the summer we had to frequently disable most data-driven triggers to keep the computers cool enough to operate.
 - Seeing some continued cooling problems recently, even in cooler weather.

Supporting an Extended Run: Computing

The screenshot shows a Zoom meeting interface. At the top, the title is 'NOvA/SCD Workshop' with a calendar icon and a time slot of 'Tuesday Oct 5, 2021, 9:00 AM → 12:10 PM US/Central'. Below the title is a 'Description' field containing a Zoom URL: 'https://fnal.zoom.us/j/96519283174?pwd=RHlhTjdtcDFtbnw4K3NzcjhhkQ0RiZz09&from=addon'. The main content area shows a meeting segment from '9:00 AM → 9:05 AM' titled 'Welcome'. The speaker is identified as 'James Amundson (Fermilab)'. A document icon is visible with the filename '2021-10-05-nova-s...'. There are also icons for muting (5m) and editing.

- Recent workshop held between NOvA & SCD experts, focused on developing a plan for future support.
 - Preparing a written report covering the topics discussed and the plans for future development.
- Many changes will be required, but most look manageable:
 - Ex: UPS/Spack, authentication, new linux distributions
- Two key areas of concern:
 - Data management tools
 - Simulation tools

Data Management Tools

- Expert opinion: SAM file catalog may not last us to final analyses in ~ 2030 .
 - Well-past specs: >200 M files, originally designed for $O(100k)$, and may not continue to scale
 - Increasing “existential” risk from changes in security, operating systems, ec.
- However, transition is a major undertaking.
 - Requires coordinated changes in DAQ, production tools, framework, and analysis software.
 - Mistakes can lead to downtime and data loss.
- Success will require substantial effort from computing professionals in FY23 or 24.
 - This would be outside the scope of currently available support from SCD
 - Also beyond the expertise available within the collaboration.



Simulation Tools

- GENIE
 - Having a neutrino generator as input to simulation and to evaluate uncertainties is vital to our physics program.
 - Not just NOvA: all FNAL neutrino experiments
 - Requires support on two fronts.
 - Technical support for building, packaging, and framework integration
 - Physics support to introduce new models
- Geant4
 - We use Geant4 in 2 key places: detector simulation and beamline simulation.
 - The critical need for support is for **G4NuMI**
 - Beamline simulation shared by NOvA, MINOS, Minerva, and μ BooNE/SBN.
 - Stuck on an older, patched version of Geant4 which is not supported on modern operating systems. Need **expert support** to modernize.



Status of NOvA-T2K Joint Fit

- Active effort on both collaborations, **goal of presenting results next year**
- Joint analysis group, made up of NOvA and T2K collaborators, has been operating since 2019.
 - Designated “liaisons” lead the effort in both collaborations.
 - Meetings every other week.
- Working with a mix of tools from both collaborations.
 - Example: Docdb used to host documents, T2K resources used for hosting shared data files
 - Computing resources of both collaborations are being used.
- Joint workshop between the collaborations held Nov 8, 15.
 - Good attendance from both collaborations.
 - Of course, anything *really* interesting I can't share yet.
 - My personal impression: on track for results next year

Summary

- 2021 likely to be a record year for NOvA Papers.
 - 1 PRL and 3 PRDs accepted, 2 PRDs in review now
 - Covering the whole breadth of our physics program:
 - 3-flavor oscillations
 - Exotic oscillations
 - Neutrino scattering
 - Astrophysics
 - Beyond the Standard Model
- An extended NOvA run into FY27 presents exciting physics opportunities.
 - Improved measurement of the asymmetry in neutrino vs antineutrino oscillation probabilities increases the chances of a mass hierarchy discovery
 - Likely to be statistics-limited for hierarchy and CP -violation throughout the run
 - Systematics are or will be important for other oscillation parameters and most other measurements (cross sections, BSM, etc.)
 - Largest systematics are from detector response – address with Test Beam
 - More opportunities for neutrino scattering and other non-oscillation physics
- However, that extended run is not free: success depends on additional support for operations and computing.