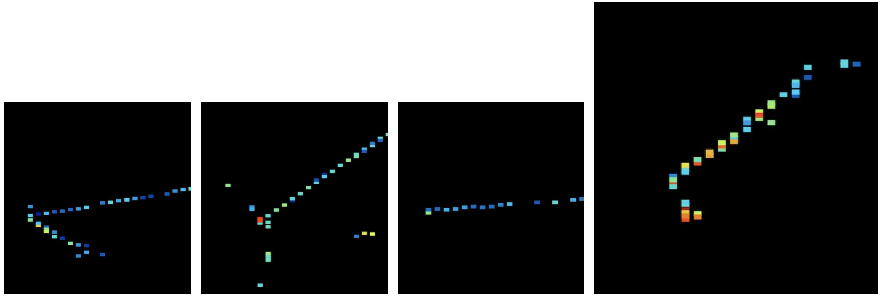


Probing Neutrino Oscillations at The NOvA Experiment

55th Annual Fermilab Users Meeting

***Adam Lister**, on behalf of the NOvA Collaboration*
University of Wisconsin – Madison

16 June 2022

NOvA

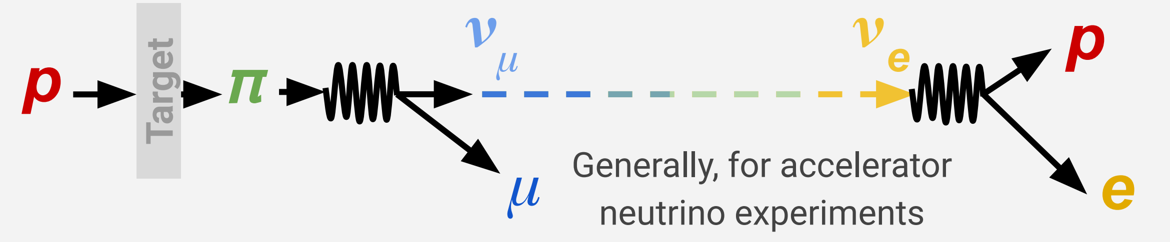
WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Neutrino Oscillations

Neutrinos mix… …and oscillate between different flavours!

Flavour eigenstates — Mixing Matrix — Mass eigenstates

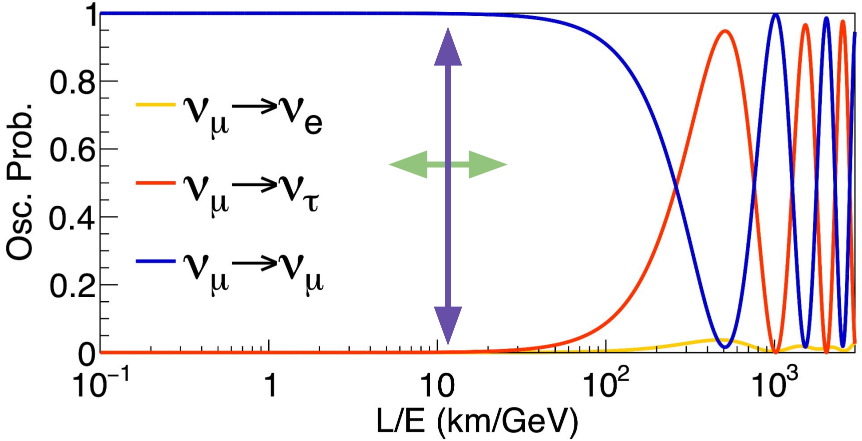
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$



The **three-flavour** model of neutrino oscillations (ν_e, ν_μ, ν_τ) has been very successful

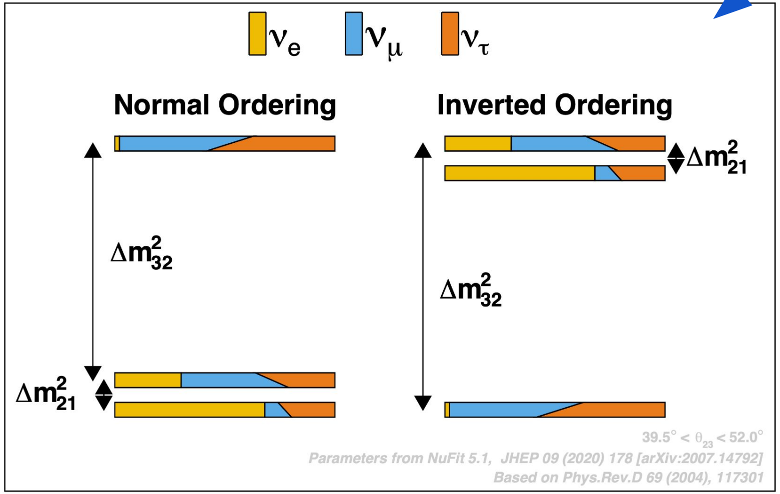
- Δm^2_{21}, Δm^2_{32} control **frequency**
- θ_{12}, θ_{13}, θ_{23} control **magnitude**
- δ_{CP} controls **ν-$\bar{\nu}$ differences**
- L (baseline)
- E (neutrino energy)

L and E: **Experimental choices!**



Open Questions

What is the Neutrino Mass Ordering?
Normal or inverted?
Implications for $\nu 0\beta\beta$, cosmology!



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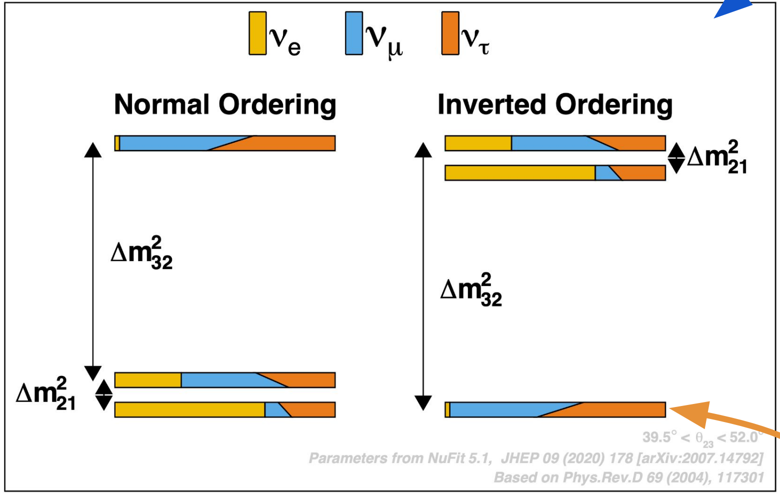

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For ν_3, does $\nu_\mu = \nu_\tau$?

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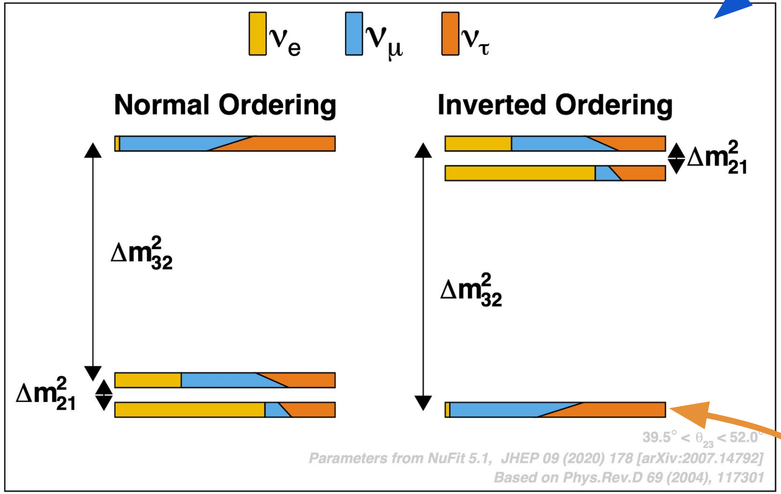

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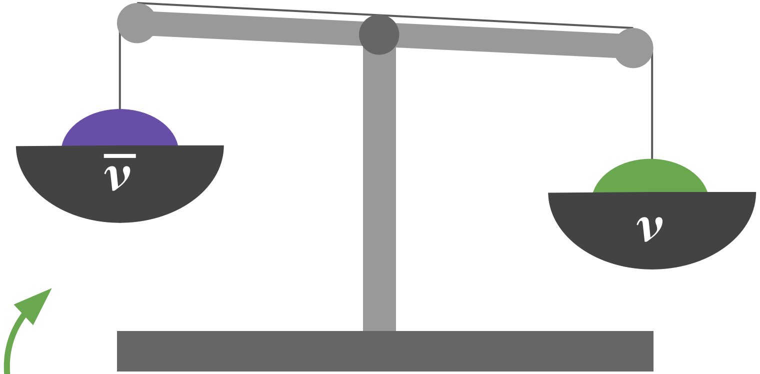

Is CP violated?
Non-conservation of CP important for matter-antimatter asymmetry

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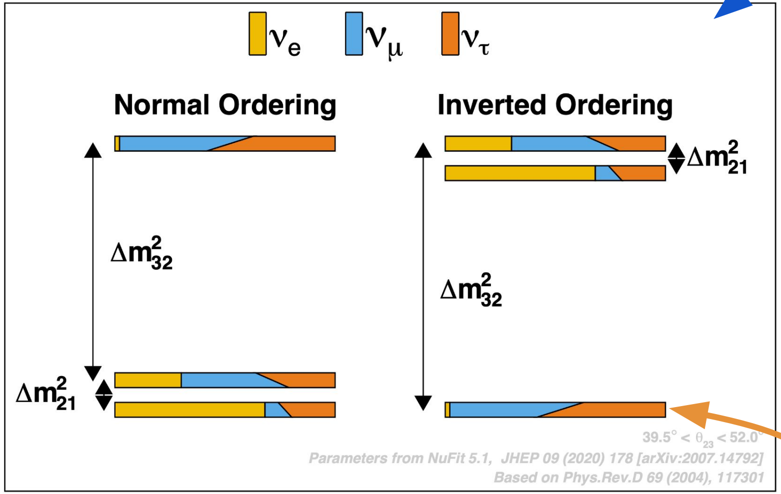

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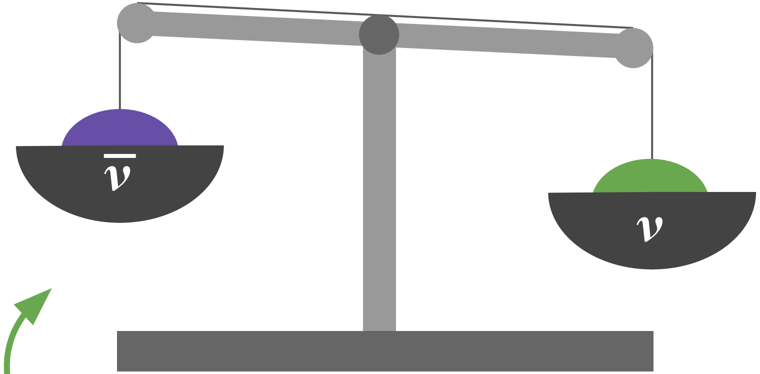
ν_μ ν_e ν_τ ?

Is three-flavour the full picture?
Additional neutrino states?
Non-standard interactions?



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In this talk
NOvA's oscillation analyses can probe these open questions!

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New Bayesian treatment of NOvAs three-flavour analysis

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A new search for sterile neutrinos in the NOvA data

<u>In this talk</u>
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New Bayesian treatment of NOvAs three-flavour analysis

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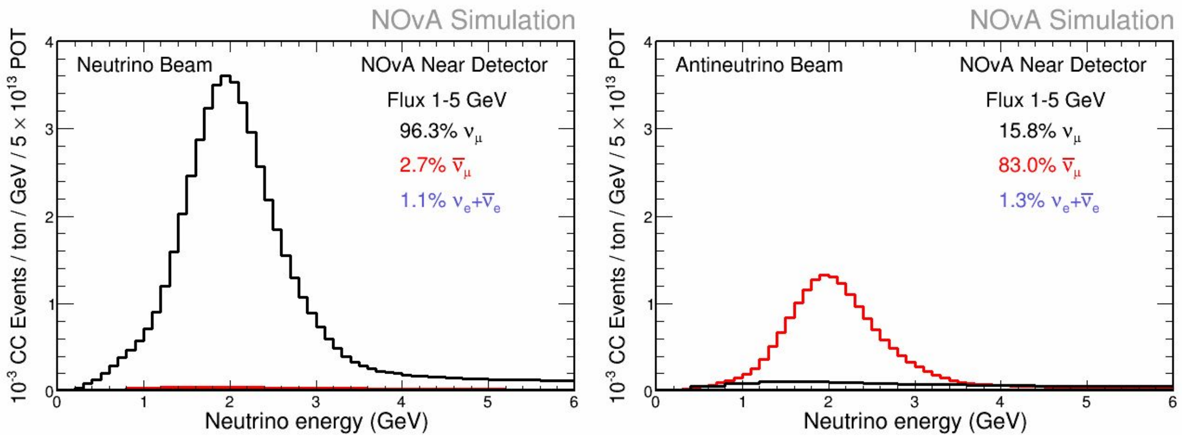
An Introduction to The NOvA Experiment

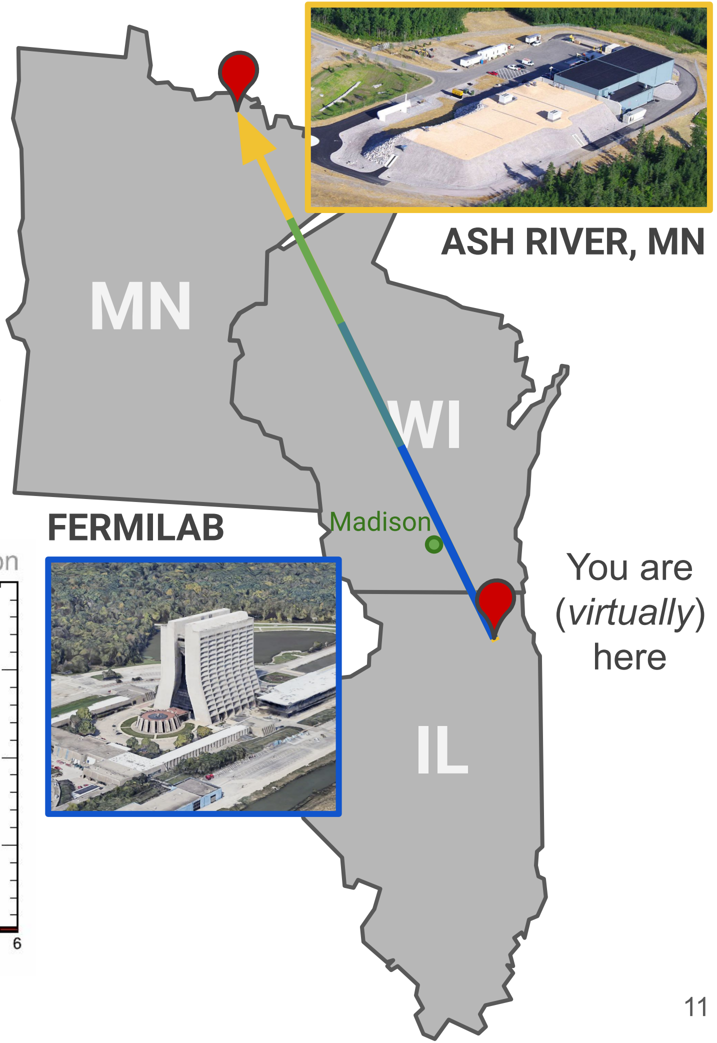
The NOvA Experiment

NOvA is a long baseline neutrino experiment.

