NOvA: Status and Plans

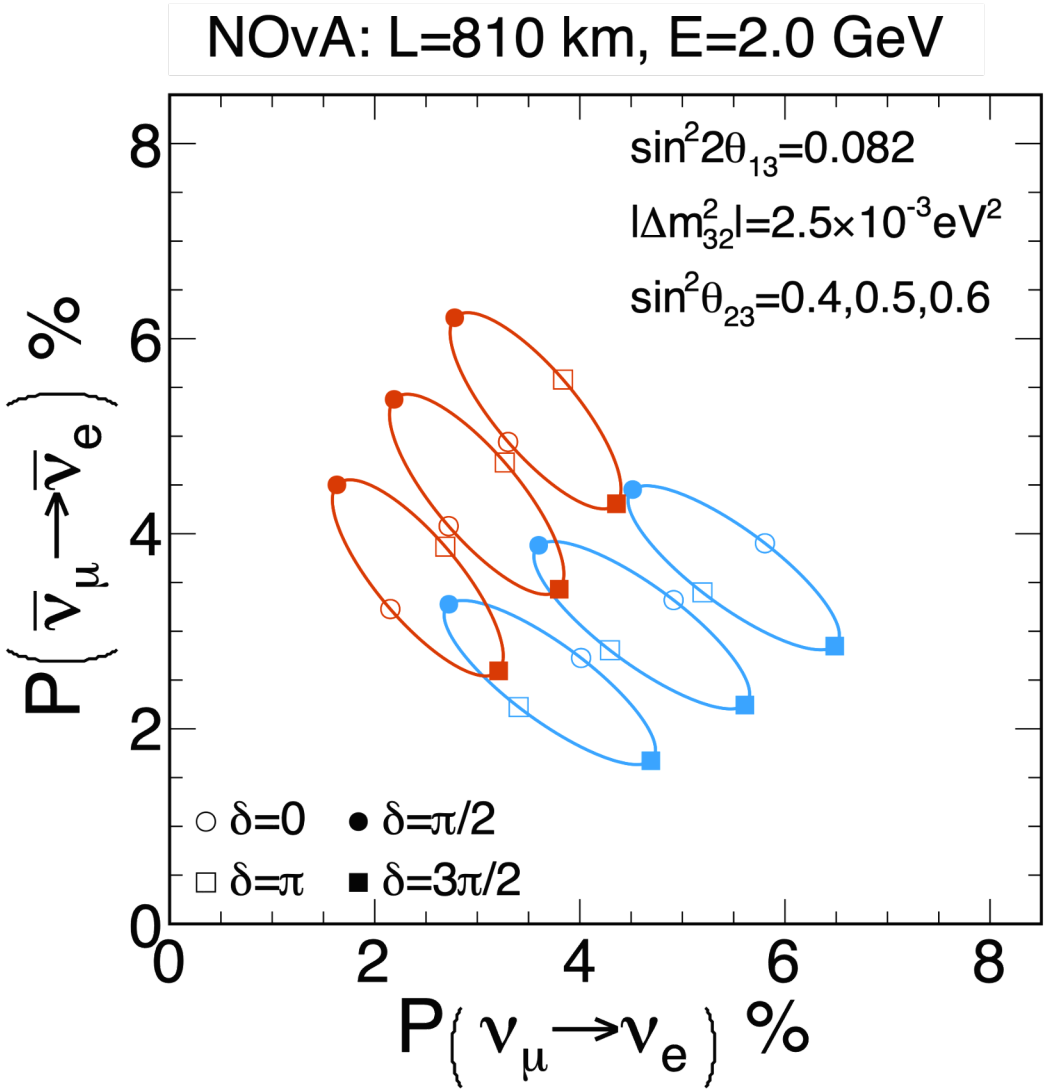
P. Vahle, Snowmass, 2022

NOvA

- Long-baseline neutrino oscillation experiment
  - High power, high purity neutrino and antineutrino beam from the NuMI beam from Fermilab
  - At 14 mrad off-axis, energy peaked at 2 GeV
  - 2 Functionally identical detectors separated by 810 km
    - ND on site at Fermilab
    - FD in Ash River, Minnesota

- NOvA addresses many compelling questions surrounding the nature of neutrino mass
  - What is the Neutrino Mass Hierarchy?
  - Is there CP symmetry violation in neutrinos?
  - Is there more to it than 3x3 PMNS?

Analysis Basics



Compare electron-neutrino appearance probability in neutrinos to antineutrinos

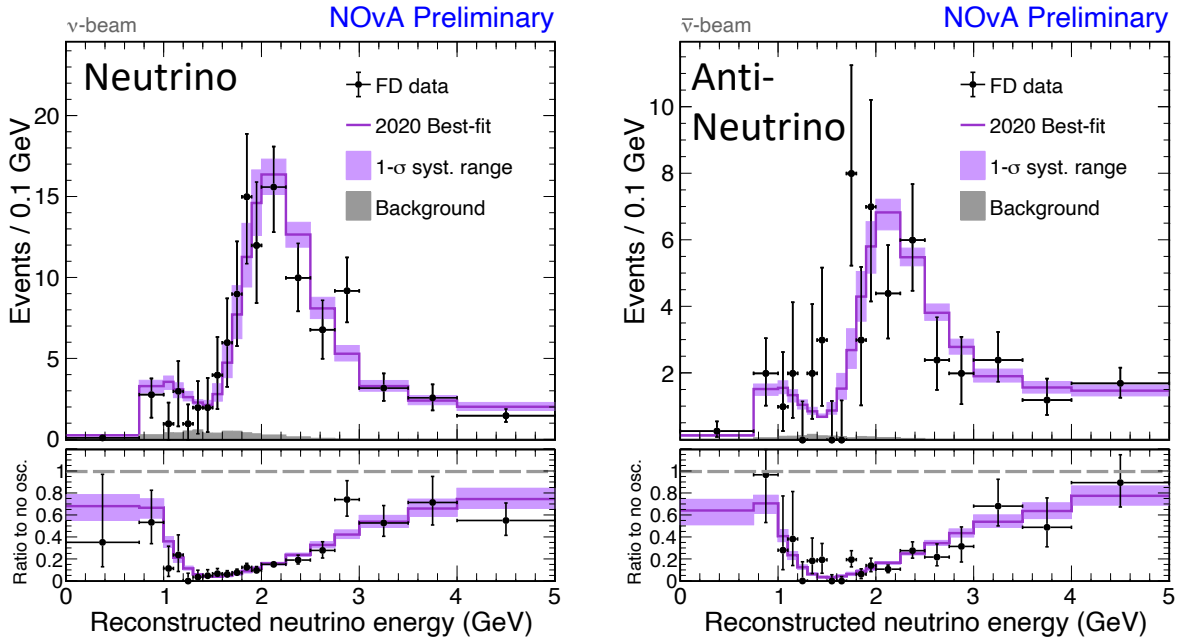
- In vacuum with no CP violation, neutrino and antineutrino oscillation probabilities the same
- CP violation enhances oscillation probability for neutrinos while suppressing it for antineutrinos, or vice-versa
- Matter effects also introduce neutrino vs. antineutrino differences that depend on mass ordering
- Upper octant enhances both neutrino and antineutrino oscillation probability, while lower octant suppresses both

Fit both disappearance and appearance energy spectra to achieve full sensitivity

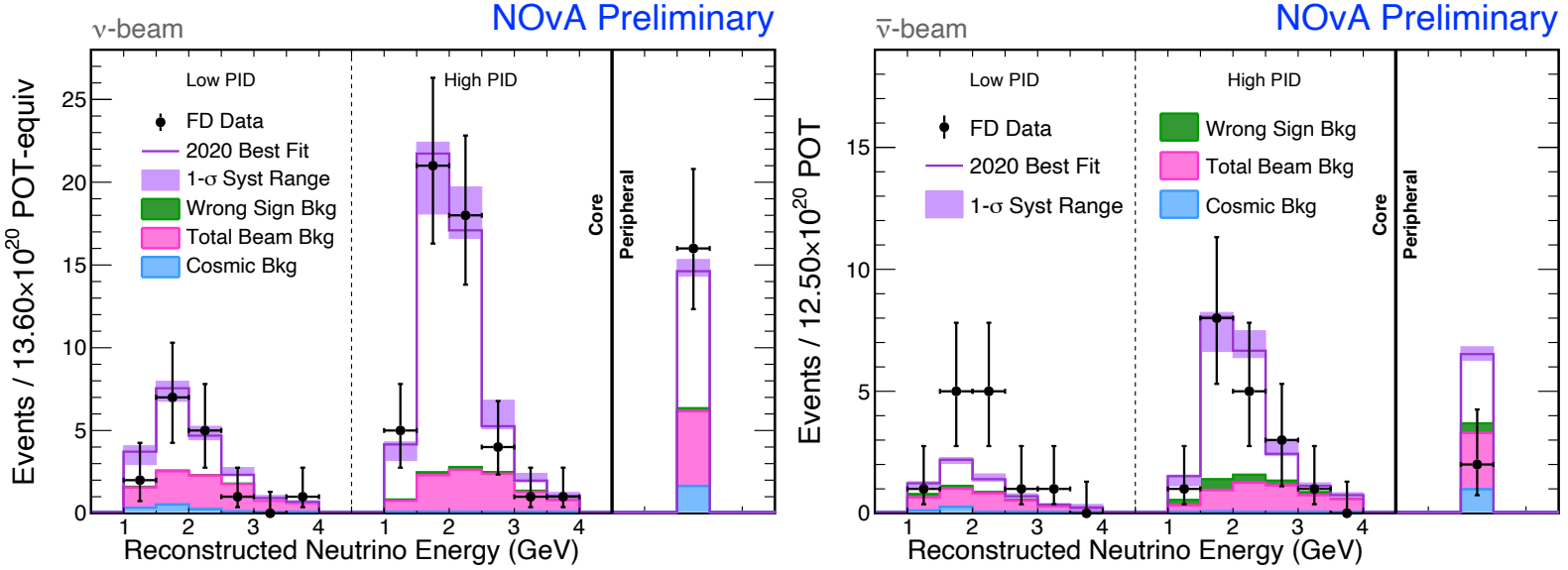
NOvA Far Detector Data

- Clear signature of disappearance and appearance in both neutrino and antineutrinos
- 4+ σ appearance of $\overline{\nu}_e$ in a $\overline{\nu}_\mu$ beam
- 3 flavor oscillation model fits data well