- **Near Detector ~1 km**, **Far Detector ~810 km**
- Detectors **14 mrad off-axis** of the NuMI beamline
  - Neutrino energy peaked around **2 GeV**

Collected 37×10^{20} protons-on-target (**Thank you Fermilab!**)
Used in these analyses: **13.6×10^{20}** POT ν-beam data
12.5×10^{20} POT $\bar{\nu}$-beam data

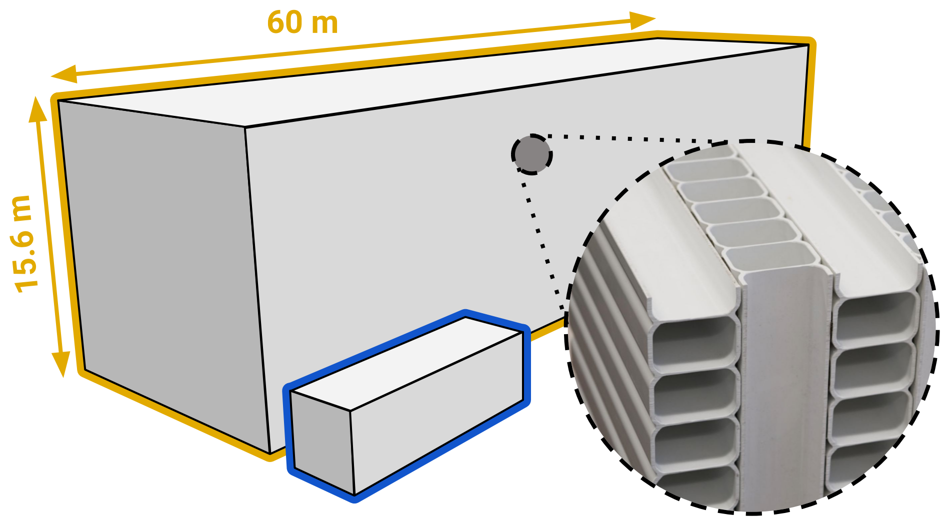




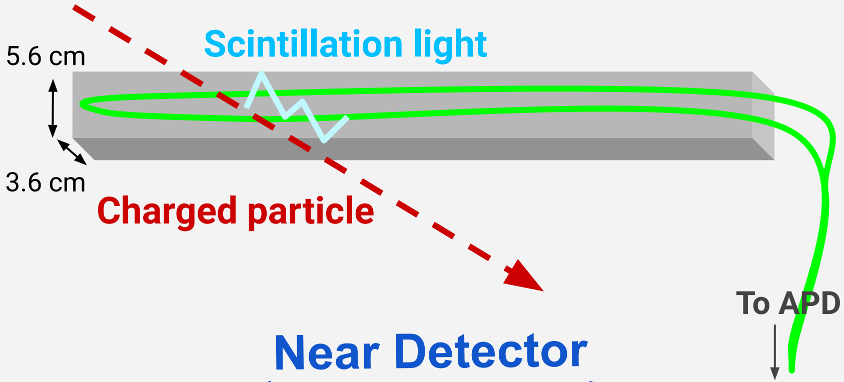
The NOvA Detectors

Functionally identical Near and Far detectors

- Segmented tracking calorimeters
- Extruded PVC cells filled with liquid scintillator



Cells! The Building Block of NOvA



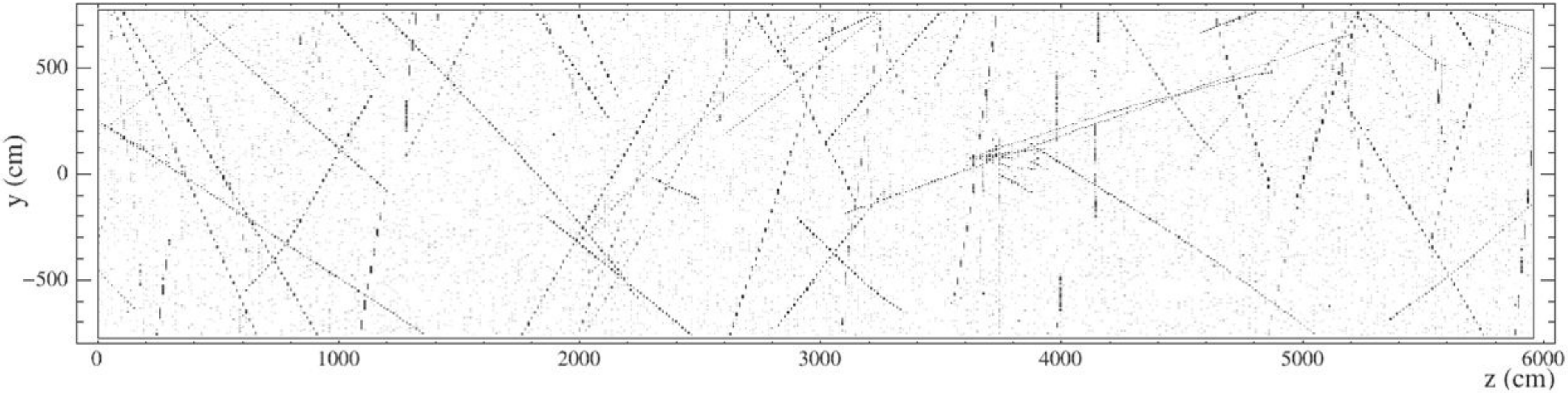
Near Detector
3.9 m
0.3 kT – 20,192 channels

Far Detector
15.6 m
14 kT – 344,064 channels

Alternating plane orientation → **two views per event**

Neutrino Interactions in NOvA

The NOvA detectors are optimised for surface running in a 2 GeV beam!



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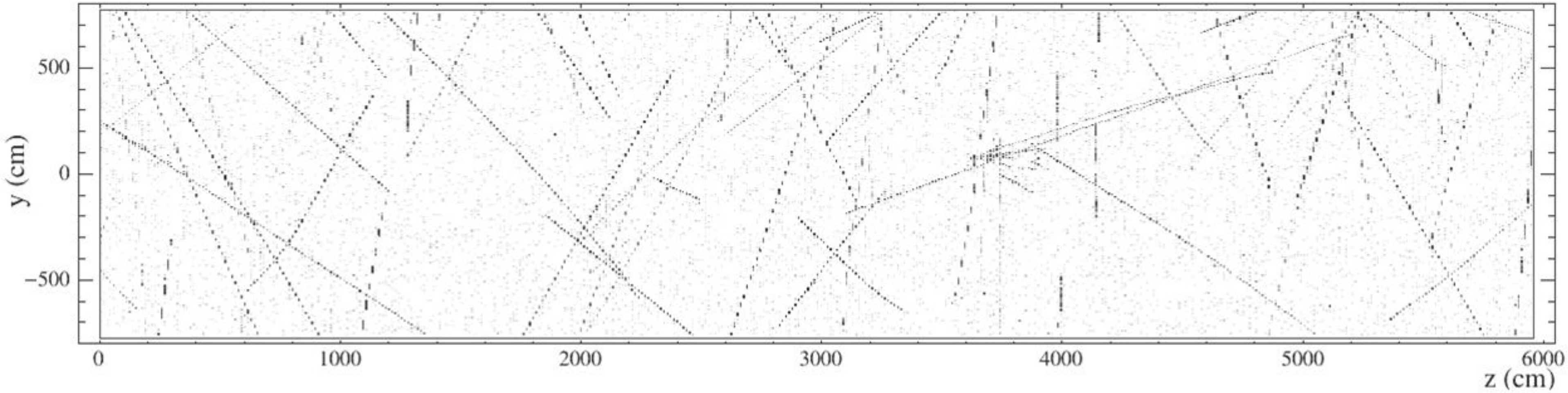
- **Have ~10 ns timing**
  - Select ν from overwhelming cosmic backgrounds (FD)
  - Separate ~10s ν per spill (ND)



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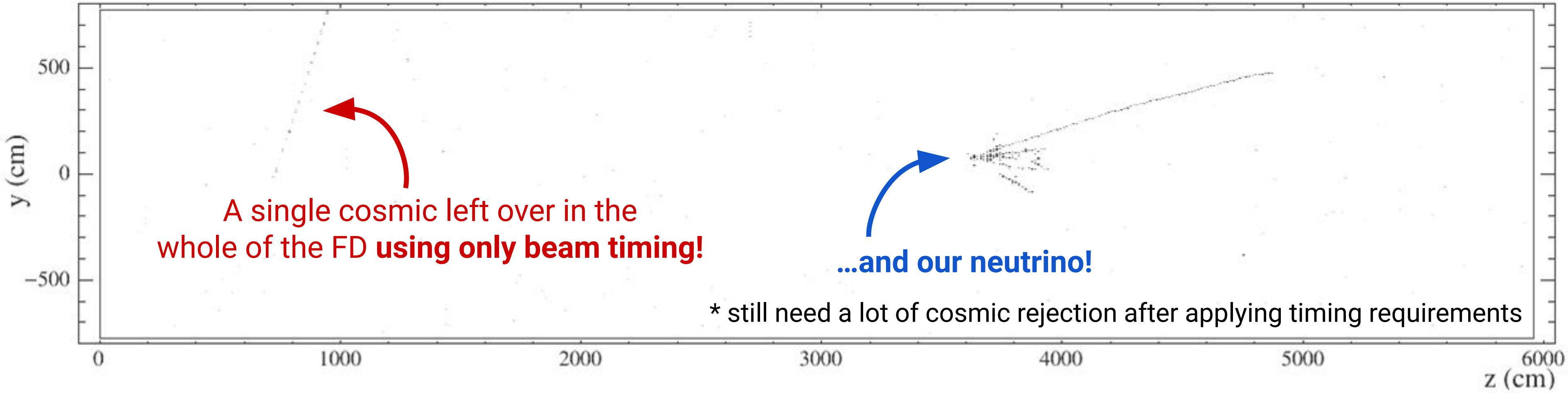

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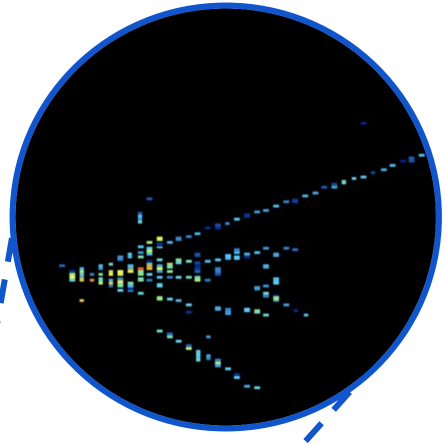

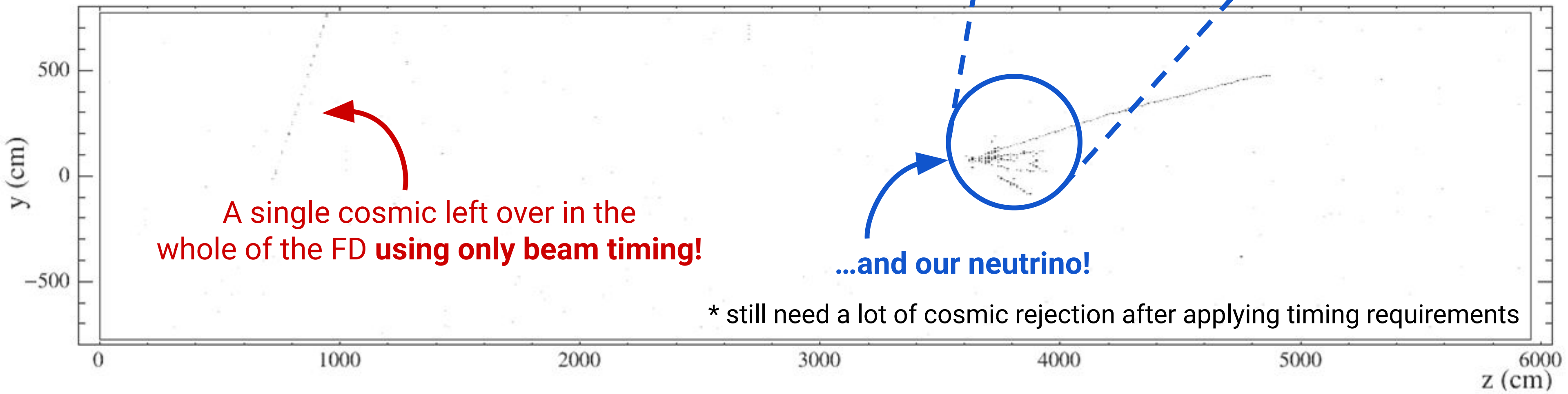

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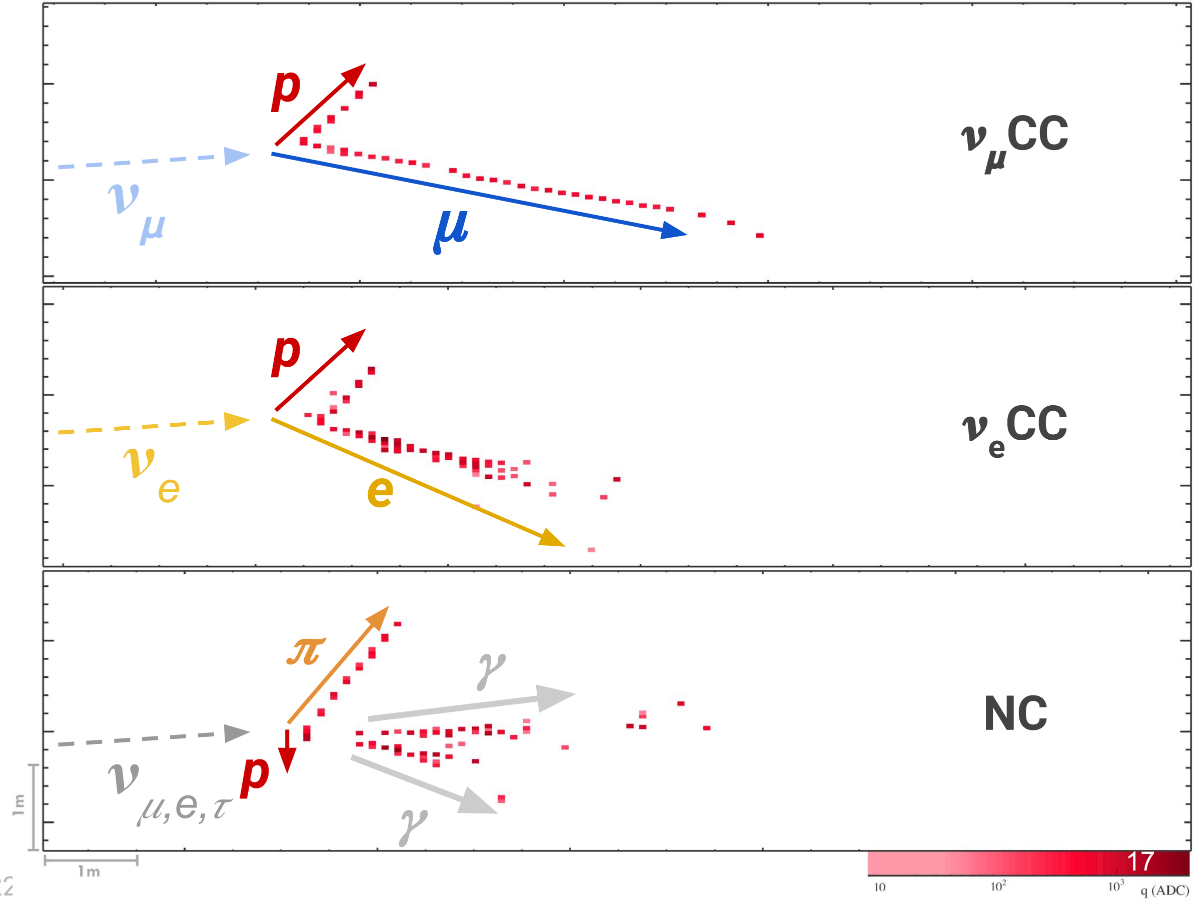
- **Small atomic mass provides radiation length ~ 40 cm**
  - ~6 samples per radiation length → **electrons** easy to disambiguate from **muons**
  - Large photon conversion distance help with π^0 background rejection



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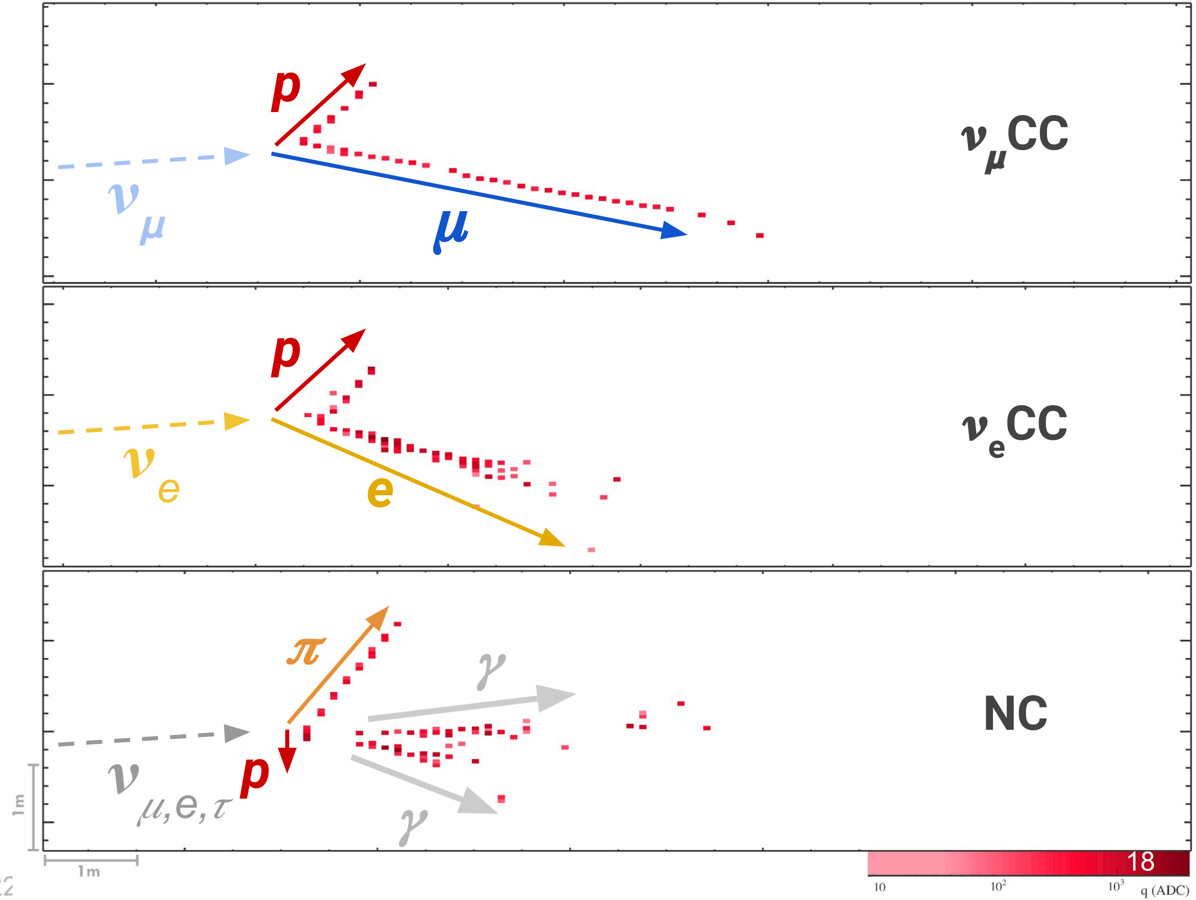
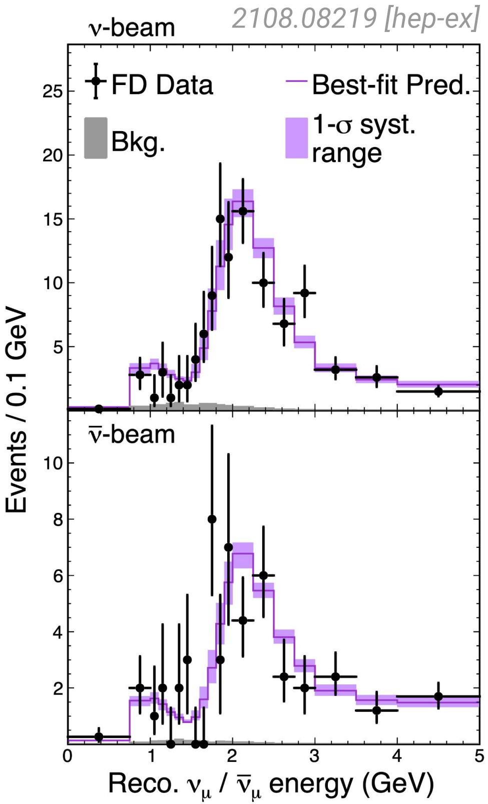
  - Large photon conversion distance help with π^0 background rejection
- **Machine Learning algorithms** used for particle ID and event ID



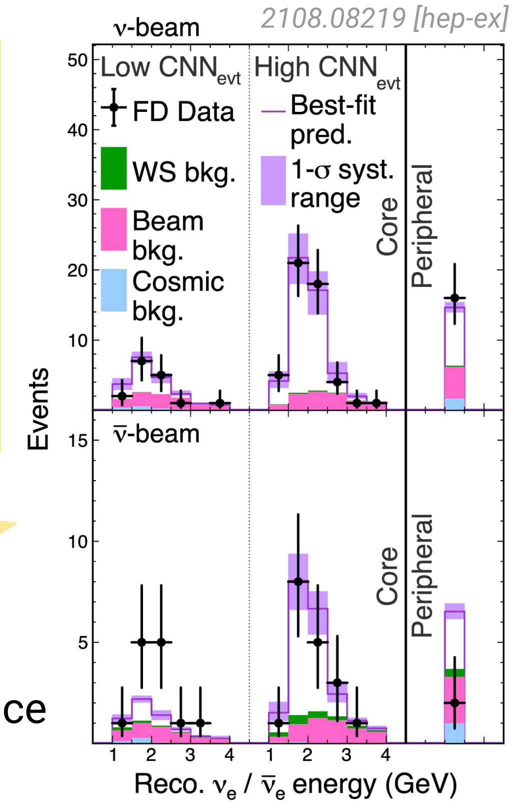
Results!

2020 Far Detector Spectra



Very high purity selection for both ν and $\bar{\nu}$ modes

Backgrounds primarily from **ν_e intrinsic** to the beam **(irreducible)**



>4σ $\bar{\nu}_e$ appearance

Disfavour strong asymmetry in ν_e-$\bar{\nu}_e$ appearance

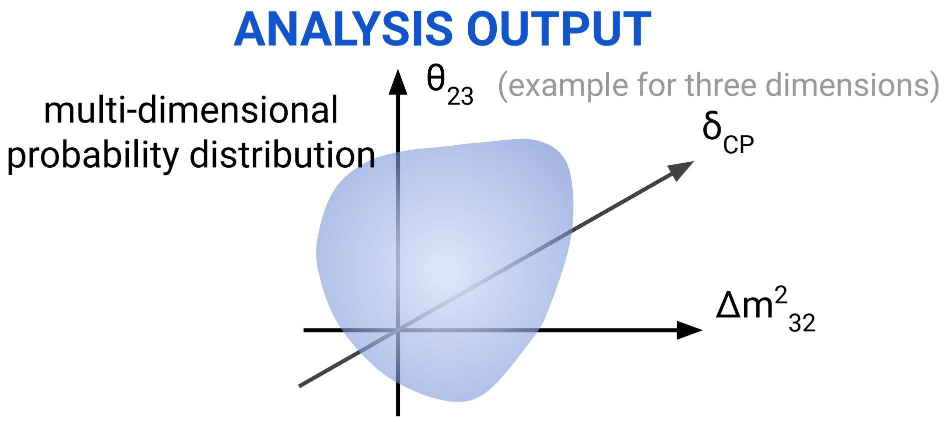
A New Bayesian Strategy!

Different statistical techniques help us probe our data in different ways!

We've developed a new Bayesian analysis in the context of our three-flavour analysis.

Main Take Away

The **probability distribution** can be used to **quickly produce credible intervals for new parameters**!



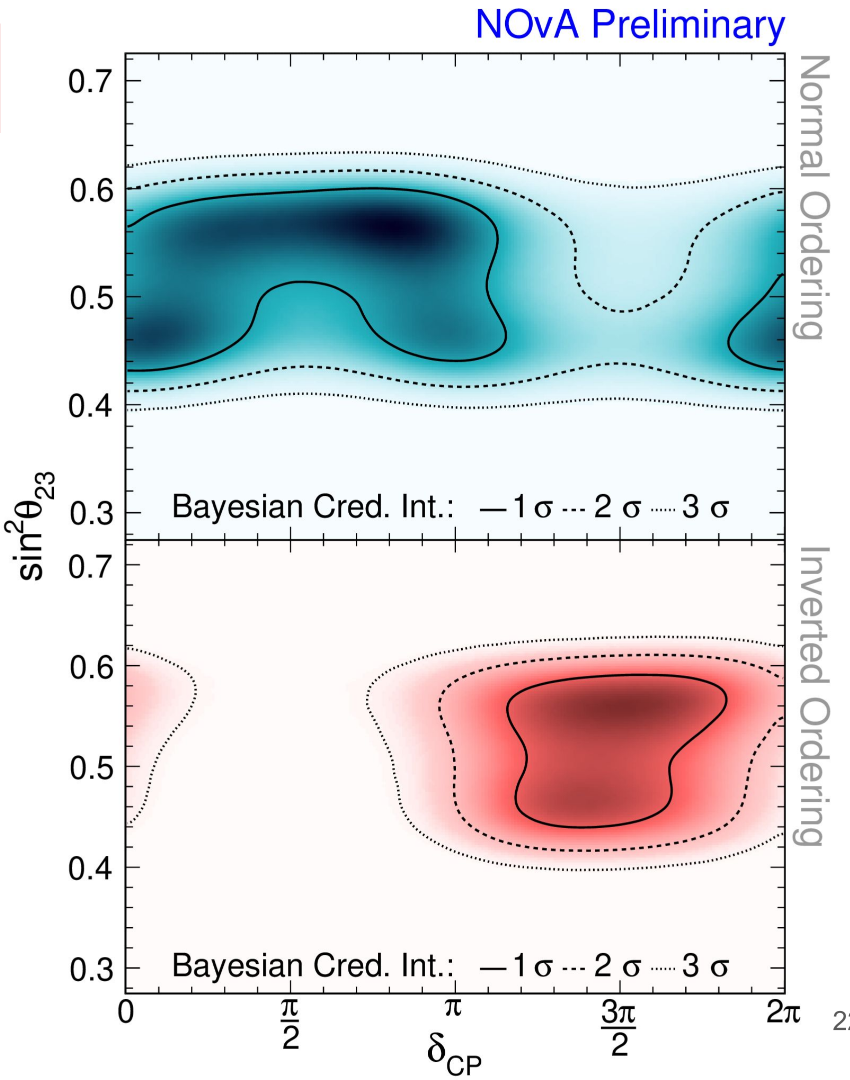
Bayesian Analysis Results

Conclusions drawn from the data are the same as in previous frequentist analysis

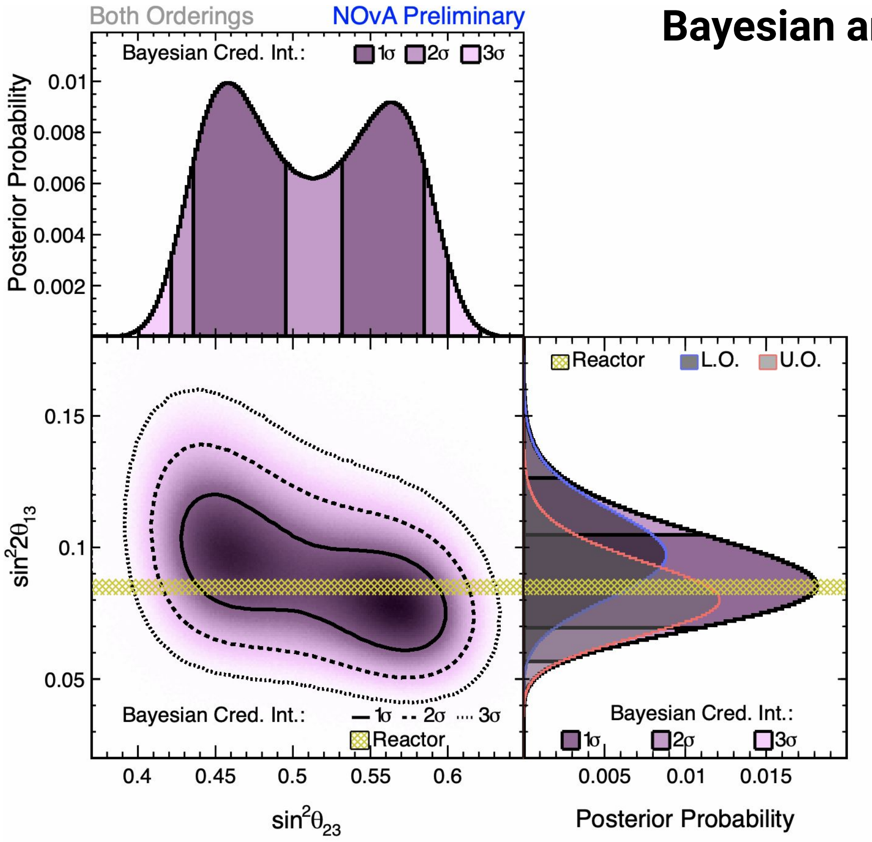
Exclude $\delta_{CP}=\pi/2$ at >3σ (IO)

Less strong constraint on δ_{CP} in the NO, but **disfavour** region around $\delta_{CP}= 3\pi/2$