Muon neutrino disappearance

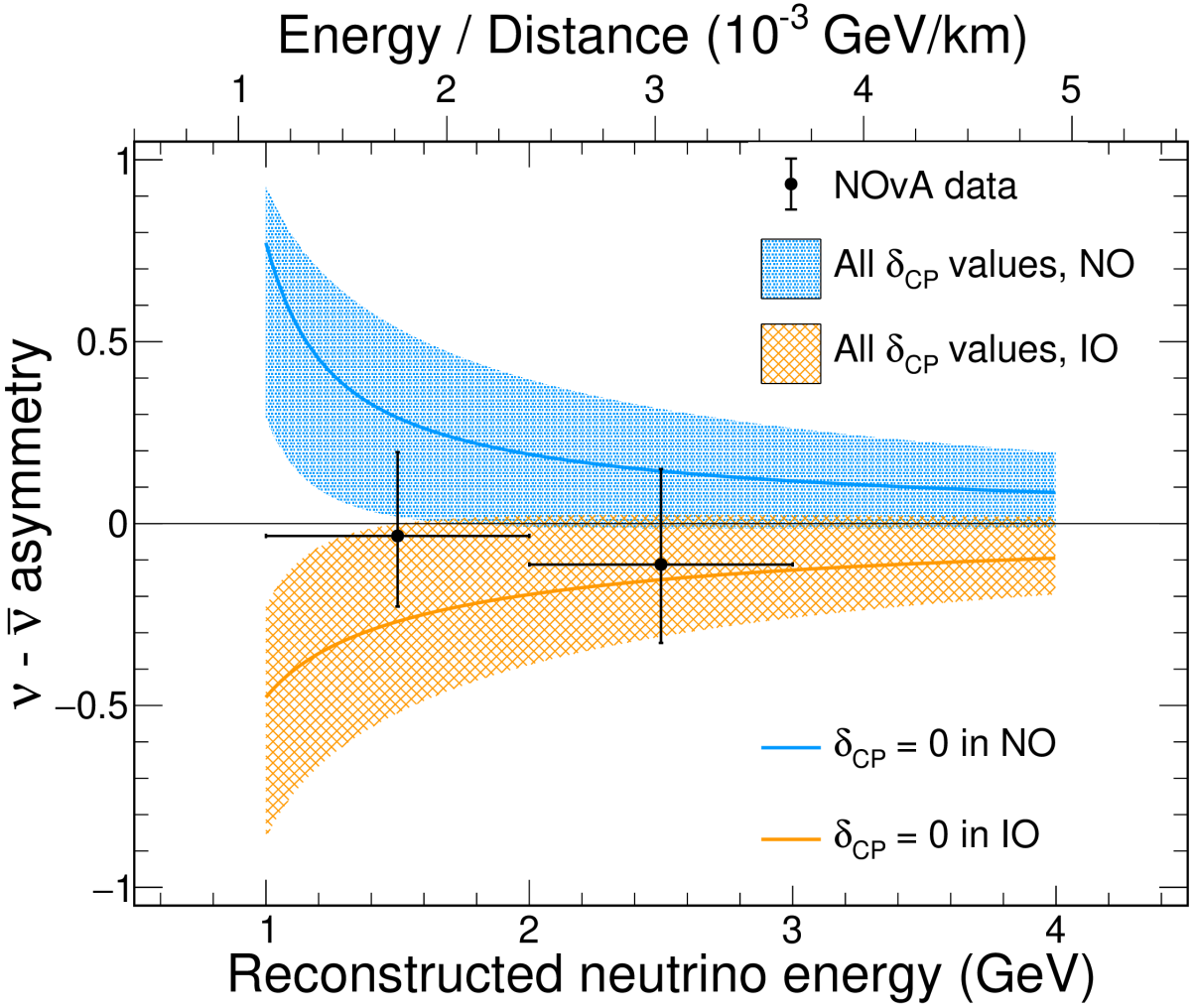


Electron neutrino appearance



NOvA Preliminary
arXiv:2108.08219

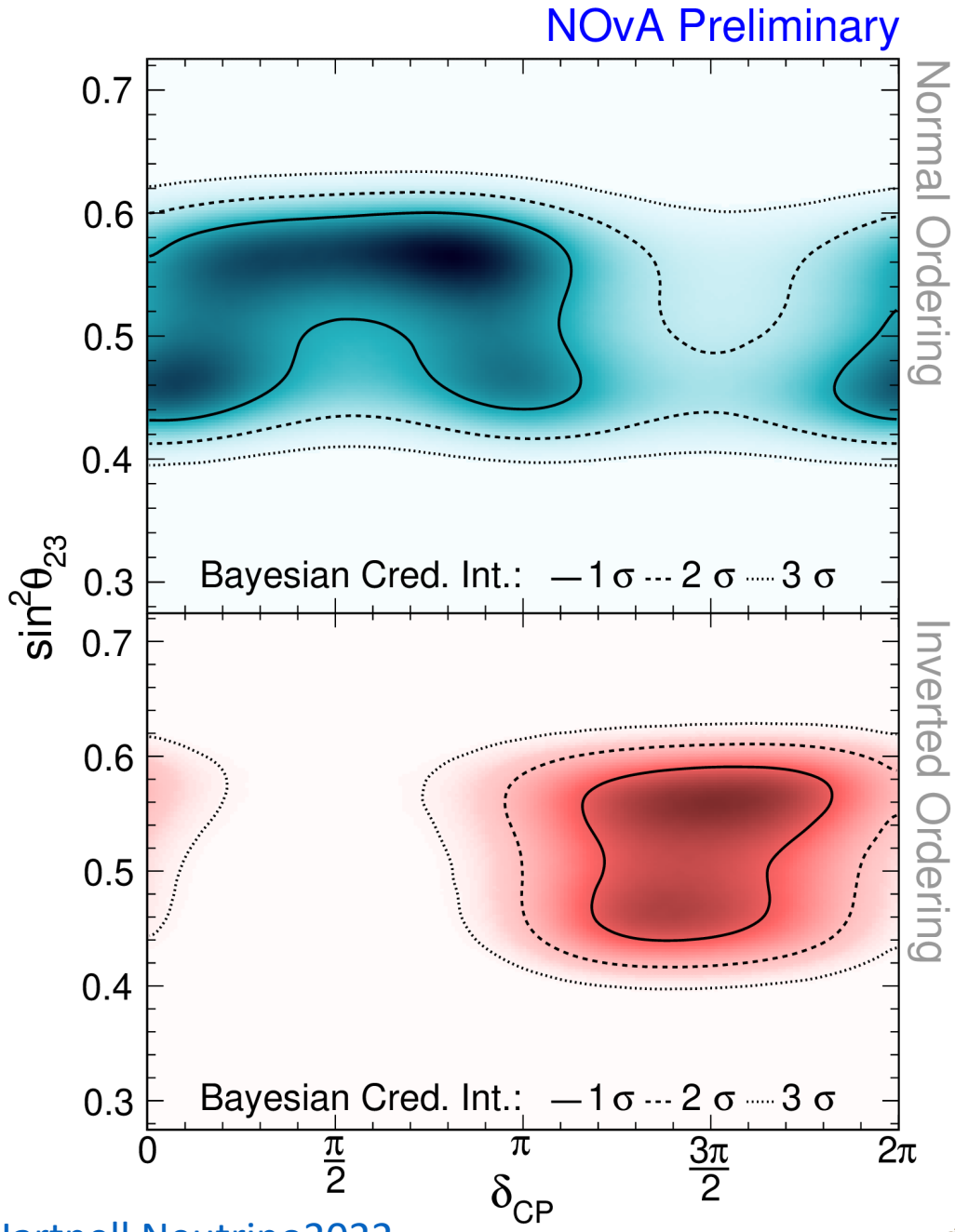
Appearance Asymmetry



- NOvA data is consistent with no asymmetry between electron neutrino and antineutrino appearance probability at 20-25% level

Bayesian Oscillation Analysis

- New fit using a Markov Chain MC with a Bayesian analysis
- Conclusions consistent with previous results.
  - Weak preference for Normal Ordering and Upper Octant
  - Strongly exclude Inverted Ordering around $\delta=\pi/2$



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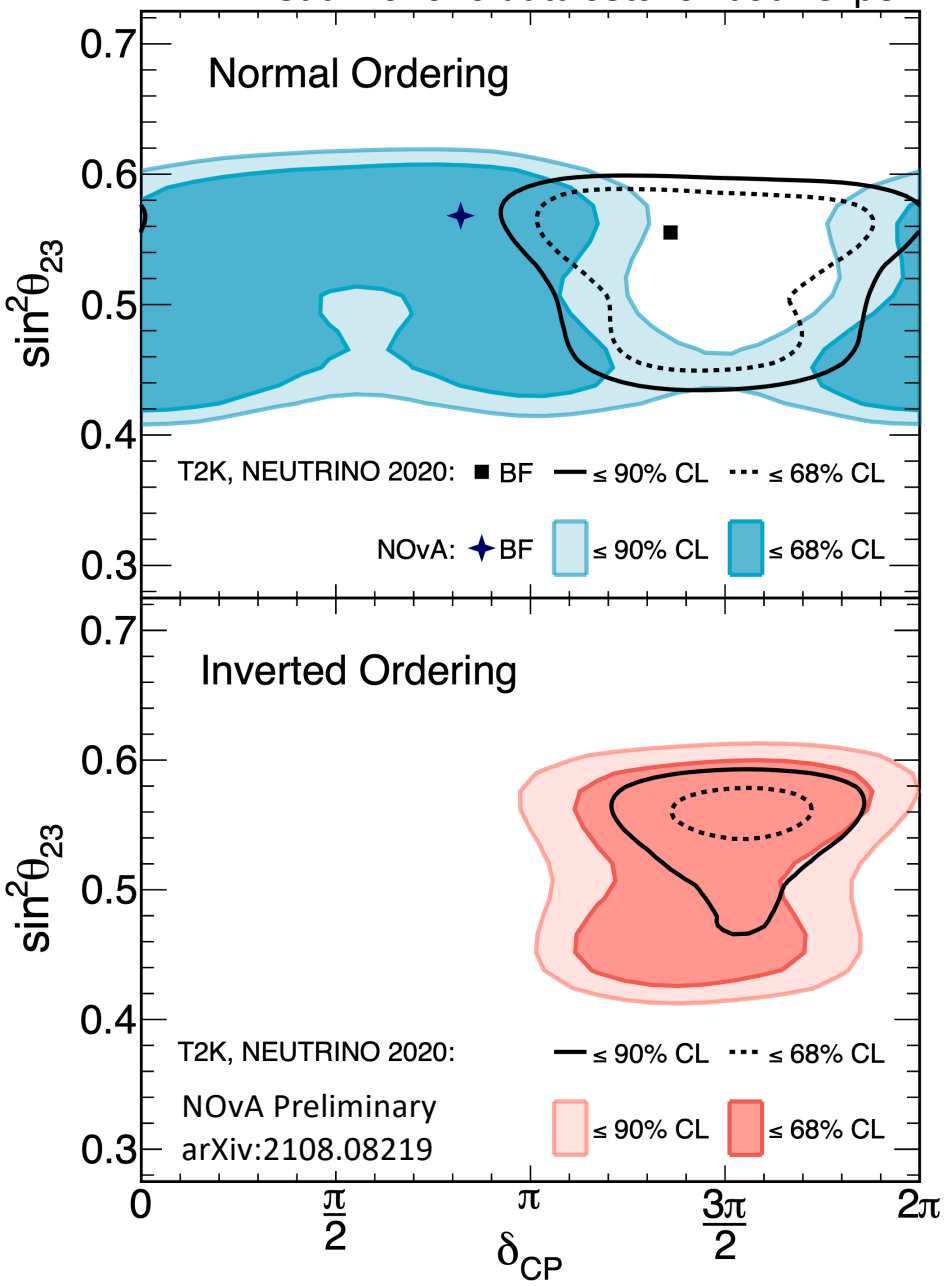
NOvA and T2K

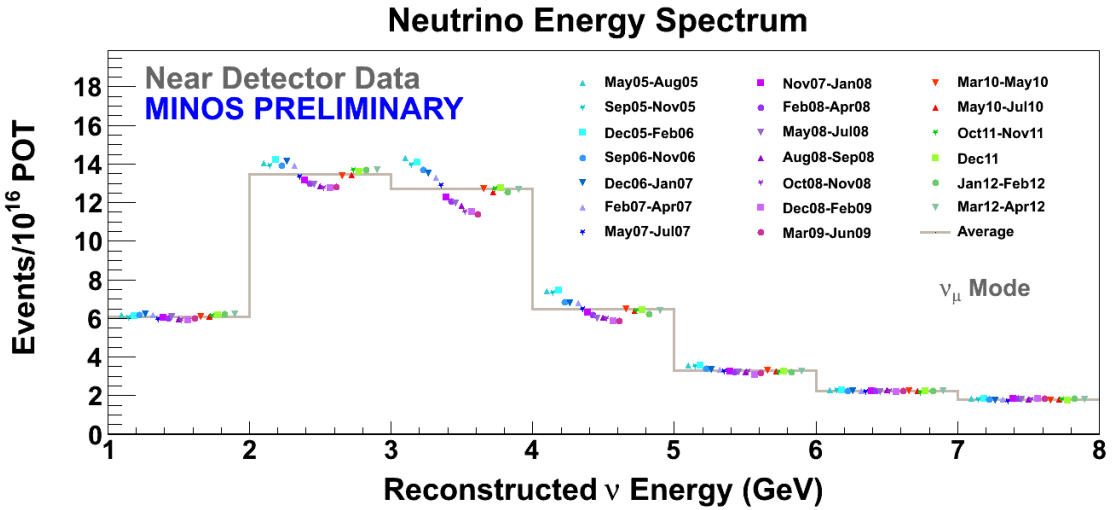
- Both experiments have best fits in the Normal Ordering, but significant overlap in the Inverted Ordering
- Early indications of “tension” seem to be easing
- Complementary experiments:
  - Different baselines and energies mean size of mass ordering and δ_{CP} is different between the two experiments
  - NOvA and T2K have joined forces for a combined fit
  - Results expected later this year