Weak preference for NO, Upper octant



NOvA θ_{13} Measurement



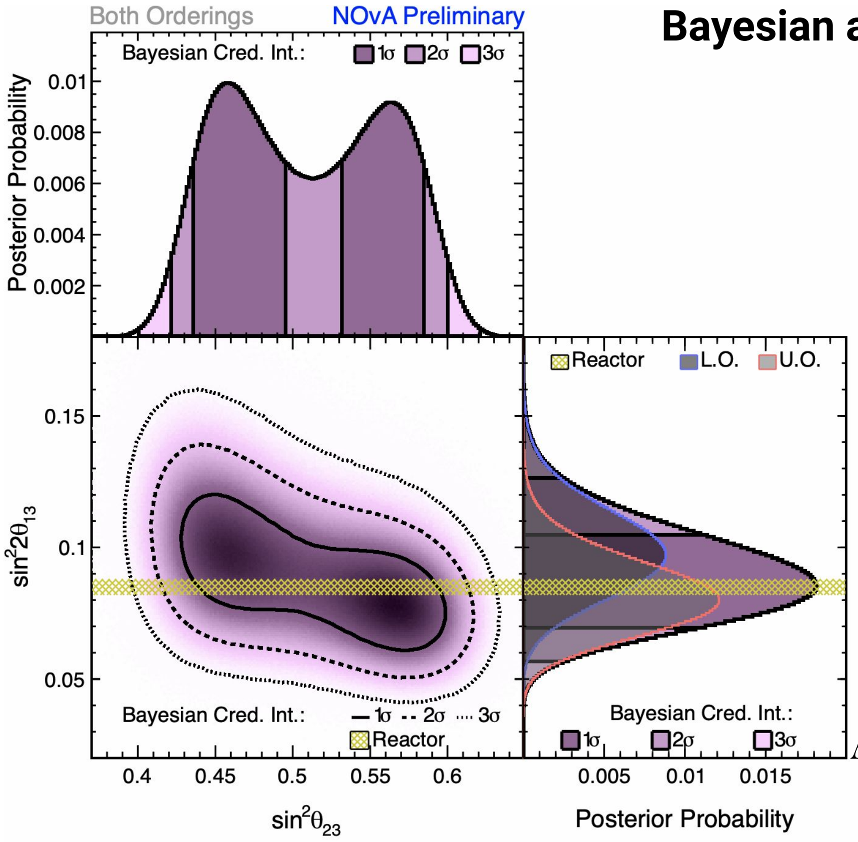
Bayesian analysis allows us to report a measurement of θ_{13}

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

When reporting measurements of other parameters, we **constrain θ_{13} using reactor neutrino** results (**yellow**, hashed).

Good agreement with reactor experiments!

NOvA θ_{13} Measurement



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Good agreement with reactor experiments!

24th June

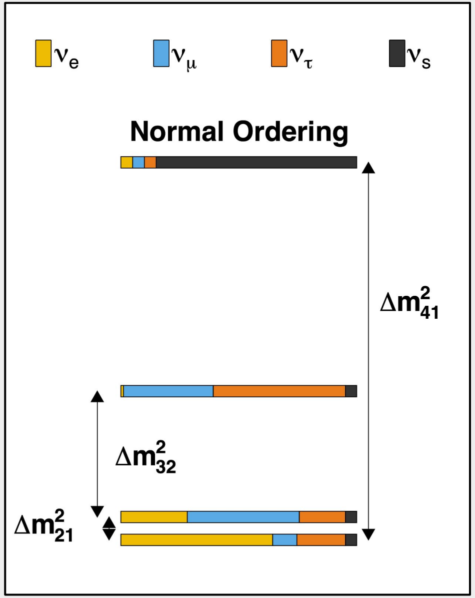
Fermilab Wine & Cheese Seminar

A Bayesian Look at 3-flavor Oscillations in NOvA: Drilling Deeper into PMNS

Artur Sztuc

Looking For New Physics

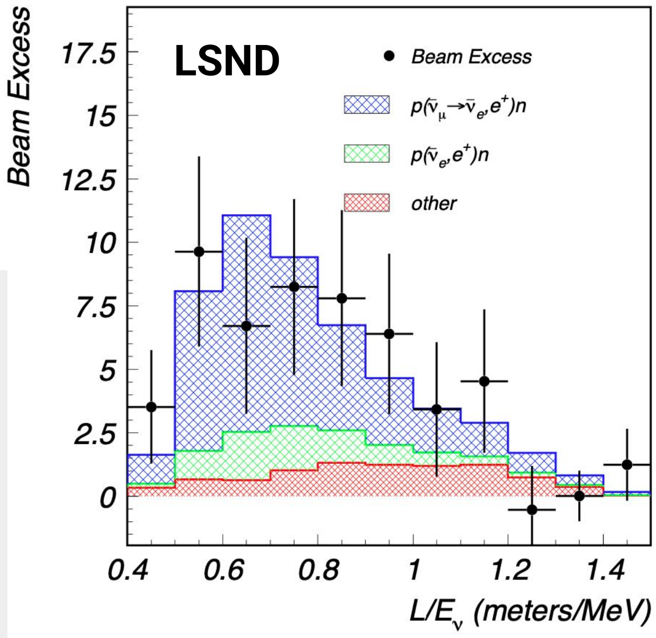
Several anomalous results potentially explained by oscillations with $\Delta m^2 >> \Delta m^2_{21}, \Delta m^2_{31}$ (**not predicted by three-flavour!**)



Previous **NOvA** analyses use NC disappearance to probe the possibility of a **3+1 model**

Phys.Rev.D 96 (2017) 7, 072006
Phys.Rev.Lett. 127 (2021) 20, 201801

Phys.Rev.D 64 (2001), 112007



Limitation was using ND data to predict far detector spectrum, using a dedicated tune of the cross-section models to NOvA data

Analysis Strategy

Two Detector Fit

No NOvA cross-section tune
Tailored systematic uncertainties
This allows us to **increase our Δm^2_{41} range**

Analysis Samples

NC sample

Any oscillation in ND is governed **entirely by sterile parameters**

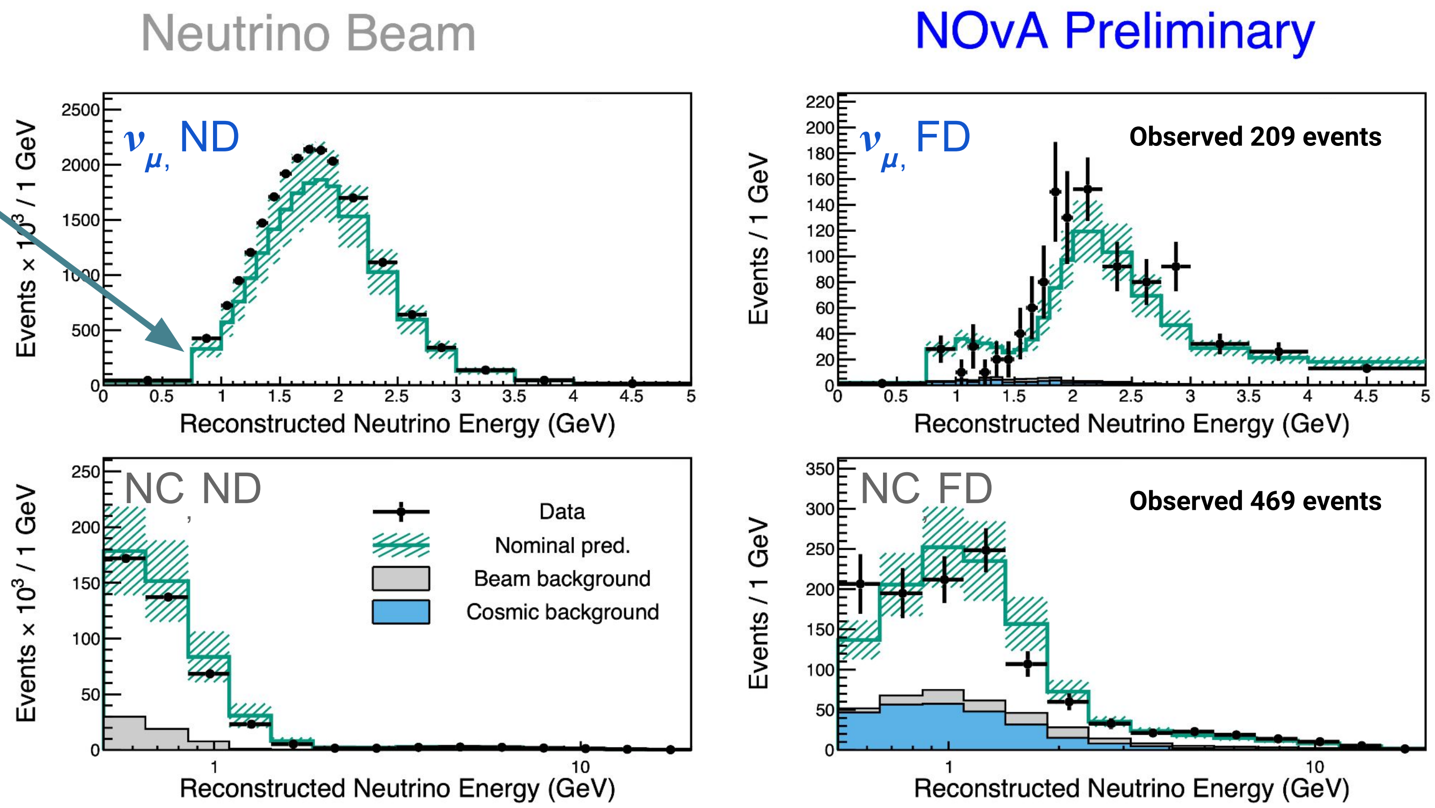
Oscillations at FD are at **atmospheric frequency** and give us access to θ_{24}, θ_{34}, δ_{24}

ν_μ sample

Constrains Δm^2_{32}, θ_{23} and size of θ_{24}

Sterile Neutrinos at NOvA

Pre-fit distributions
(No NOvA cross-section tune)



Sterile Neutrinos at NOvA

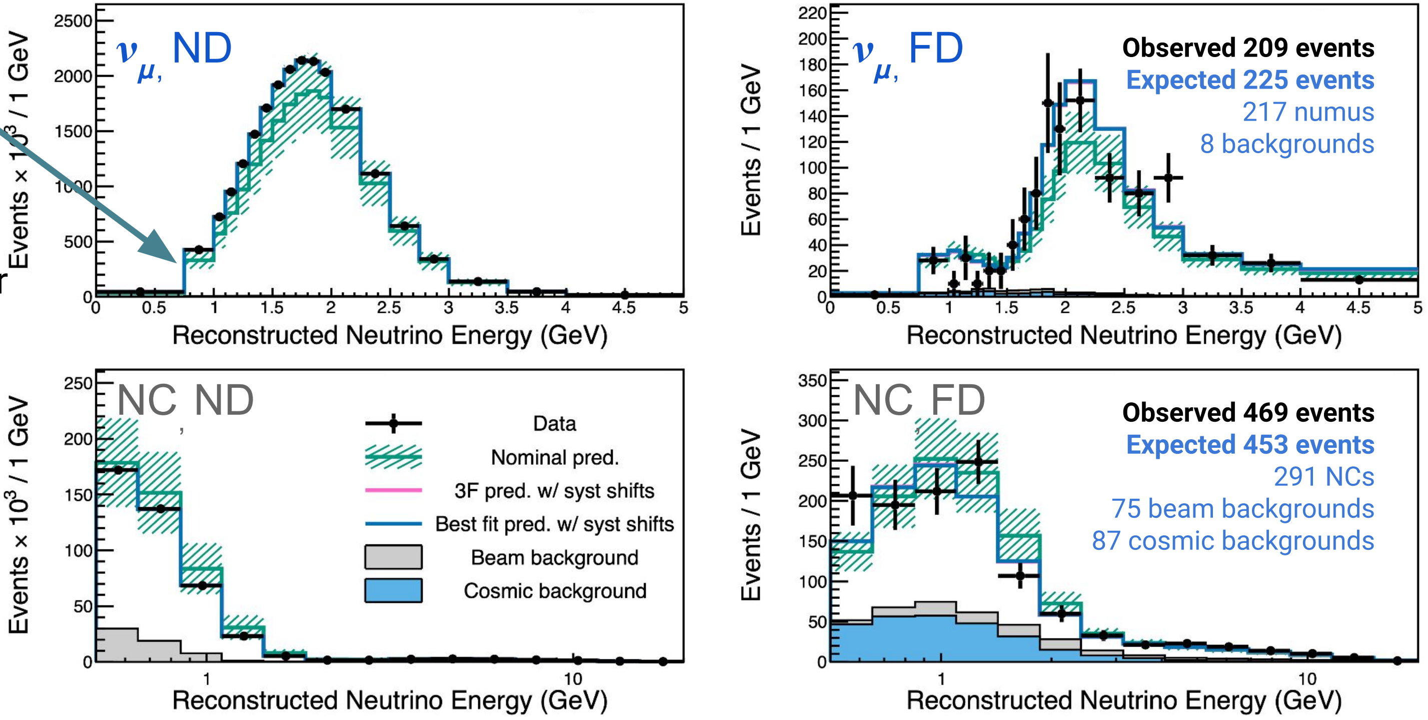
Neutrino Beam

NOvA Preliminary

Pre-fit distributions
(No NOvA cross-section tune)

Three-flavour prediction lays almost perfectly under our **3+1 best fit**

This data can be well described by 3-flavour oscillations within our systematic uncertainties



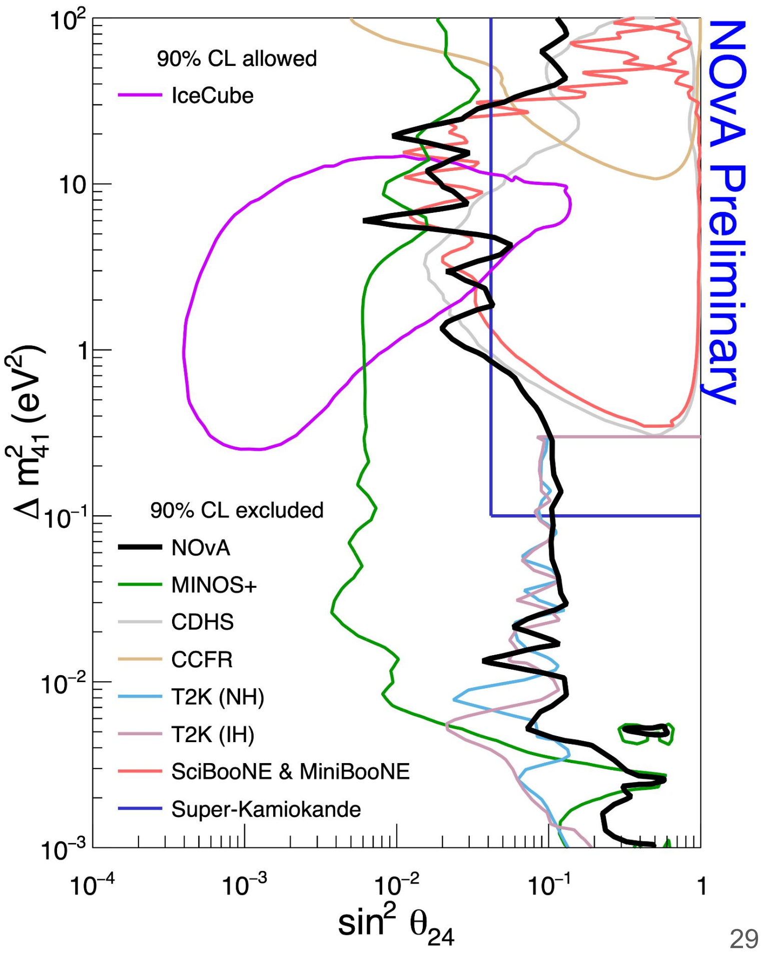
Sterile Neutrino Results

NOvA data shows no evidence for sterile neutrinos under 3+1 model

Sensitivity **at high Δm^2_{41} driven by the Near Detector**, and is systematics limited