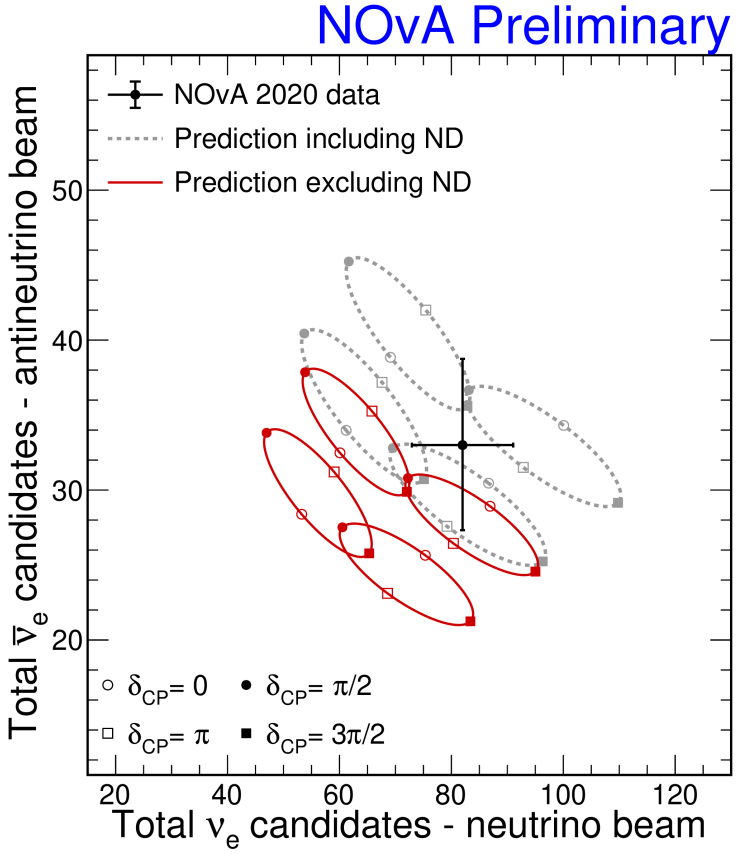
NB: Frequentist contours,
Neutrino2020 data sets for both experiments



A Note on Near Detectors

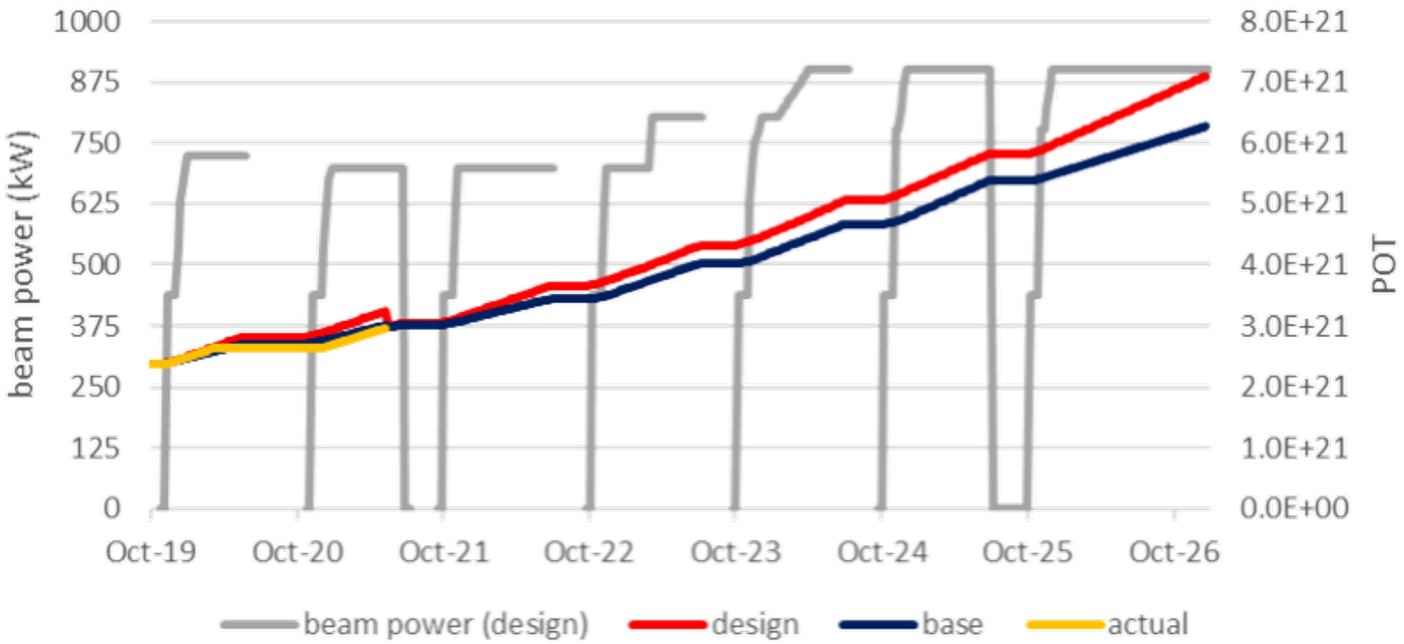
A capable Near Detector enables a robust, precise, and correct experiment!





- Lessons from MINOS:
  - Different targets, helium in decay pipe, target degradation
  - ND data naturally accounts for time variation of beam conditions and beam line hardware
- Lessons from NOvA:
  - Even after 8 years of external cross section results, we don't use simulation to dead reckon our prediction
  - ND is crucial for systematic control, both from known sources and unknown sources

The Future of NOvA



- NOvA will run at least until the beginning of the long LBNF shutdown, through 2026
- 63/72e20 POT pessimistic/optimistic predictions
  - Last results: 29e20
  - Total recorded: 38e20


1 MW horn installed 2020


1 MW target installed 2019

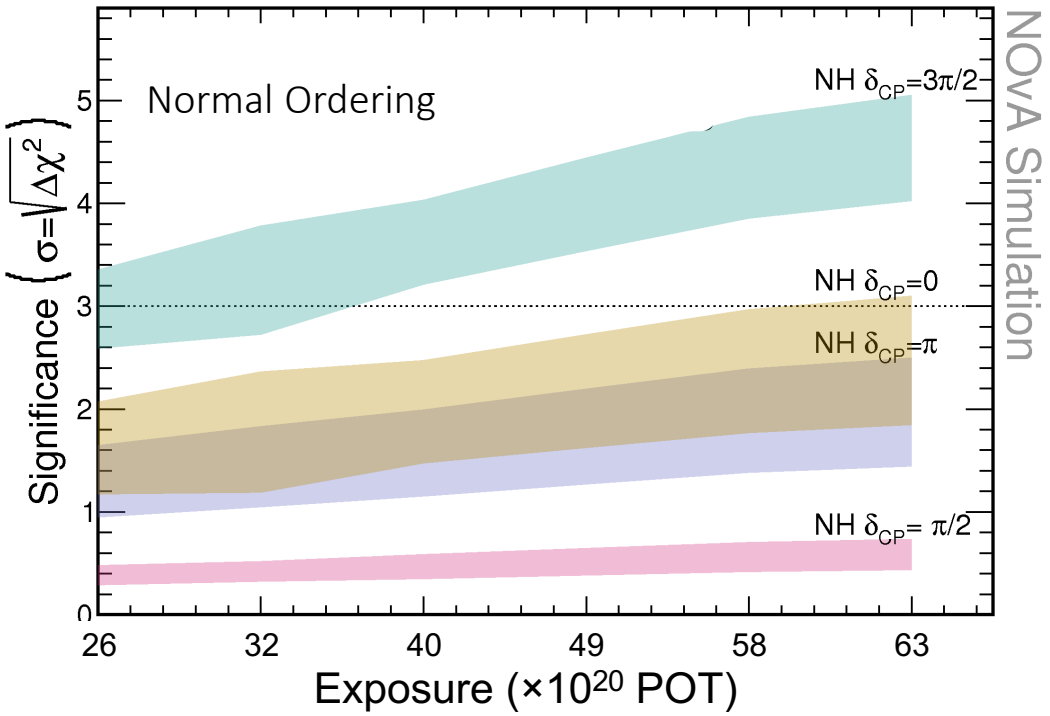
FY22 Highlights:

- 1-hour average power record: 895 kW
- Yearly integrated exposure record: 5.81e20 POT delivered

Future Sensitivity

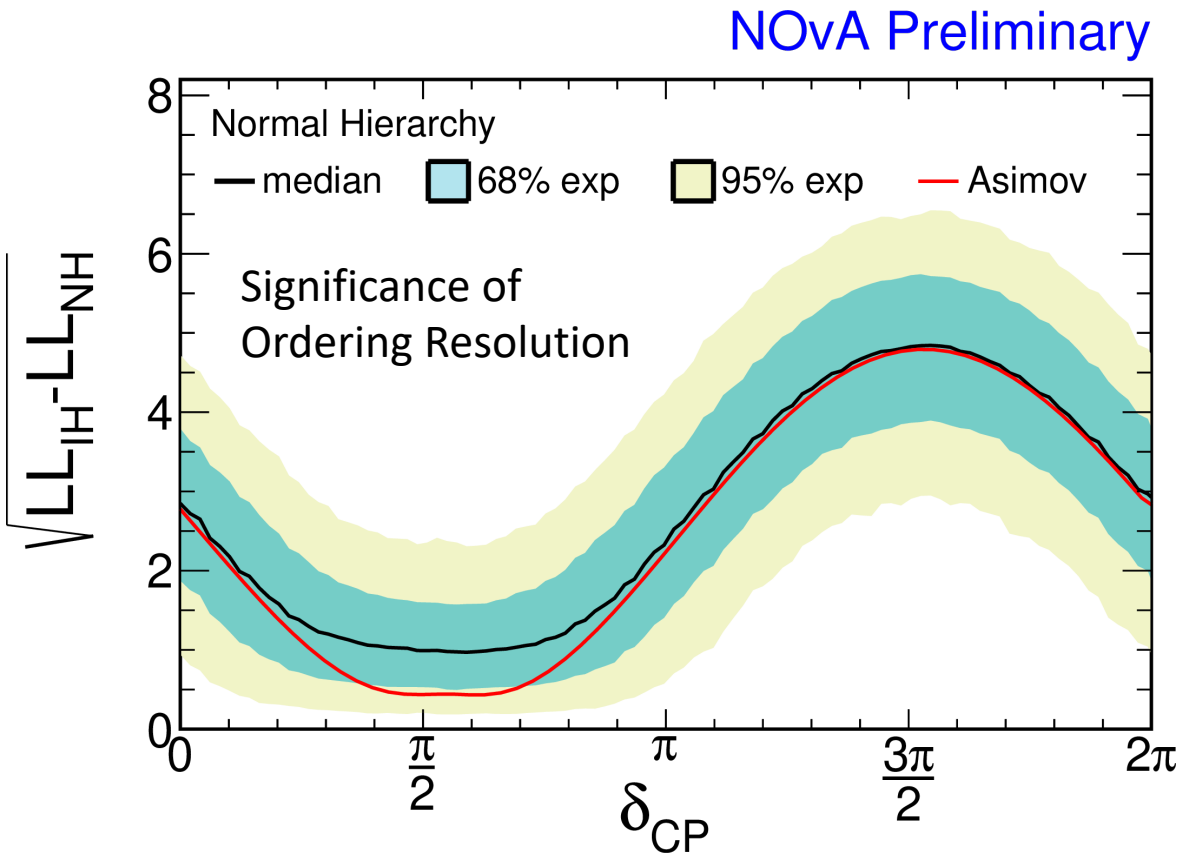
- Errors on Δm^2 and $\sin^2(\theta_{23})$ near equal stats/syst uncertainty at end of run (assuming no improvement in systematics)
  - 1-2% measurement on Δm^2
  - ~5% measurement on $\sin^2(\theta_{23})$
- Ordering, δ_{CP}, and neutrino/antineutrino appearance asymmetry will not be limited by systematic uncertainty
- Asymmetry error will improve significantly with exposure:
  - Current: 0.21
  - 63e20 POT: 0.15 (30% improvement)
  - 72e20 POT: 0.14 (35% improvement)
- Ordering resolution depends strongly on true parameters

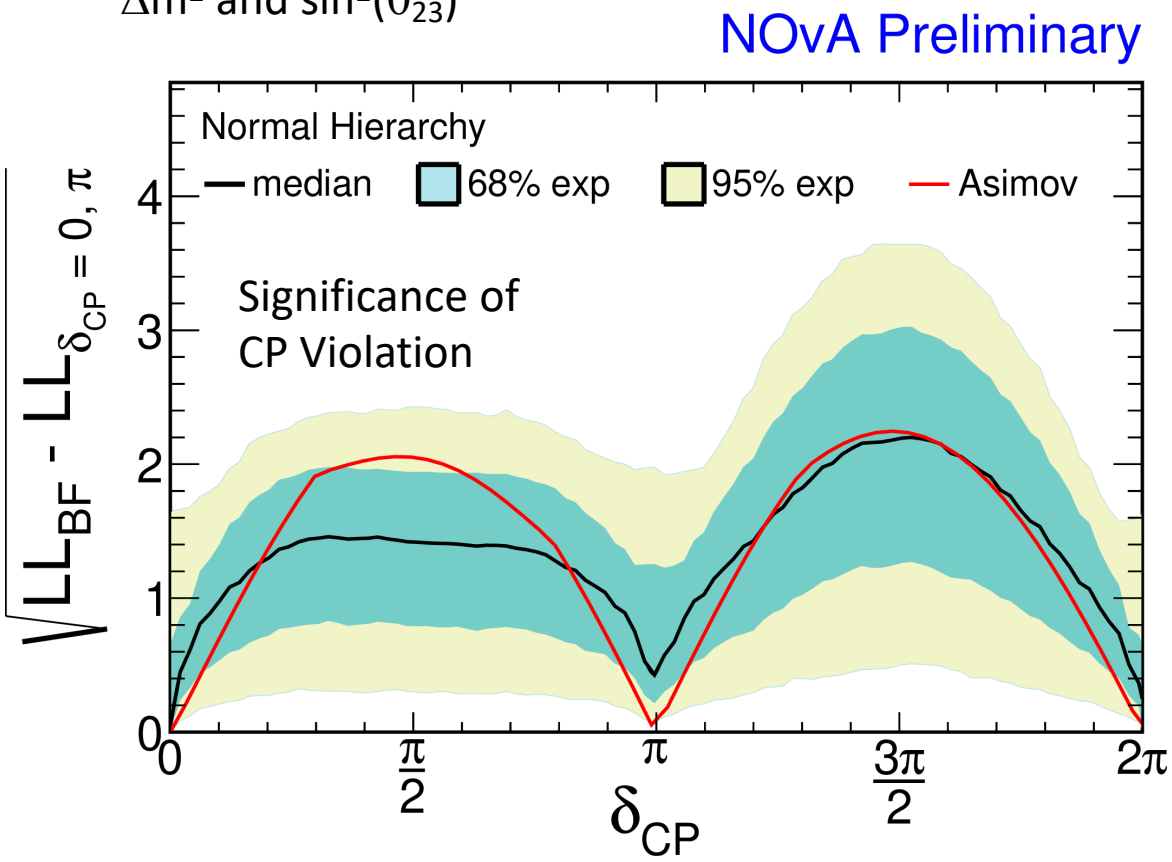
Significance of Mass Ordering resolution



Future Sensitivity

NB: Statistical errors only, but impact is not large at 63e20 POT. Assumes Neutrino2020 best fit values for Δm^2 and $\sin^2(\theta_{23})$





- Small datasets: luck will matter and every proton counts!
- Measuring CP violation is tough in NOvA, luck matters even more

NOvA Broader Impact

- Quadruple differential cross section measurements, good precision measurements of rare interactions (SNOWMASS21-NF6_NF8_Jonathan_Paley-068)
- Search for oscillations involving steriles over Δm^2 from 10^{-3} to 10^2 eV^2, non-standard interactions in matter ((SNOWMASS21-NF2_NF3_Gavin_Davies-117)
- Extensive program of astrophysical and beyond-the-standard-model searches (SNOWMASS21-NF4_NF3_Matthew_Strait-090)

See new cross-section, sterile and NSI results in J. Hartnell Neutrino2022 and G. Davies ICHEP2022 talks!

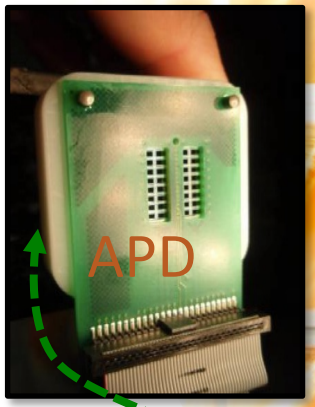
- Broader impact on the future program
  - Scientist development: 53 PhDs and counting
  - Experience in high power neutrino beam operations
  - Experience in running remote shifts and operations
  - Experience in long-baseline oscillation analyses
  - Our machine learning techniques for flavor identification, event reconstruction, energy reconstruction influence DUNE
  - Our CAF analysis framework is in use on DUNE

Summary

- NOvA expects to run through 2026 and looks forward to many exciting physics opportunities.
  - Likely to be statistics-limited for hierarchy and CP-violation throughout the run
  - Reach 3σ sensitivity to the mass ordering for 30-50% of δ_{CP} values
  - More opportunities for neutrino scattering and other non-oscillation physics
- We're engaged in a fruitful collaboration with T2K to fit our combined data to standard 3 flavor oscillations. Results expected this year

Backup

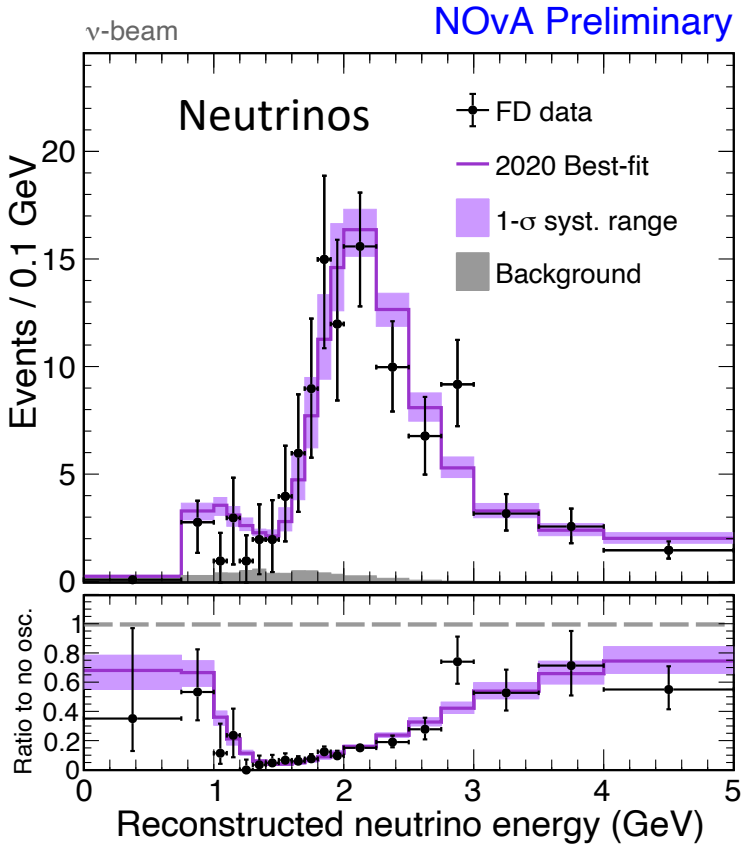
The NOvA Detectors

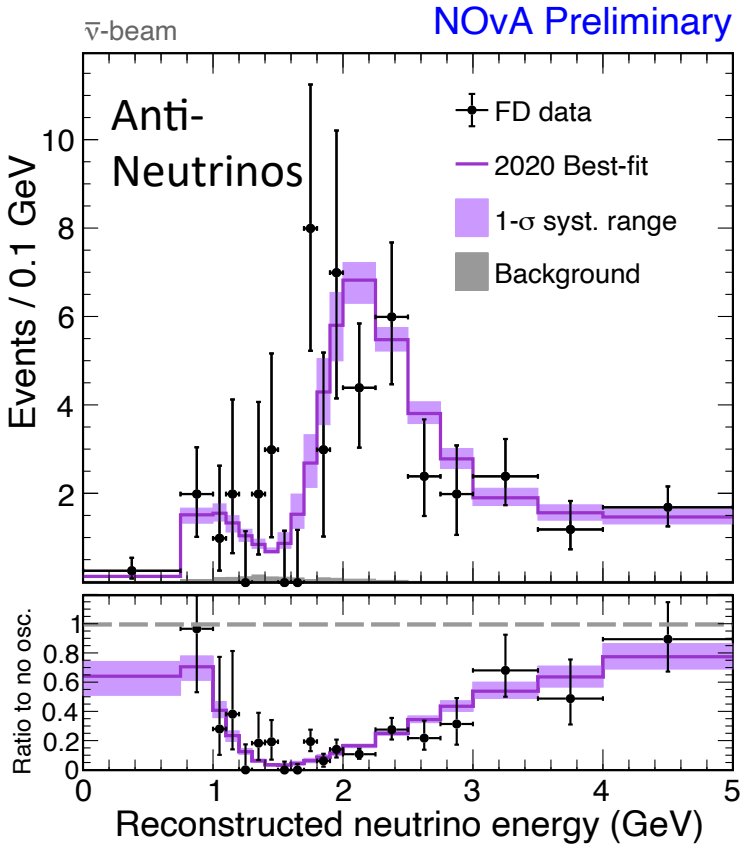


- 65% Active PVC+Liquid Scintillator
  - Mineral Oil
  - 5% pseudocumene
  - Read out via WLS fiber to APD
- Layered planes of orthogonal views
  - muon crossing far end ~40 PE
  - 0.17 X_0 per layer