Sensitivity **at low Δm^2_{41} driven by the Far Detector**, and is less systematics limited

Limits on θ_{24} are competitive around Δm^2_{41} = 10 eV^2
→Limits come from both ν_μ and **NC** samples



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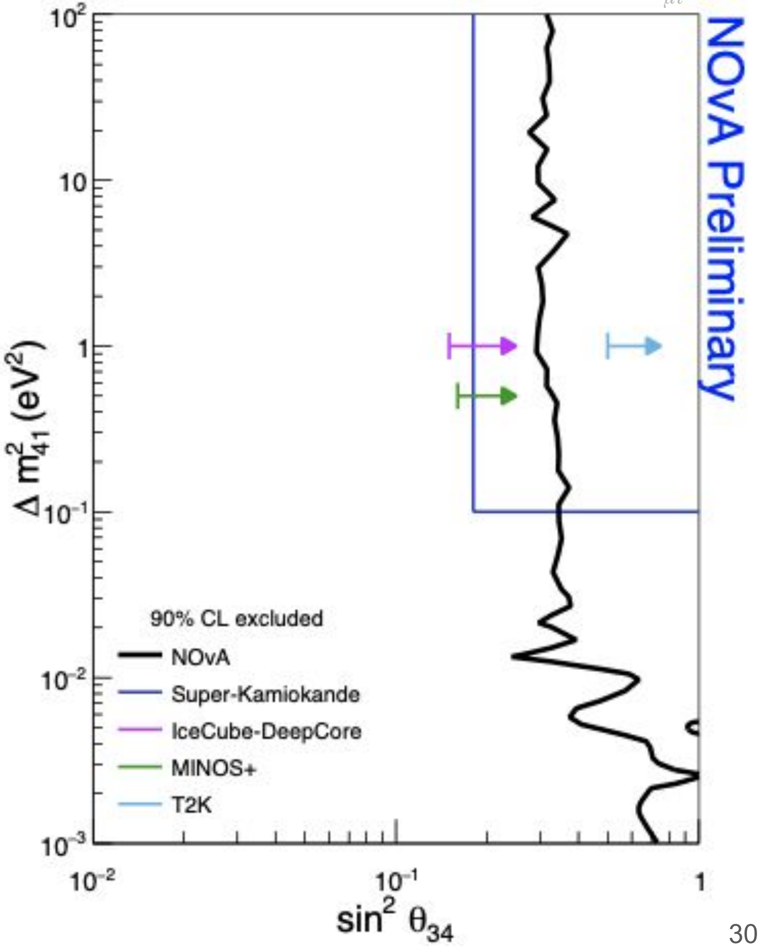
Sensitivity **at low Δm^2_{41} driven by the Far Detector**, and is less systematics limited

NC disappearance gives us direct access to θ_{34}
→ This has generally been accessed by short baseline ν_τ appearance searches, which give access to $\theta_{\mu\tau}$

not including contours from ν_τ appearance searches that measure $\theta_{\mu\tau}$



NOvA Into The Future

- New analyses
  - ν_μ CC low-hadronic activity ★
    - [**Poster**, *Leo Aliaga*]
  - ν_μ CC coherent pion production ★
    - [**Poster**, *Chatura Kuruppu*]
    - [**New Perspectives talk**, *Chatura Kuruppu*]
  - Studies towards ν-e elastic scattering ★
    - [**New Perspectives talk**, *Barnali Brahma*]
  - NOvA-T2K joint fit!

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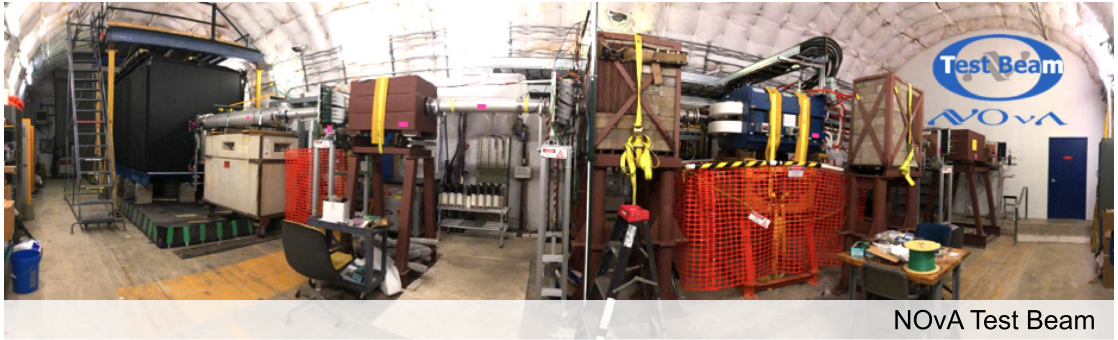

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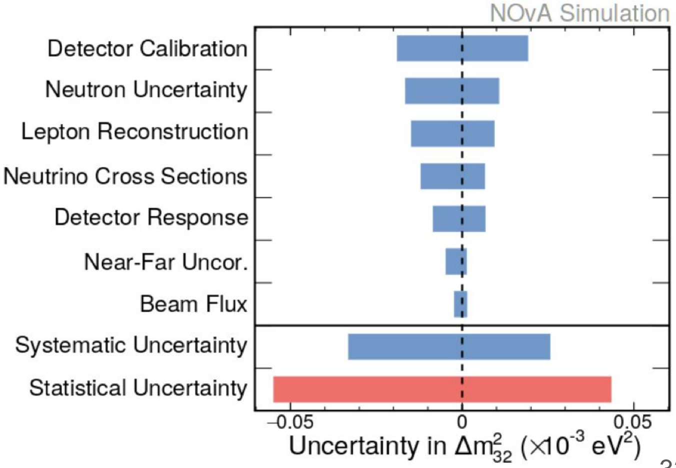

3-flavour analysis

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  - NOvA-T2K joint fit!
- NOvA Test Beam
- New MW-capable target and MW-capable horn installed
  - New power record **893 kW!**

NOvA Test Beam


MW-capable target

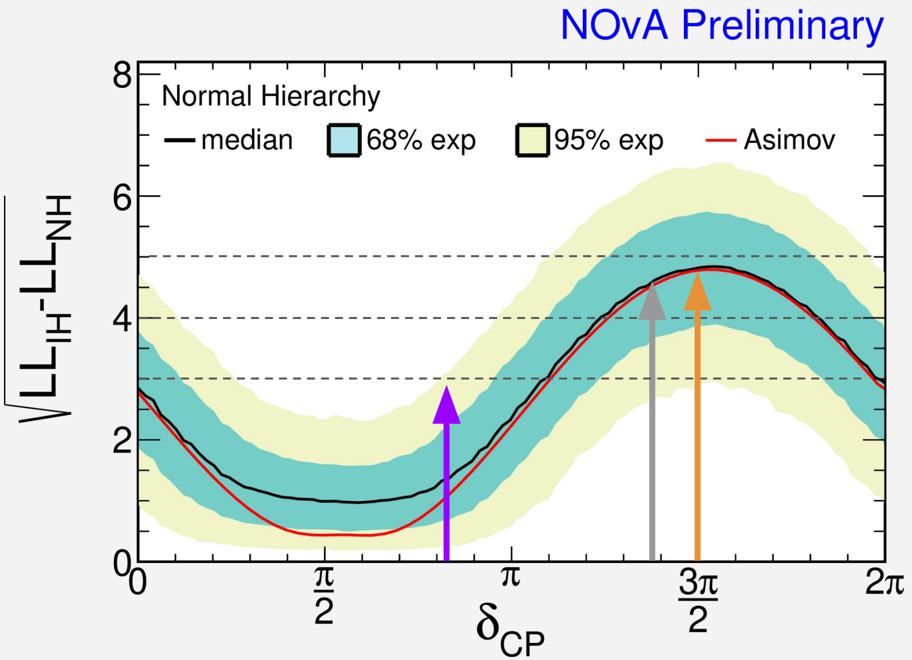

MW-capable horn

Future Sensitivities

Expect > 2x **current protons-on-target** (both $\nu/\bar{\nu}$!)

Mass hierarchy determination depends on **the true value of δ_{CP}, and statistics**.

For MH = Normal
δ_{CP}= 0.82π (**NOvA** best fit) ~2.5% chance of 3σ MH determination
δ_{CP}= 1.37π (**T2K** best fit, ~most favourable params) >50% chance at 4σ MH determination



Statistical uncertainties only

Measurement uncertainty still statistics-dominated with full dataset

Conclusions

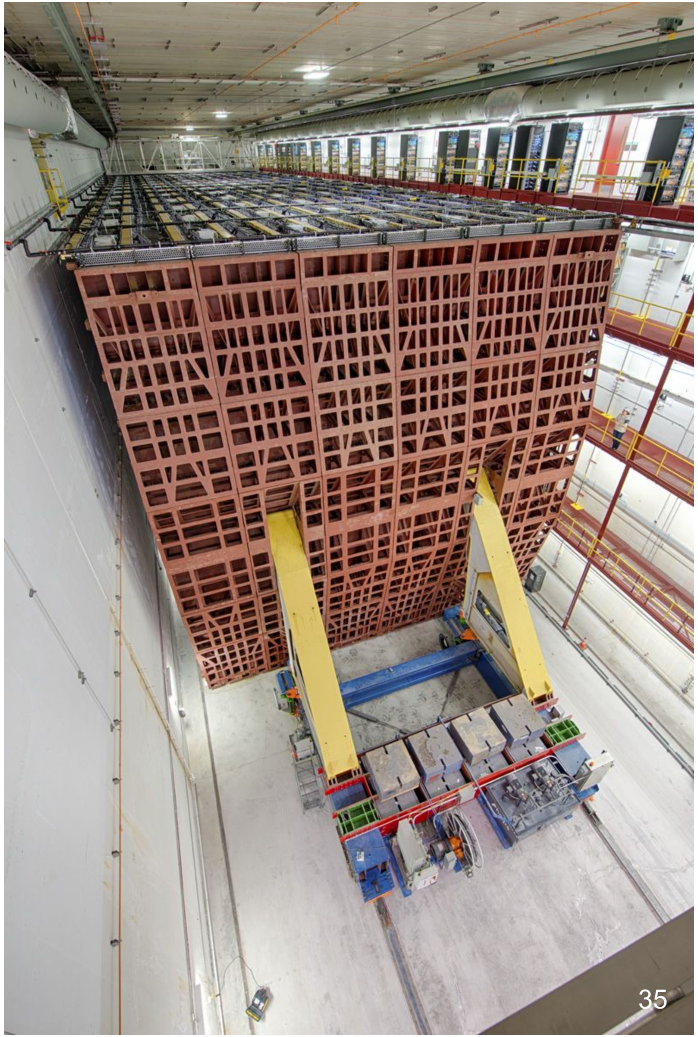
NOvA has an extensive physics program!

- Three-flavour oscillation physics
- Oscillation physics with alternate models
- Neutrino cross-sections
- Exotic phenomena searches

From this talk:

- New Bayesian techniques: new measurement of θ_{13}
- We find no evidence for sterile neutrinos in the NOvA data (under the 3+1 model)

Many more exciting results to come in the future!