Far Detector Data—muon neutrinos

NOvA Preliminary
arXiv:2108.08219





211 events, 8.2 background

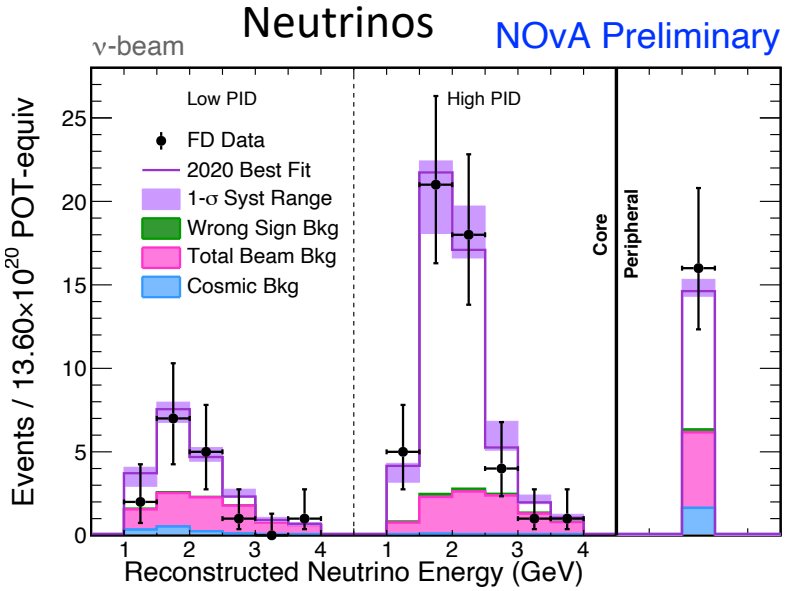
(1156 expected with no oscillations)

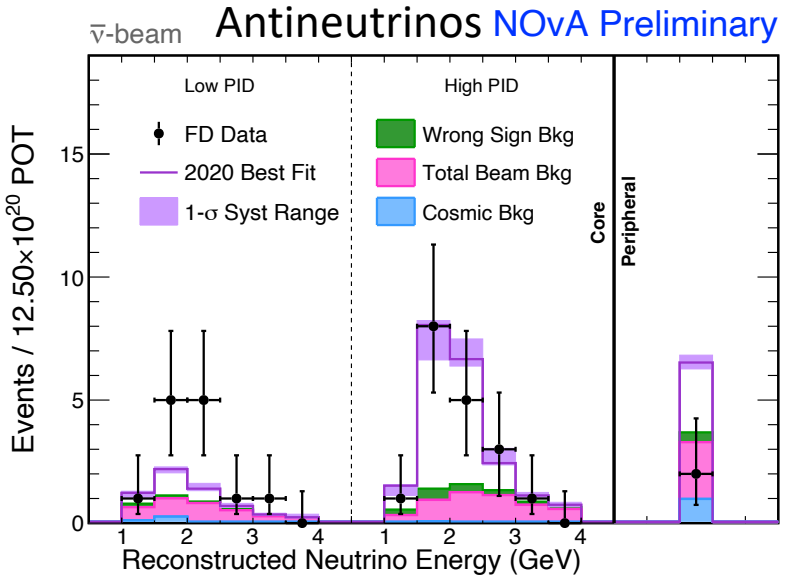
105 events, 2.1 background

(488 expected with no oscillations)