Thank you from the

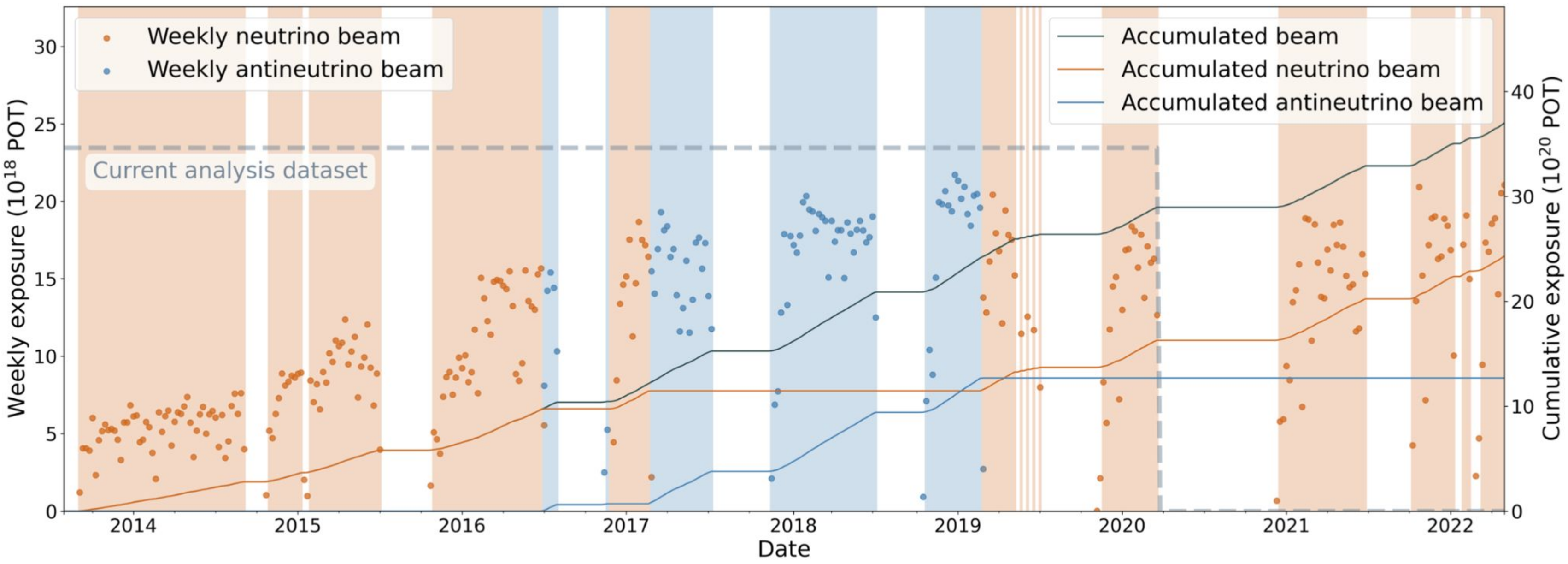
NOvA

collaboration

April 2022

Additional Slides

The NuMI Beam

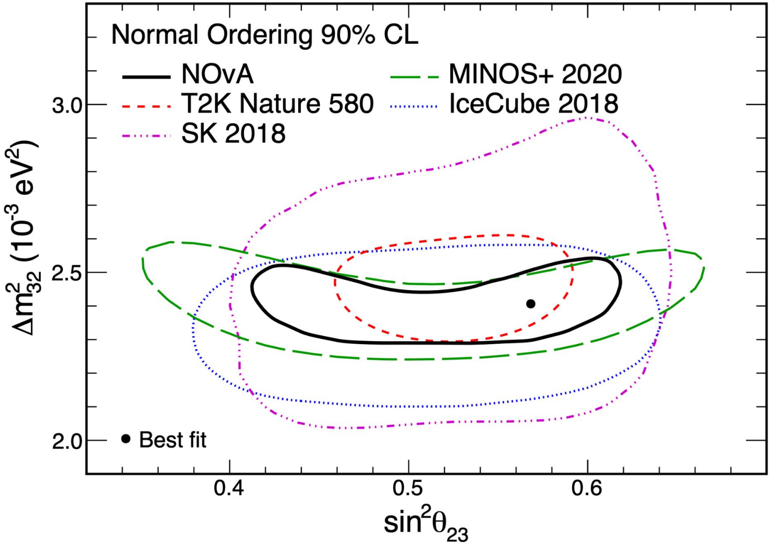


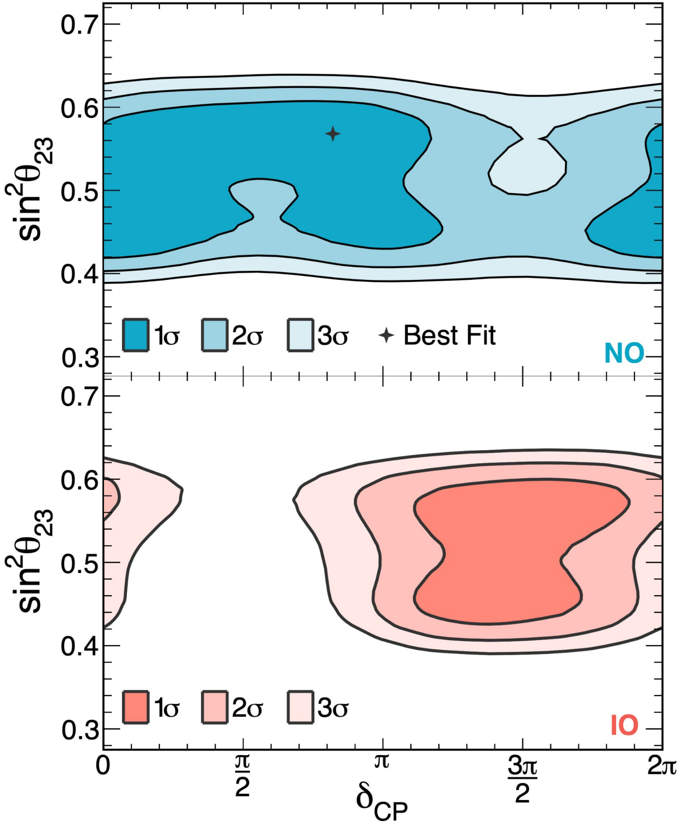
Collected 37x10^{20} protons-on-target to date

Current analysis dataset uses

13.6 x 10^{20} POT neutrino-beam data and 12.5 x 10^{20} POT antineutrino-beam data

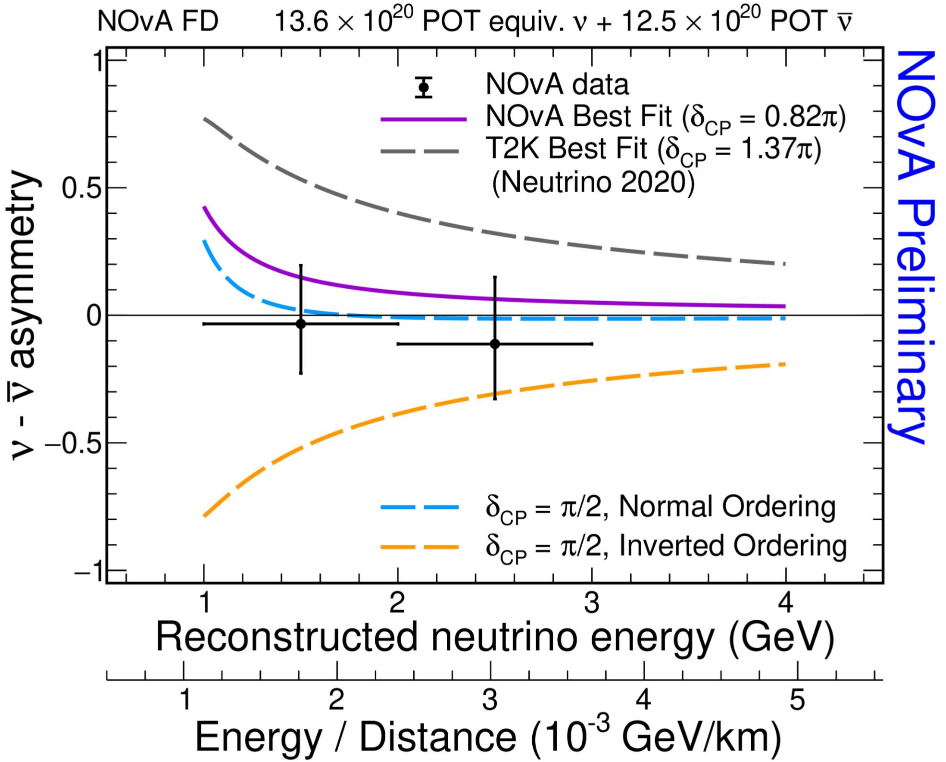
2020 Frequentist Analysis



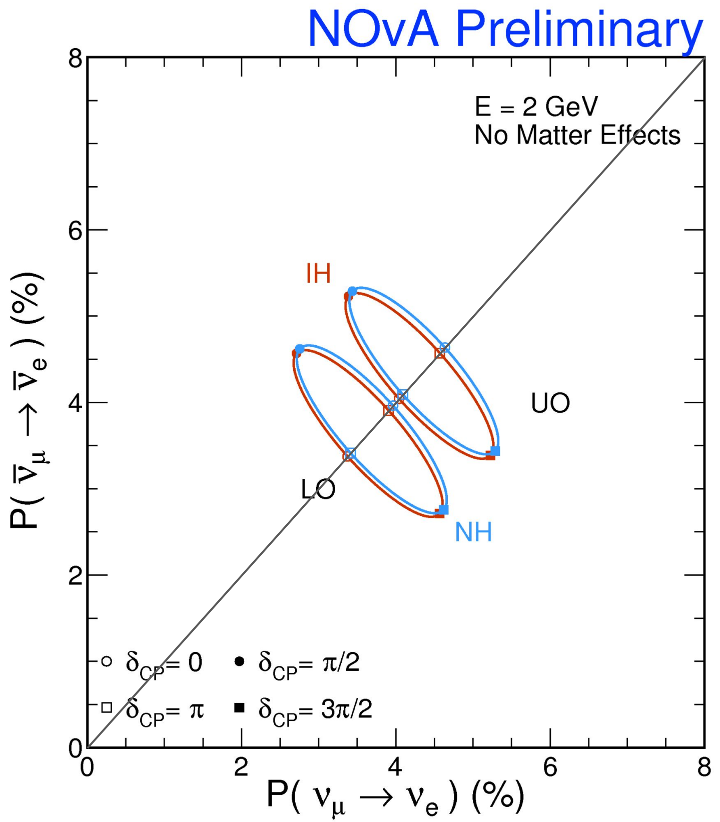


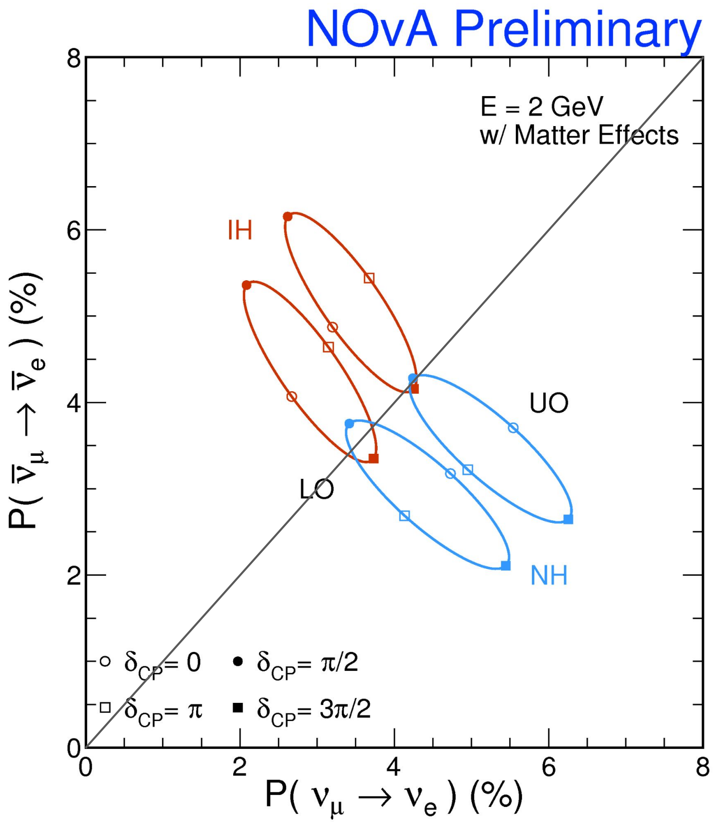
Asymmetry

$$\mathcal{A}_{CP} = \frac{P_{\nu_\mu \rightarrow \nu_e} - P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}}{P_{\nu_\mu \rightarrow \nu_e} + P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}}$$

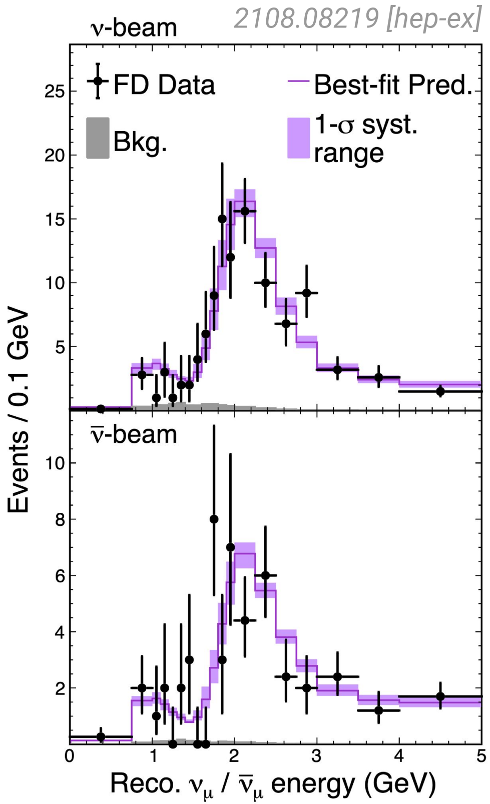


Matter Effects & Asymmetry





2020 Far Detector Spectra



ν_μ	Obs.	Best Fit	Bg.
ν	211	222.3	8.2
$\bar{\nu}$	105	105.4	2.1

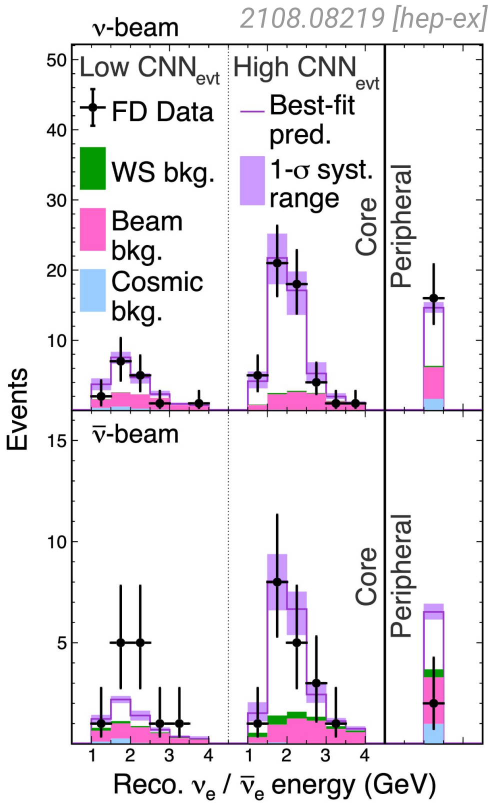
Very high purity selection for both ν and $\bar{\nu}$ modes

ν_e	Obs.	Best Fit	Bg.
ν	82	85.8	26.8
$\bar{\nu}$	33	33.2	14.0

Backgrounds primarily from **ν_e intrinsic** to the beam (irreducible)

>4σ $\bar{\nu}_e$ appearance

Disfavour strong asymmetry in ν_e-$\bar{\nu}_e$ appearance



3F Oscillation Analysis Strategy

ND DATA

DATA-DRIVEN CORRECTION

Data-driven correction to signal/backgrounds in ND

DATA-DRIVEN PREDICTION

Use corrected ND simulation to predict spectra at the FD (constrains uncertainties)

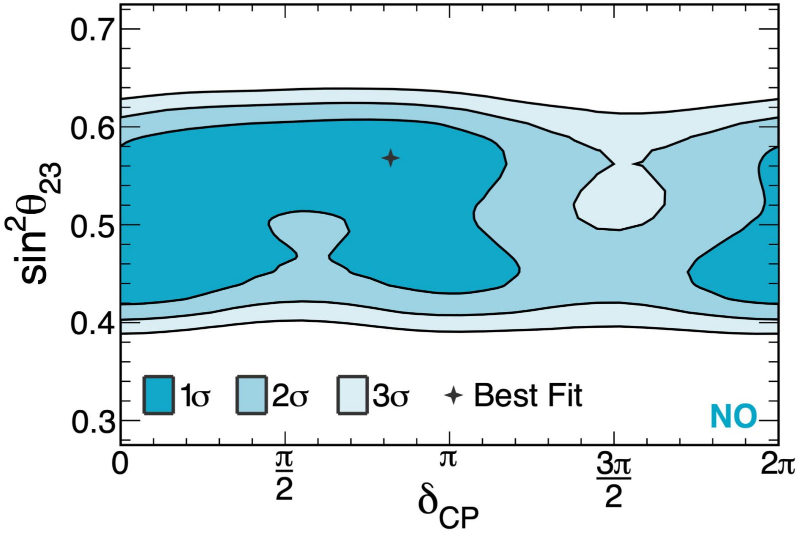
FIT FOR OSCILLATIONS

Best Fit: fit all parameters NOvA is sensitive to

- Δm^2_{32}, θ_{23}, δ_{CP}
- θ_{13} constrained from reactor experiments
- Solar parameters fixed

CONFIDENCE INTERVALS

- **Choose parameter(s)** (eg δ_{CP}, $\sin^2\theta_{23}$)
- For each point in space, minimise χ^2
- Frequentist correction for coverage



CHOOSE ANOTHER SPACE

A New Bayesian Strategy!