Far Detector Data—electron neutrinos

NOvA Preliminary
arXiv:2108.08219

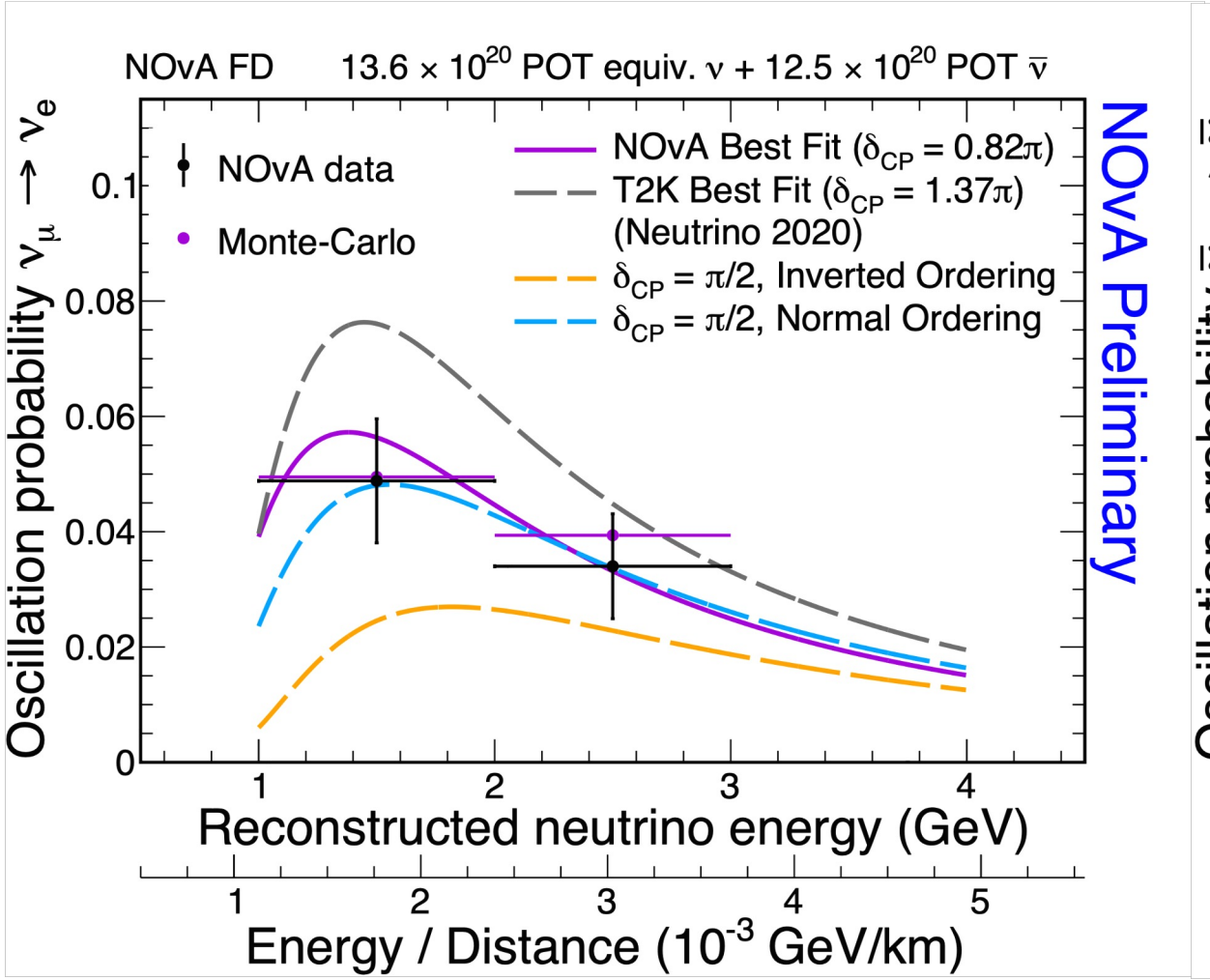


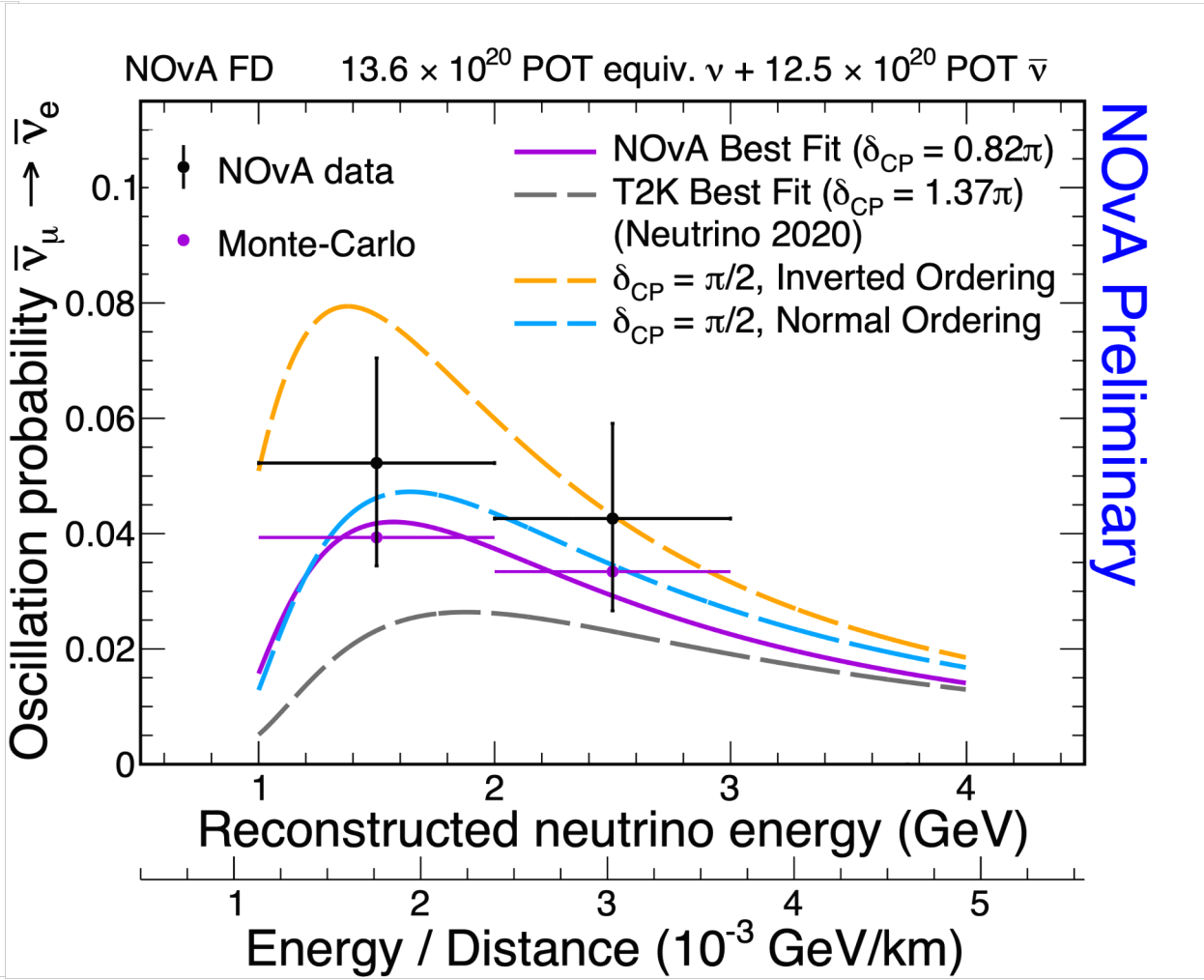


Total Observed	**82**	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

Total Observed	**33**	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

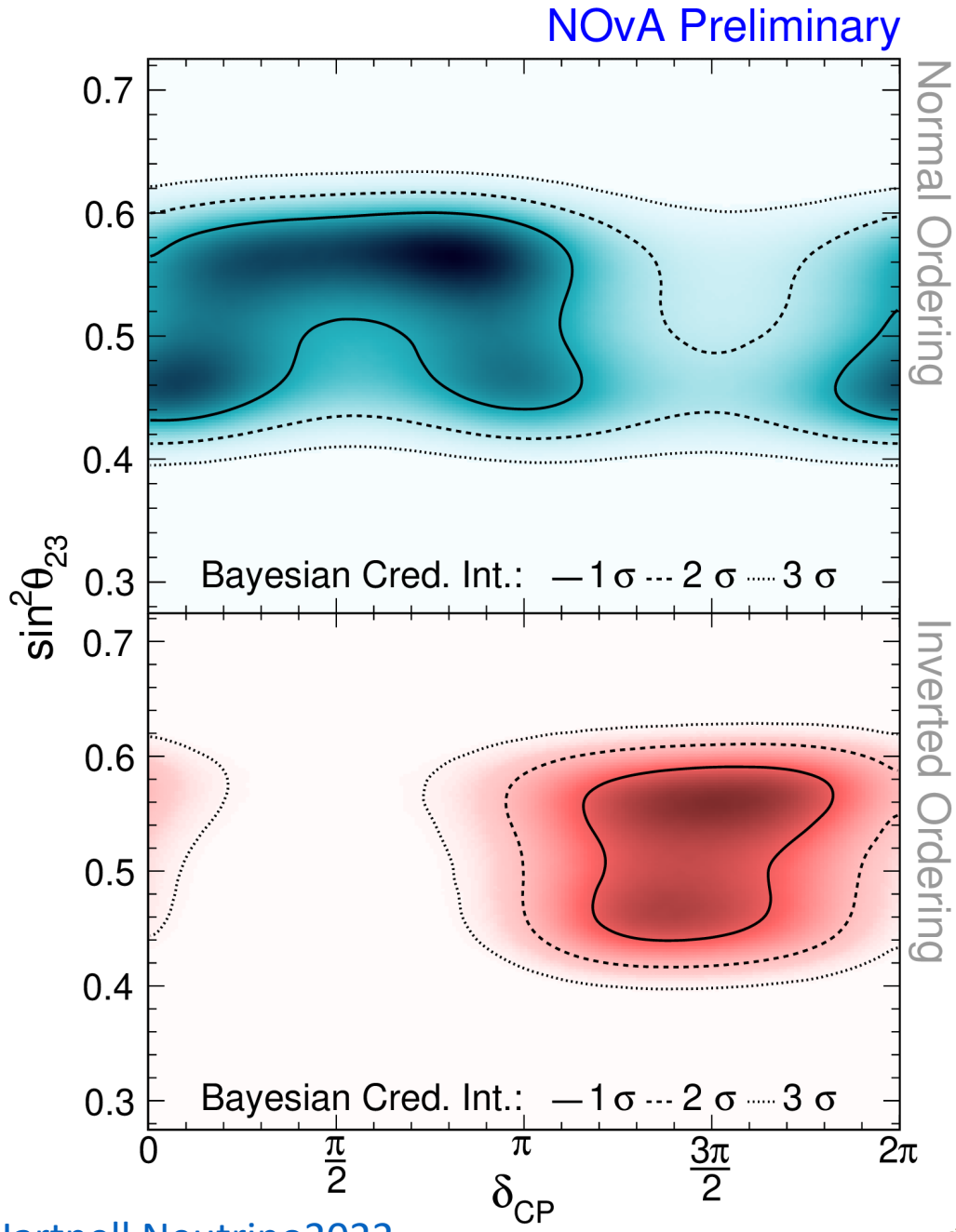
Appearance Probability





Bayesian Oscillation Analysis

- New fit using a Markov Chain MC with a Bayesian analysis
- New fit answers additional questions with the published FD dataset:
  - NOvA-only results for θ_{13}
  - Combinations of parameters interesting to theorists (Jarlskog Invariant)
  - See A. Sztuc Fermilab JETPS June 24, 2022
- Conclusions consistent with previous results.
  - Similar intervals (when using reactor constraint)
  - Weak preference for Normal Ordering and Upper Octant
  - Strongly exclude Inverted Ordering around $\delta=\pi/2$



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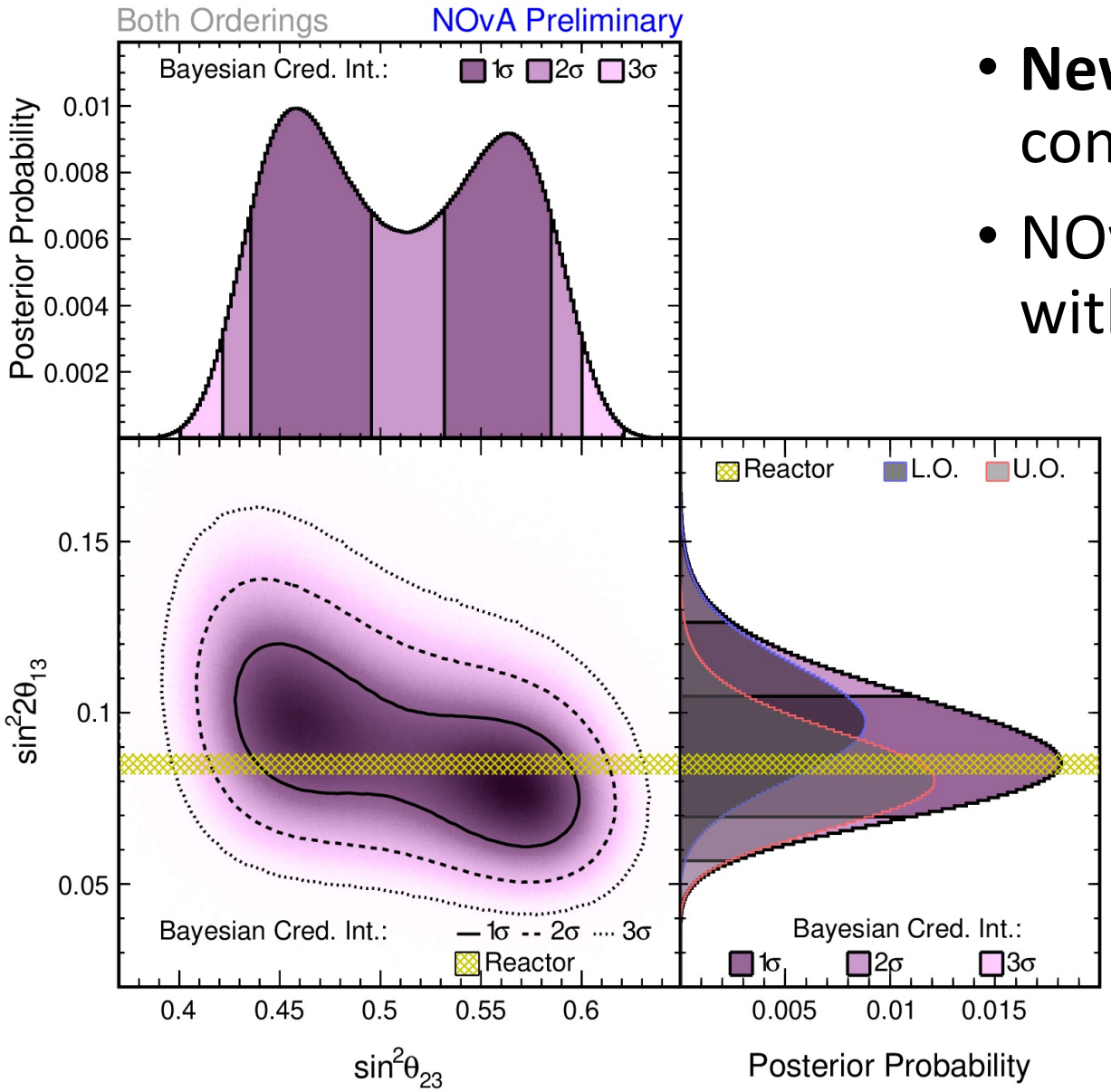
Bayesian Oscillation Analysis



- **New**: fits without reactor constraint on θ_{13}
- NOvA-only value (consistent with reactor average):

$$\sin^2 2\theta_{13} = 0.085^{+0.020}_{-0.016}$$

  - Removing reactor constraint does not strongly impact other NOvA results.

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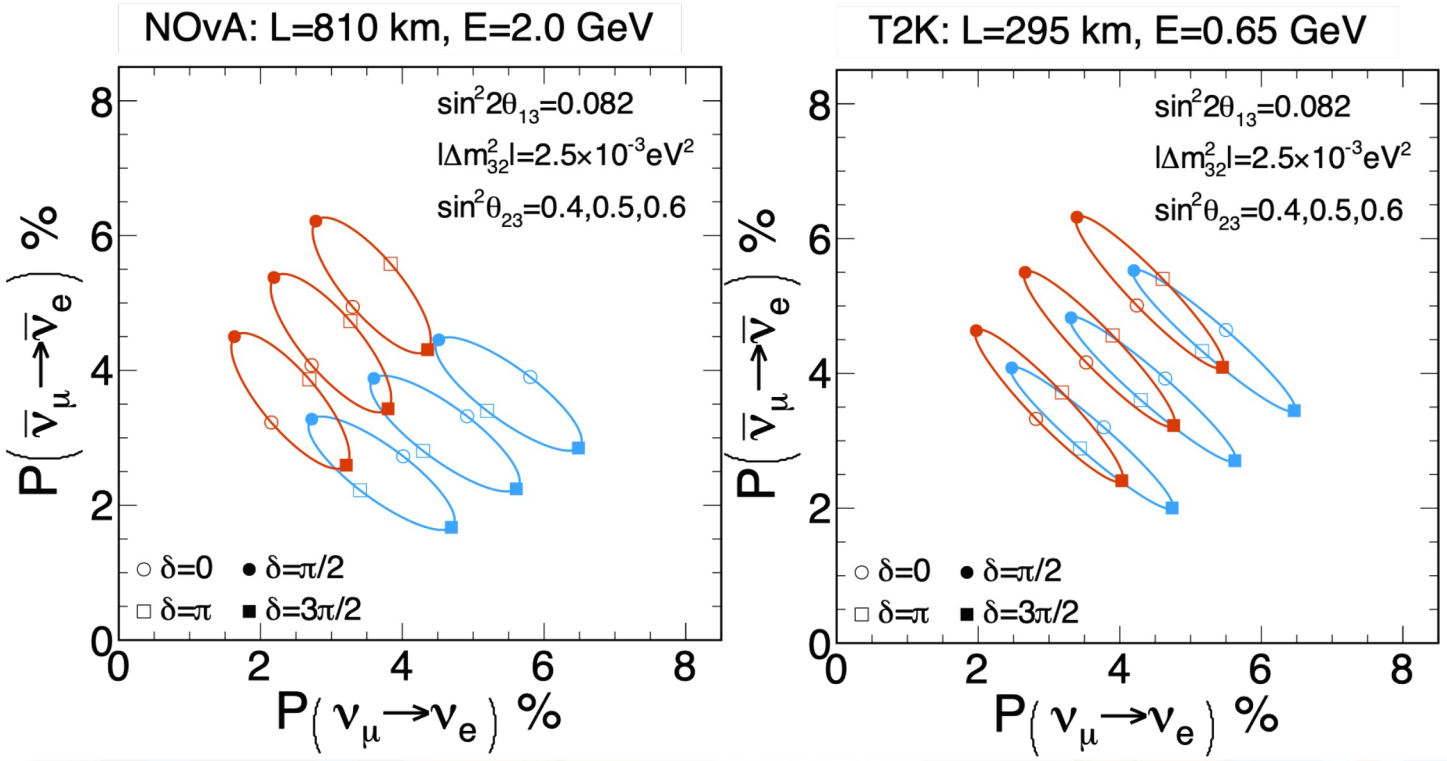
Joint Fit with T2K



- NOvA and T2K have joined forces to produce a combined fit
- T2K's shorter baseline means smaller difference due to mass ordering
  - ±10% T2K compared to ±20% NOvA
- T2K's L/E optimizes CP violation differences
  - NOvA runs a bit above oscillation max to optimize hierarchy determination
  - ±30% T2K compared to ±22% NOvA
- Results expected this year

Future of NOvA

https://ppp-docdb.fnal.gov/cgi-bin/sso/RetrieveFile?docid=724&filename=10yr-PLAN-Current.pdf