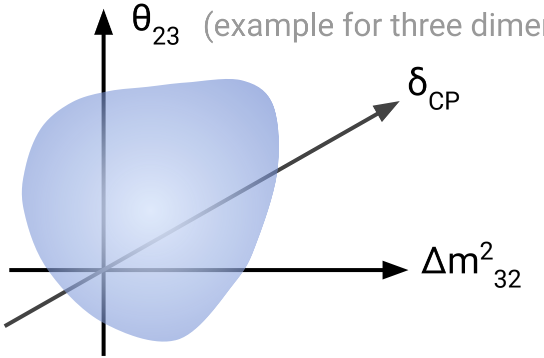
DATA **stays the same!*

DATA-DRIVEN CORRECTION
Data-driven correction to signal/backgrounds in ND

DATA-DRIVEN PREDICTION
Use corrected ND simulation to predict spectra at the FD (constrains uncertainties)

PRODUCE POSTERIOR PROBABILITY SPACE
Use our current ("prior") understanding of parameter values to construct a **multi-dimensional "posterior" probability distribution**.

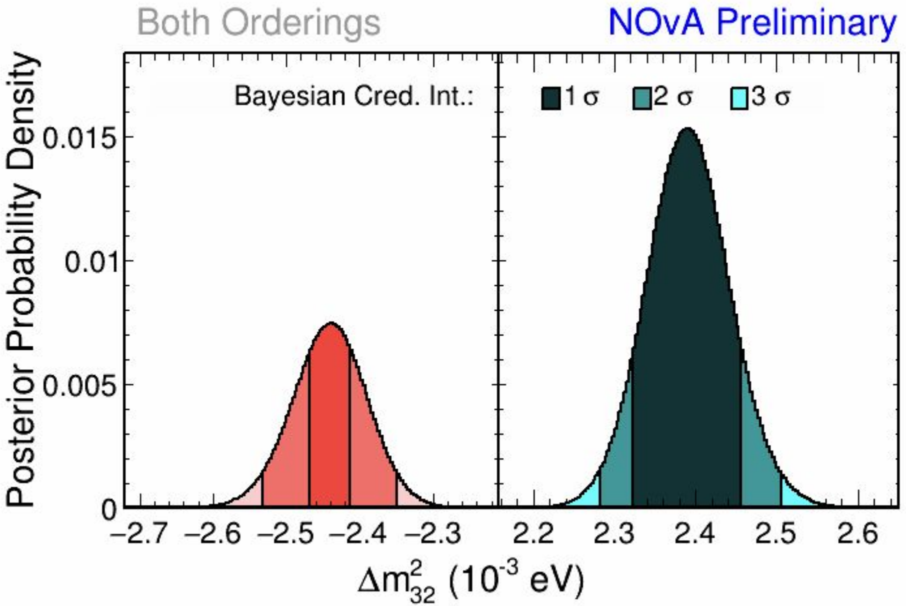
CREDIBLE INTERVALS
Use probability distribution to produce credible intervals for parameters we're interested in, marginalising over other parameters



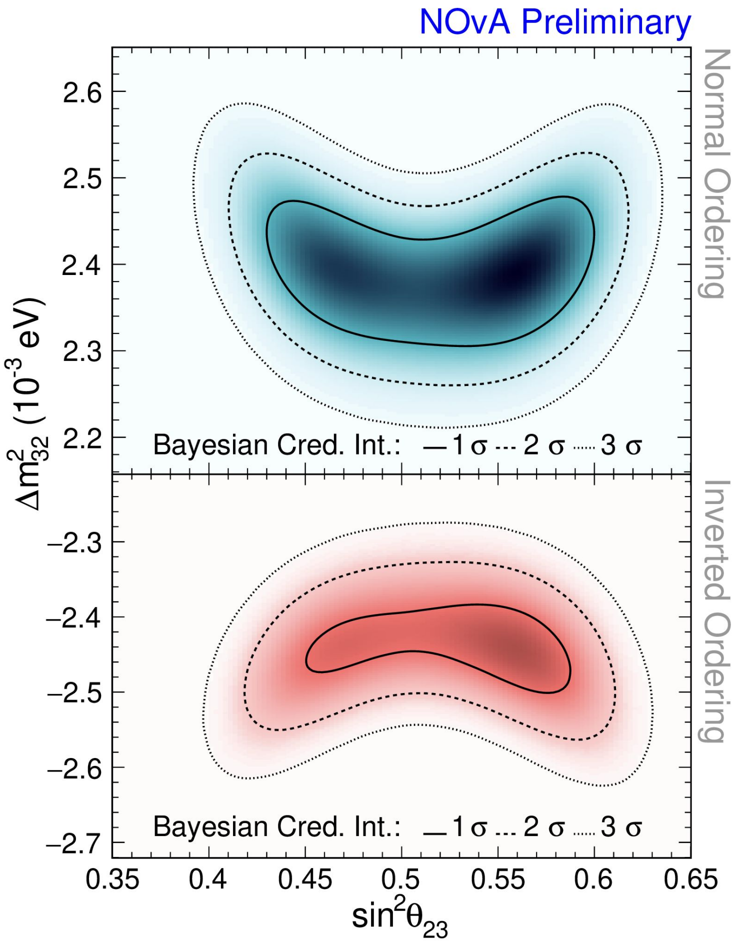
Posterior probability distribution means quick to produce credible intervals in new parameters

DONE!

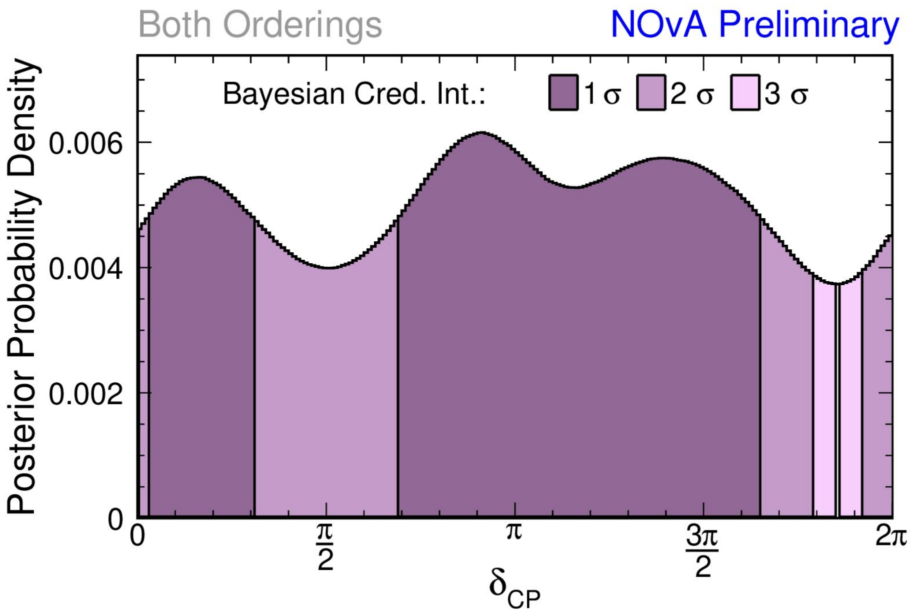
Additional Bayesian Plots



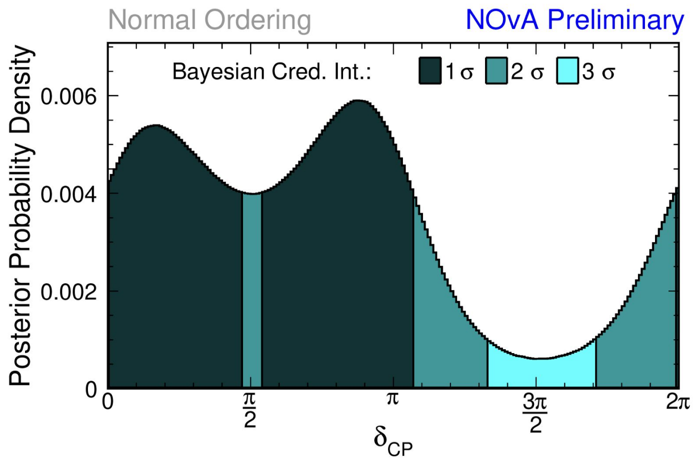
Weak preference for normal ordering, upper octant

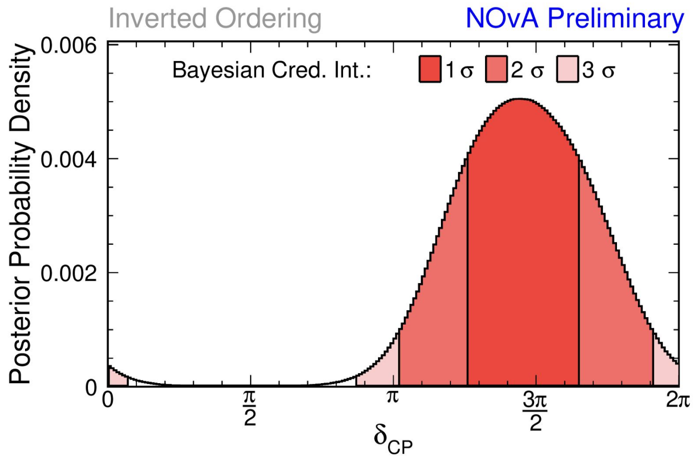


Additional Bayesian Plots

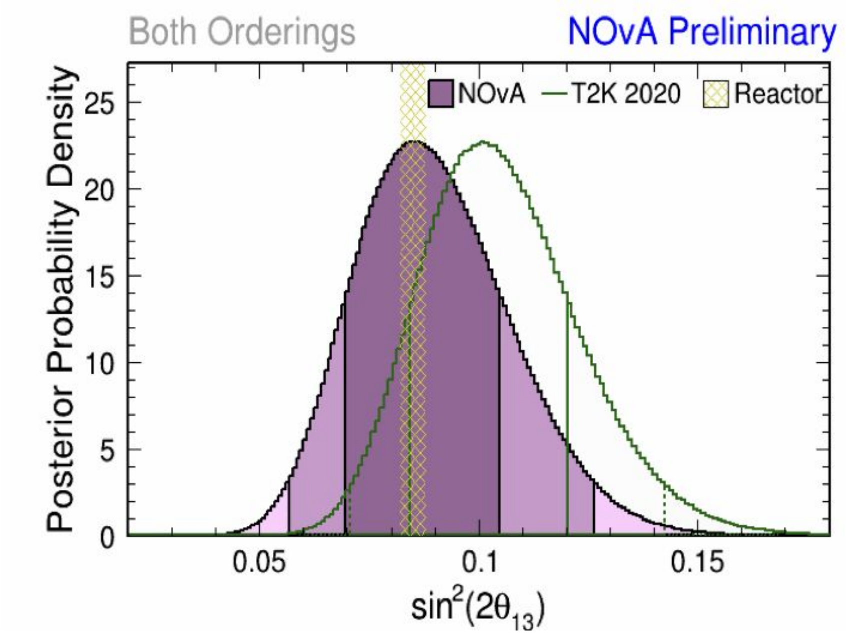


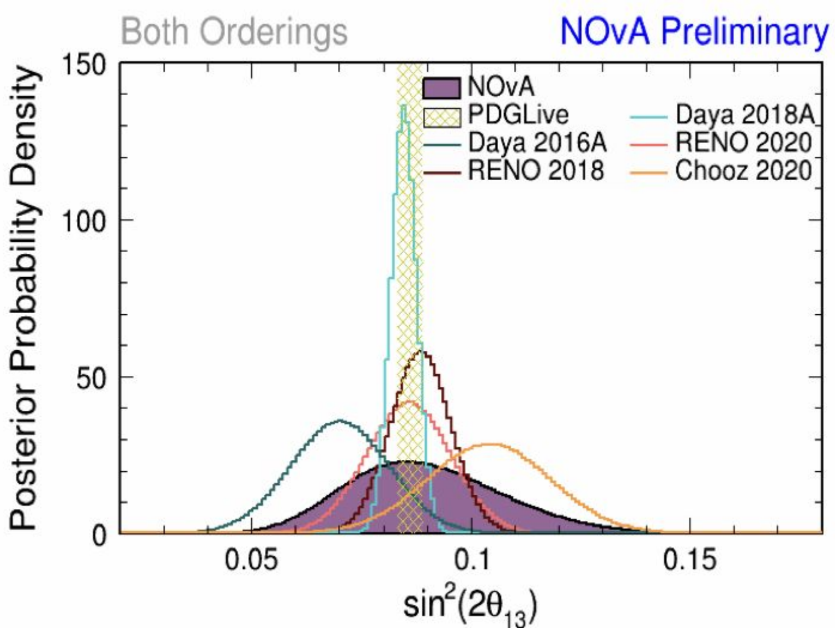
When taking both orderings into account, we have no strong preference for δ_{CP}





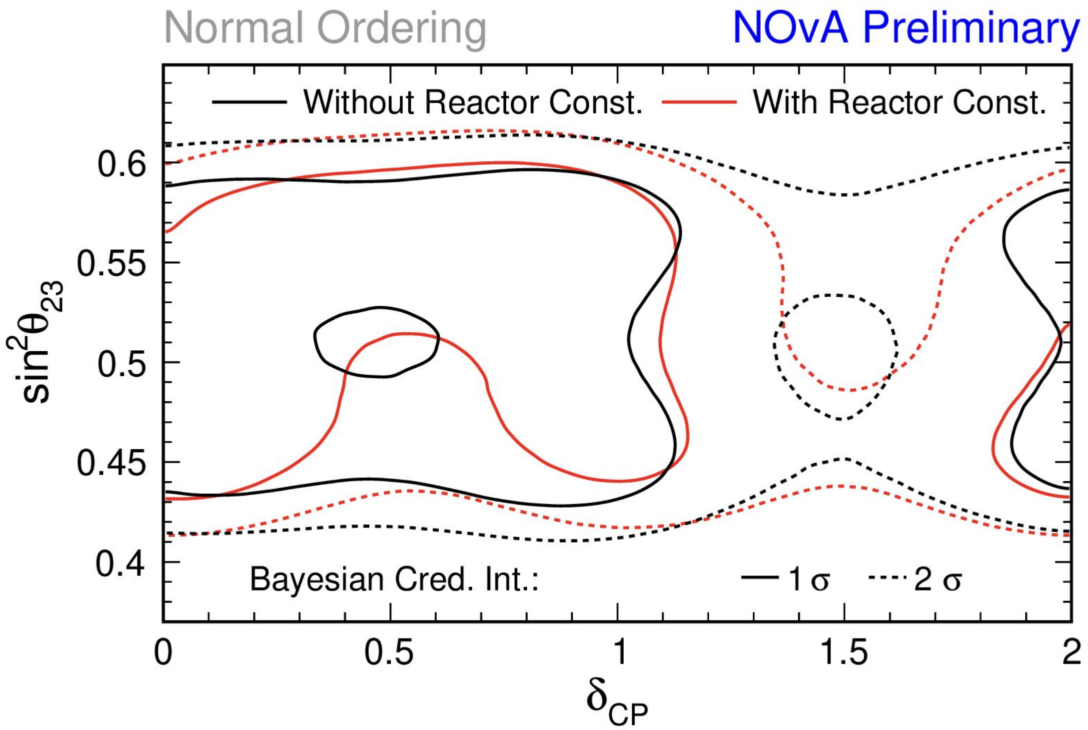
Additional Bayesian Plots





- No tension between NOvA and T2K for θ_{13}
- No tension with measurements from reactor experiments