Office of the CRO January 2022

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	
PIP II	FNAL				LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	
NuMI	MI	MINERvA	MINERvA	OPEN	OPEN	2x2	2x2	2x2	2x2	2x2	See Note 4				ν
		NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA					
BNB	B	MicroBooNE	MicroBooNE	BooNE	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	LONG SHUTDOWN		OPEN	OPEN	
		CARUS	CARUS	CARU	CARUS	CARUS	CARUS	CARUS	CARUS	ICARUS			OPEN	OPEN	
		SBND	SBND	SBND	SBND	SBND	SBND	SBND	SBND	SBND			OPEN	OPEN	
Muon Complex		g-2	g-2	g-2	g-2	g-2	g-2								μ
		Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e			Mu2e	Mu2e	
SY 120	MT	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF			FTBF	FTBF	p
	MC	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF			FTBF	FTBF	
	NM4	OPEN	SpinQ	SpinQ	SpinQ	SpinQ	SpinQ	SpinQ	OPEN	OPEN			OPEN	OPEN	
LINAC	MTA				ITA	ITA	ITA	ITA	ITA	ITA					
		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	

Construction / commissioning | Run | Subject to further review | Shutdown

Capability ended | Capability unavailable

NOTES

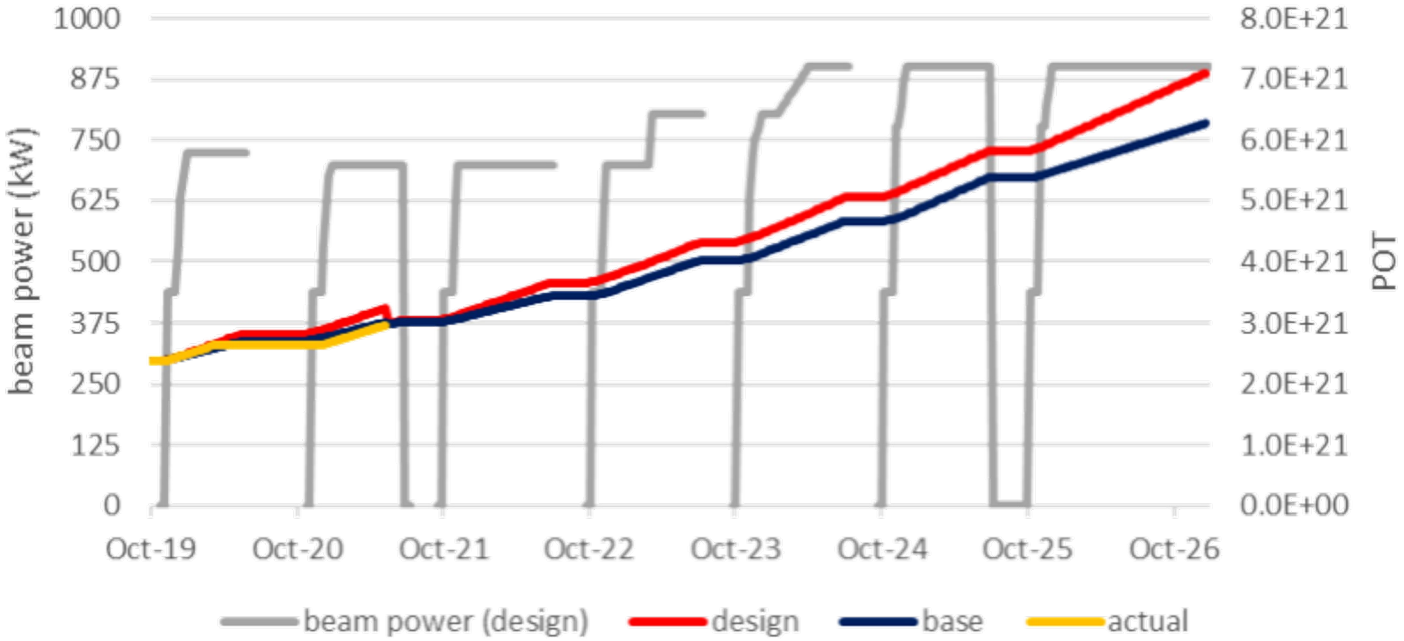
1. This draft long-range plan is updated bi-annually, typically following PAC meetings.
2. The timing and length of the Long Shutdown associated with the major construction activities at the lab will become clearer as the projects are baselined. Optimized commissioning and physics startup plans will be developed. Summer shutdowns will typically last about 4 months during the construction of LBNF/DUNE and PIP-II.

4. NOvA will run at least until the beginning of the Long Shutdown. A decision on whether to run after the Long Shutdown using PIP-II will be made before the Long Shutdown begins. The NOvA experiment will continue to alternate between neutrino and anti-neutrino running.

review.

6. The MTA beamline and the Irradiation Test Area (ITA) began operations in FY21. It will not return in FY29.
7. The optimal timing of the Muon Complex switch from Muon g-2 to Mu2e commisioning and data running will continue to be monitored as Mu2e construction and g-2 data collection progress.

The Future of NOvA



- NOvA will run at least until the beginning of the long LBNF shutdown, through 2026
- Beam power to ~900 kW by FY23
  - New MW-capable targets and horns
  - Early PIP-II work enables higher pulse intensity
  - Faster cycle time after the g-2 run ends.
- 63/72e20 POT pessimistic/optimistic predictions
  - Last results: 29e20
  - Total recorded: 38e20

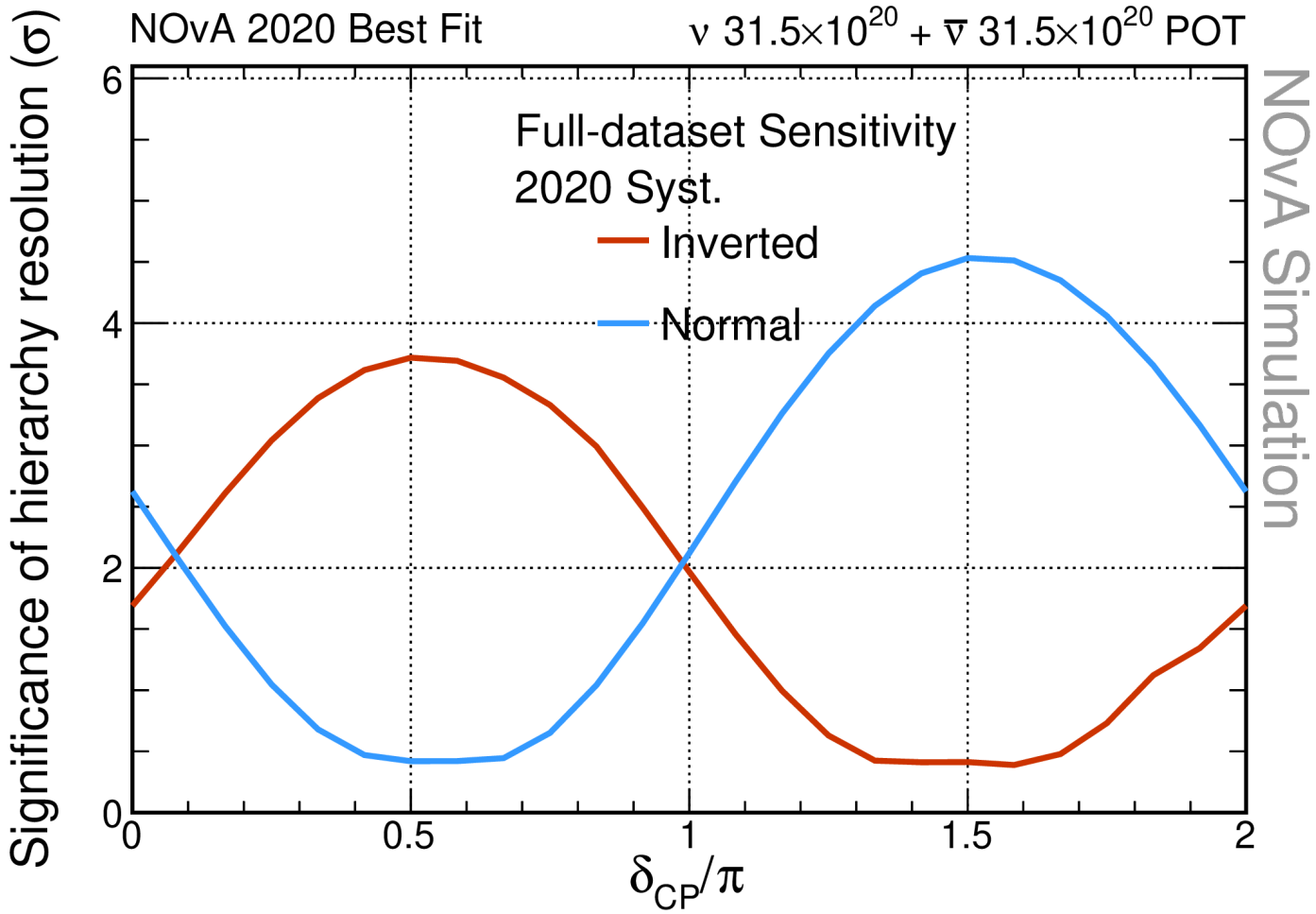

1 MW horn installed 2020


1 MW target installed 2019

FY22 Highlights:

- 1-hour average power record: 895 kW
- Yearly integrated exposure record: 5.81e20 POT delivered

Future Sensitivity: Hierarchy



- Mass ordering significance at 63e20 POT

Other Recent Results

- **New search for non-standard interactions in matter**
  - Simultaneous measurement of δ_{CP} and complex NSI parameters
  - Data consistent with no NSI, introducing NSI does not improve fit quality
  - Presence of NSI does alter our standard 3 flavor oscillation preferences
- New search for mixing into steriles
  - Oscillations including sterile states require anomalous ν_μ disappearance and neutral current disappearance
  - Key innovation: covariance matrix analyses allow oscillations in both detectors (i.e. short and long baselines), spans Δm^2 from 10^{-3} to 10^2 eV^2.
  - No evidence of sterile neutrinos.
- Cross-section measurements aimed at multi-nucleon interactions
  - Very uncertain part of the neutrino interaction model
  - Introduces uncertainty in selection efficiency and apparent energy of the neutrino, influencing precision of oscillation measurements.