Additional Bayesian Plots



Slightly higher preference for NO with reactor constraint

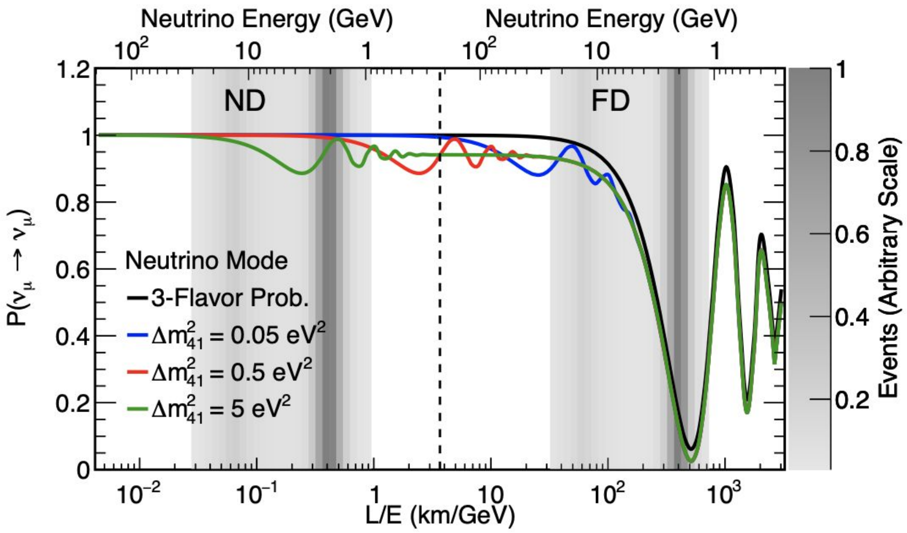
Sterile ν_μ Disappearance

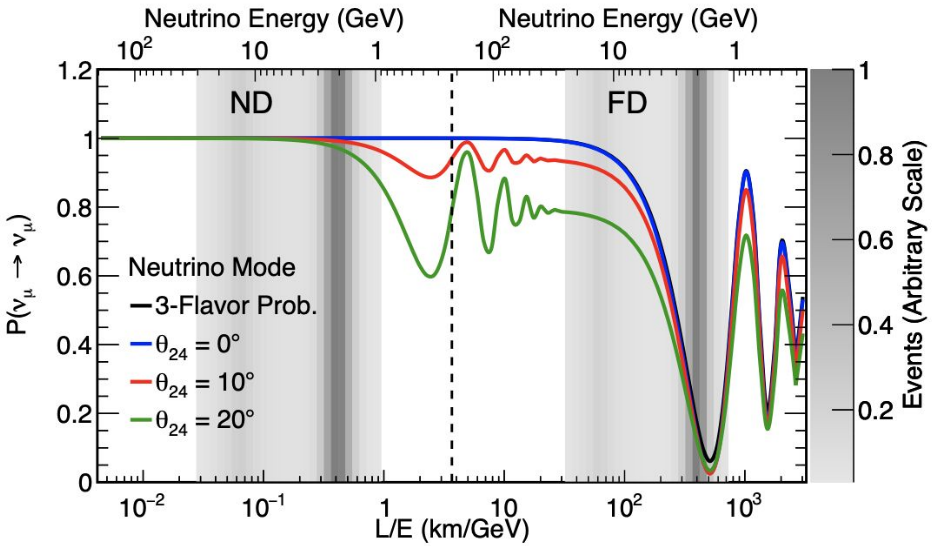
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{24} \Delta_{41} + 2\sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31} - \sin^2 2\theta_{23} \sin^2 \Delta_{31}$$

ND Oscillations from Δm^2_{41}

Oscillations at **atmospheric frequency**, notably does not depend on θ_{34}, δ_{24}

ν_μ sample **constrains atmospheric parameters** and size of θ_{24}



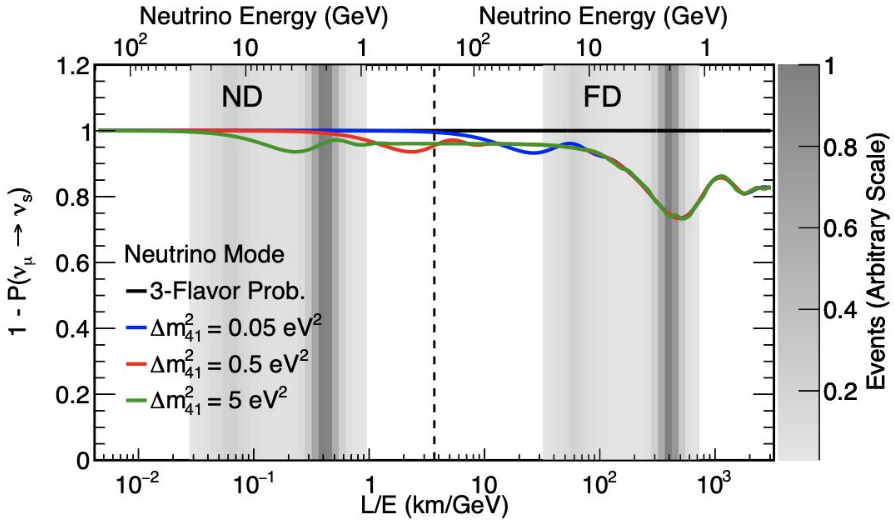


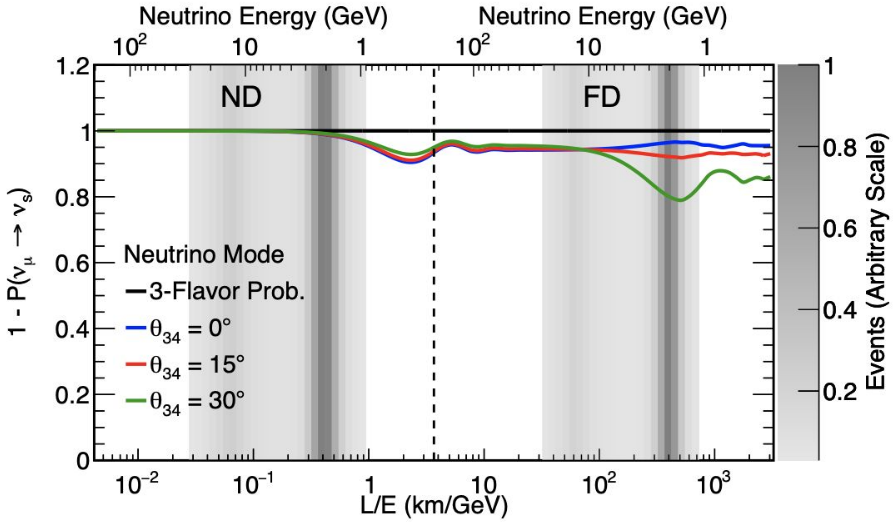
Sterile NC Disappearance

$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41}$$
$$- \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31}$$
$$+ \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{23}\sin\Delta_{31}$$

ND Oscillations from Δm^2_{41}

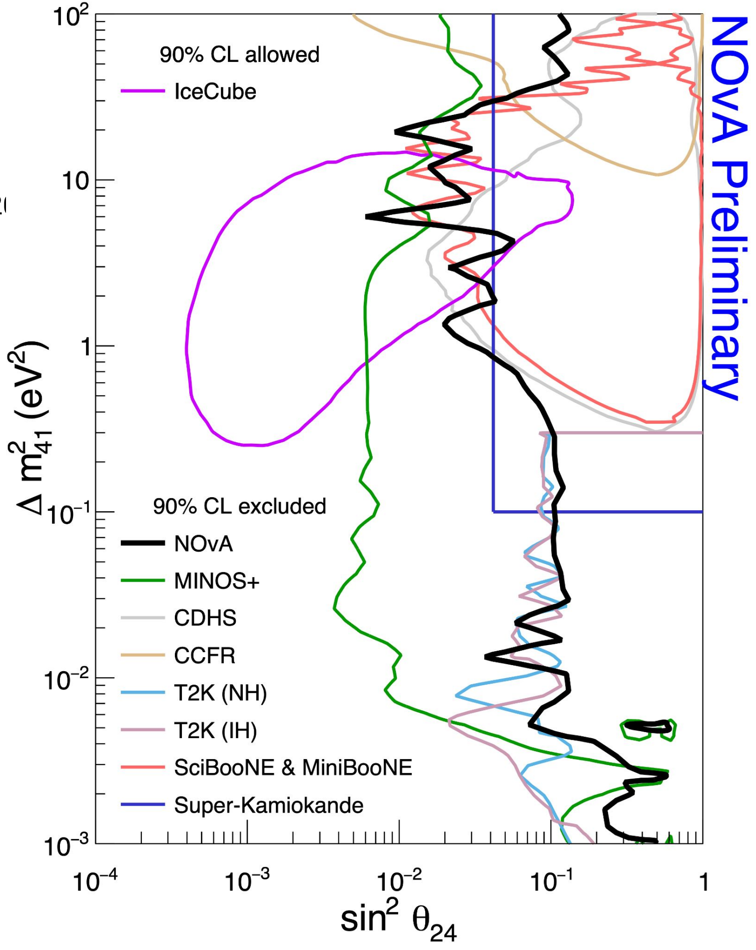
Oscillations at **atmospheric frequency**, gives us access to θ_{24}, θ_{34}, δ_{24}





Citations

- SK: K. Abe et al. (Super- Kamiokande), Phys. Rev. D 91, 052019 (2015)
- CDHS: F. Dydak et al. (CDHSW), Phys. Lett. B 134, 281 (1984)
- CCFR: I.E. Stockdale et al. (CCFR), Phys. Rev. Lett. 52, 1384 (1984)
- SciBooNE: K. B. M. Mahn et al. (SciBooNE, MiniBooNE), Phys. Rev. D 85, 032007 (2
- MINOS+: P. Adamson et al. (MINOS+) Phys. Rev. Lett. 122, 091803 (2019)
- T2K: K. Abe et al. (T2K) Phys. Rev. D 99, 071103(R) (2019)
- IceCube: M. G. Aartsen et al. (IceCube), Phys. Rev. Lett. 125, 141801 (2020)



What Are Those Arrows?

The arrows are because these three experiments report either

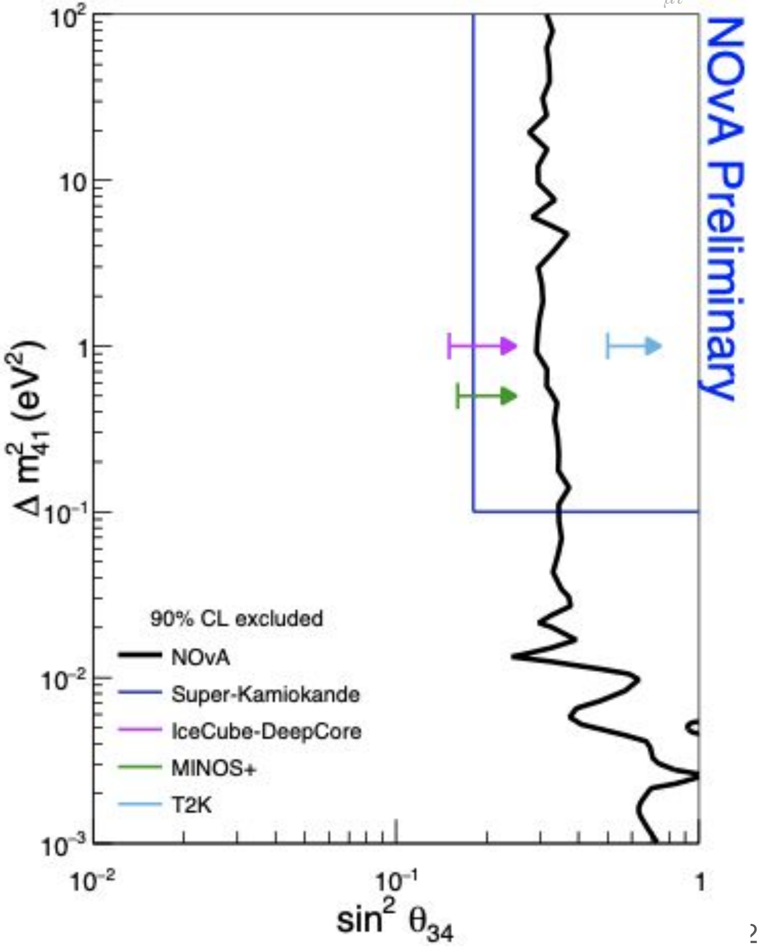
$$|U_{\tau 4}|^2 = \cos^2\theta_{24}\sin^2\theta_{34}$$

Or θ_{34} directly for a given value of Δm^2_{41}.

Anomalous ν_τ appearance searches measure

$$\sin^2 2\theta_{\mu\tau} = \cos^4\theta_{14}\sin^2 2\theta_{24}\sin^2\theta_{34}$$

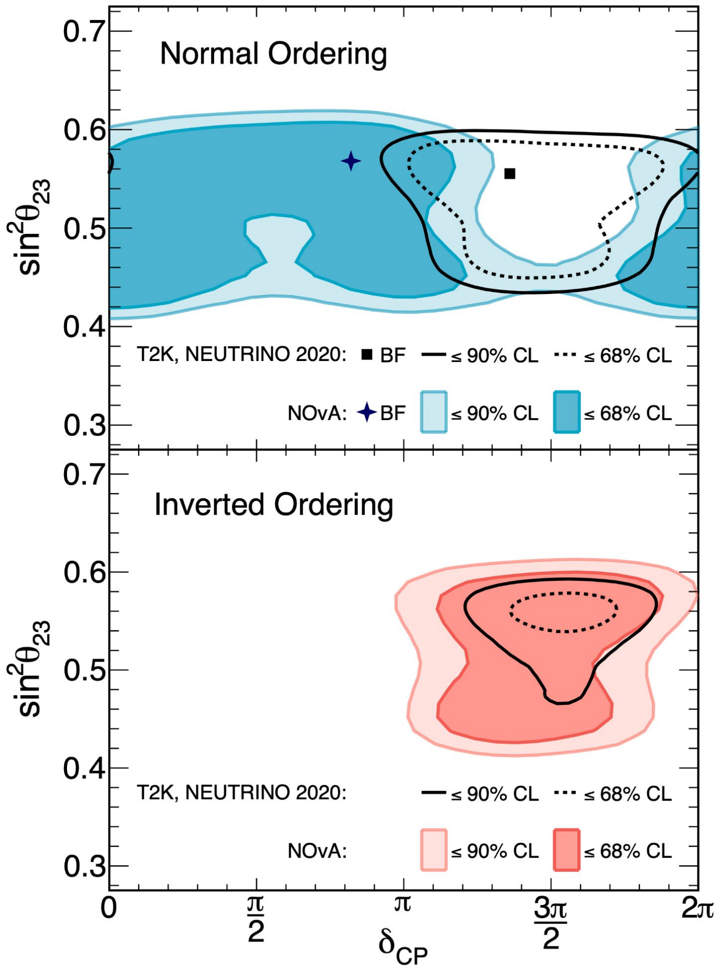
not including contours from ν_τ appearance searches that measure $\theta_{\mu\tau}$



NOvA-T2K Joint Analysis

Different best fit points, but still overlap at 1σ.

Made good progress, hoping for public results **this year**



Future Sensitivities