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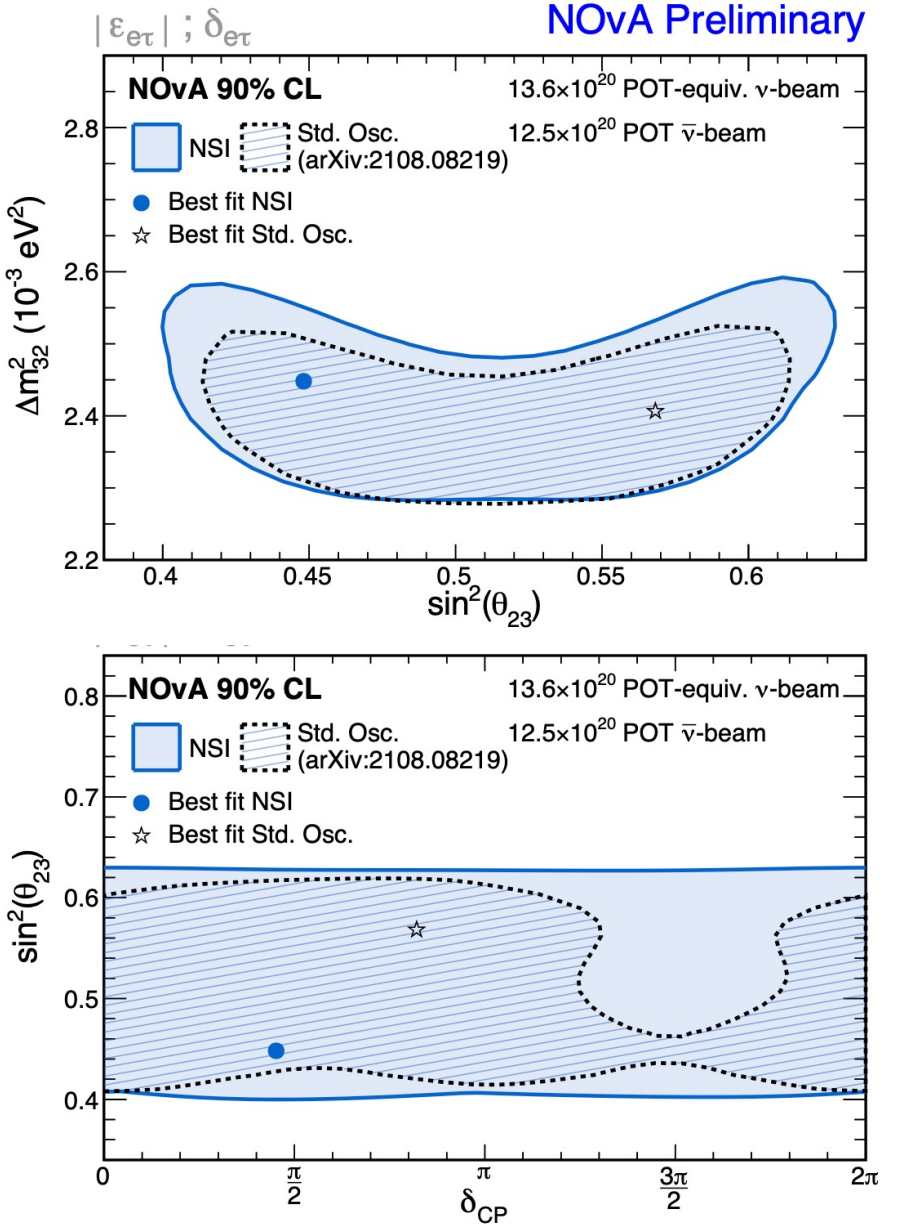
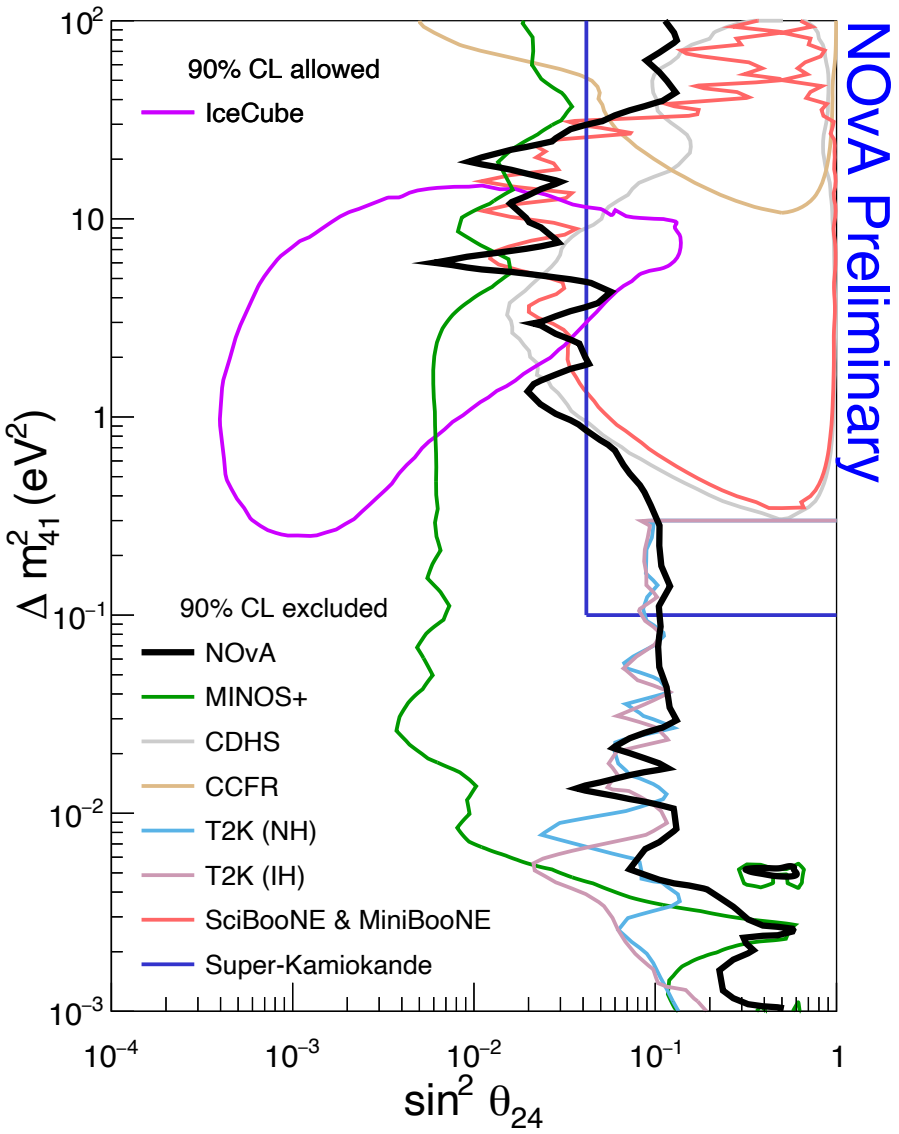
G. Davies ICHEP2022



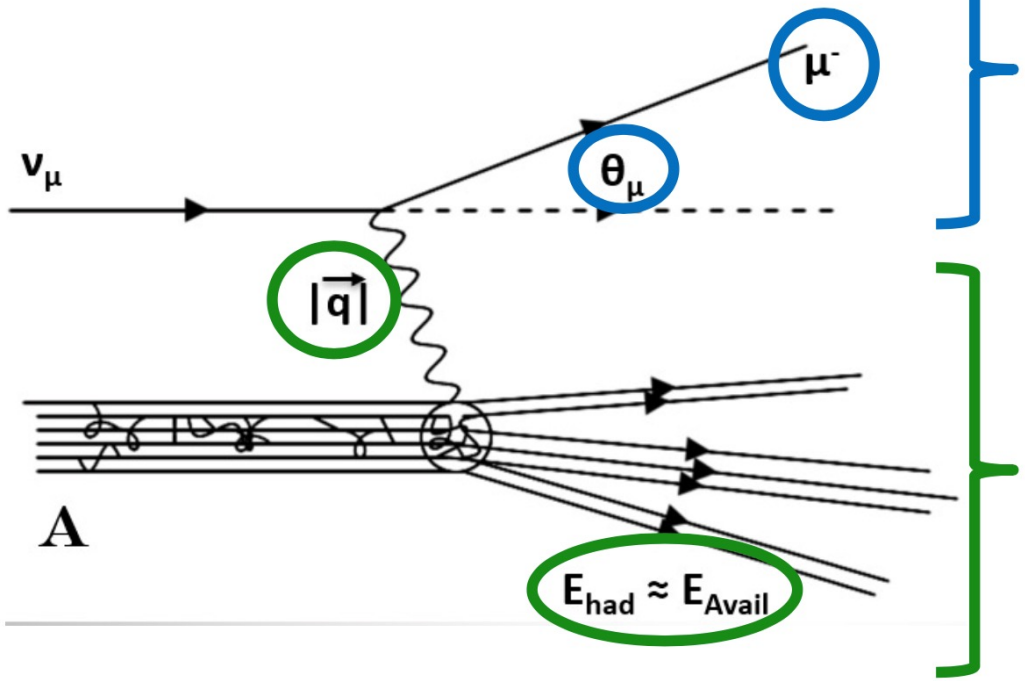
Sterile Neutrino Search

- New analysis technique for 2022, sensitive to Δm^2 from 10^{-3} to 10^2 eV^2.
  - Oscillations including sterile states require anomalous ν_μ disappearance and neutral current disappearance
  - Key innovation: covariance matrix analyses allow oscillations in both detectors (i.e. short and long baselines).
- No evidence of sterile neutrinos. At right: limits on $\sin^2\vartheta_{24}$ vs Δm^2 from disappearance searches
  - NOvA limit is competitive at ~10 eV^2
  - Exclude areas right of the curves
- Also (not shown): absence of neutral current disappearance sets new limits on $\sin^2\vartheta_{34}$ vs Δm^2



Probing Multi-nucleon Interactions

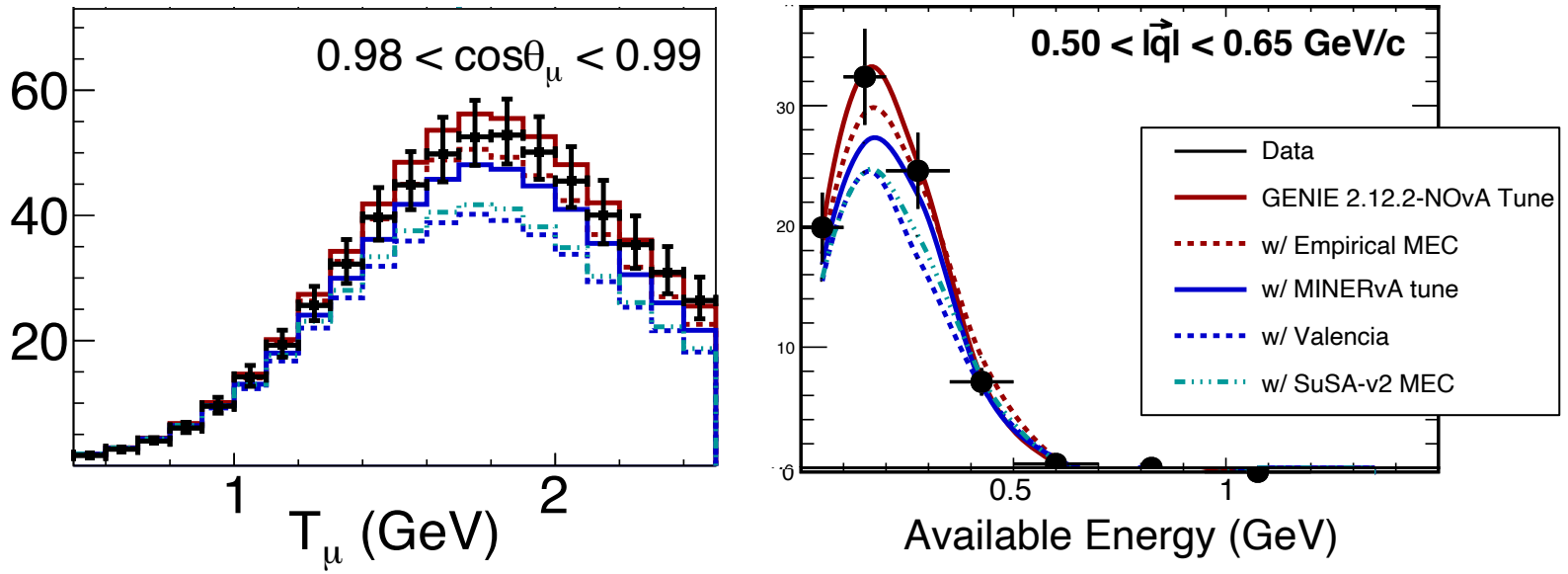
- 2 new measurements aimed at **multi-nucleon interactions**
  - Most uncertain part of the neutrino interaction model relevant to neutrino oscillations.
  - Important since it can alter the selection efficiency and apparent energy of the neutrino and thus influence oscillation measurements.
- Since it is challenging, we use two complimentary methods:



Select events with low hadronic energy, analyze in muon energy and angle

Select all ν_μ CC events, then analyze in 3-momentum transfer vs. hadronic energy

Measurements of Multi-nucleon Cross Section



- Examples of results shown above.
  - Measurements are two-dimensional, so multiple plots like those above make up the full results.
- NOvA data is more consistent with empirical tunes (red, dashed red, blue) than pure theory models (dashed blue, teal)
  - Based on a χ^2 calculation including the correlated impact of systematic uncertainties.