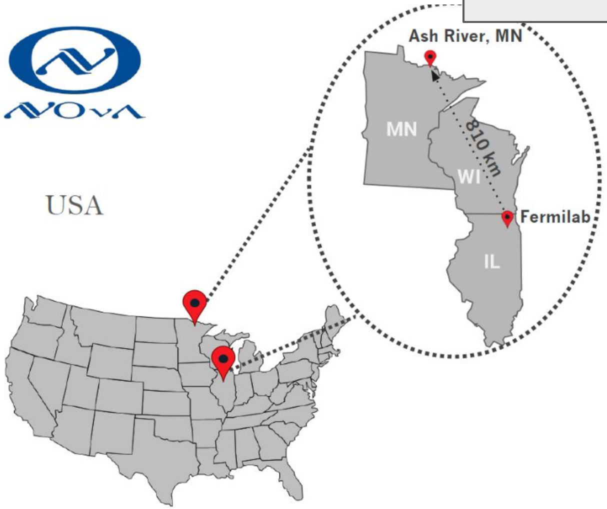
Caption box

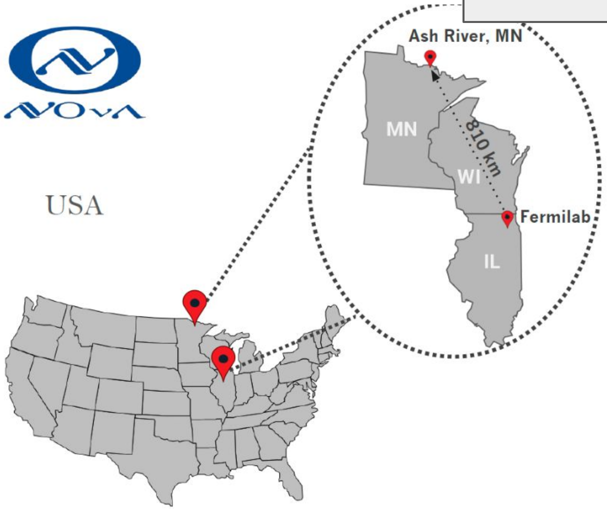
Results from T2K and NOvA



Kendall Mahn, Michigan State University

Overview

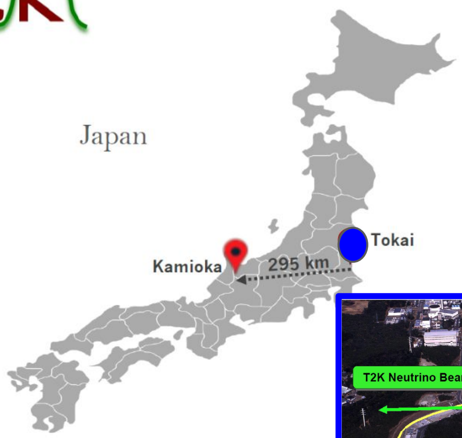
Caption box

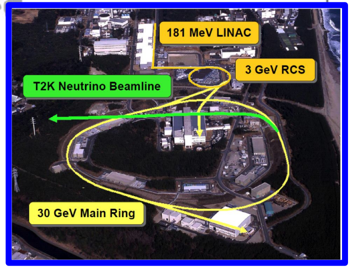


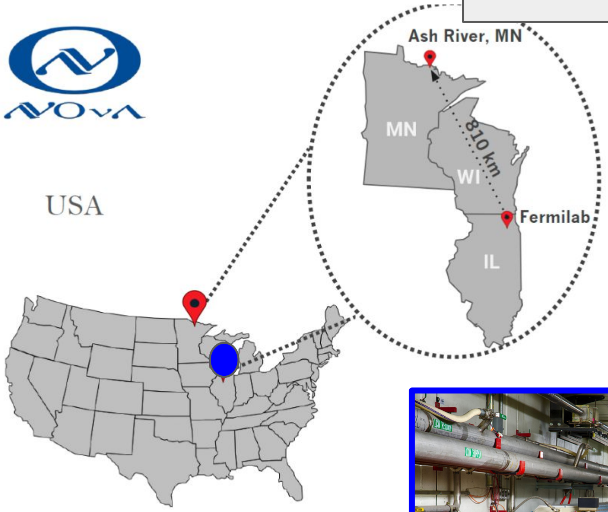
The T2K (Tokai-to-Kamioka) and NOvA (NuMI off-axis ν_e appearance) experiments are accelerator based neutrino oscillation experiments

Accelerator based oscillation expts

Caption box





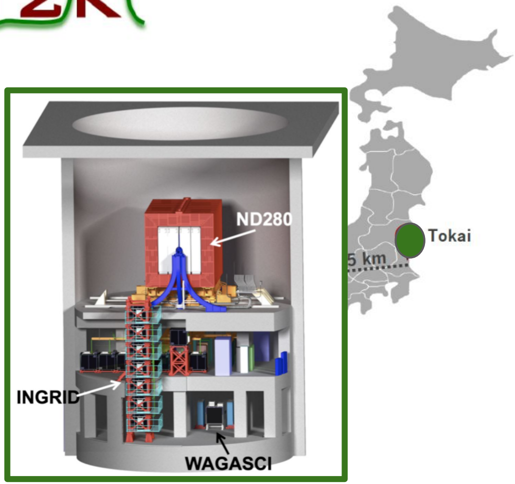


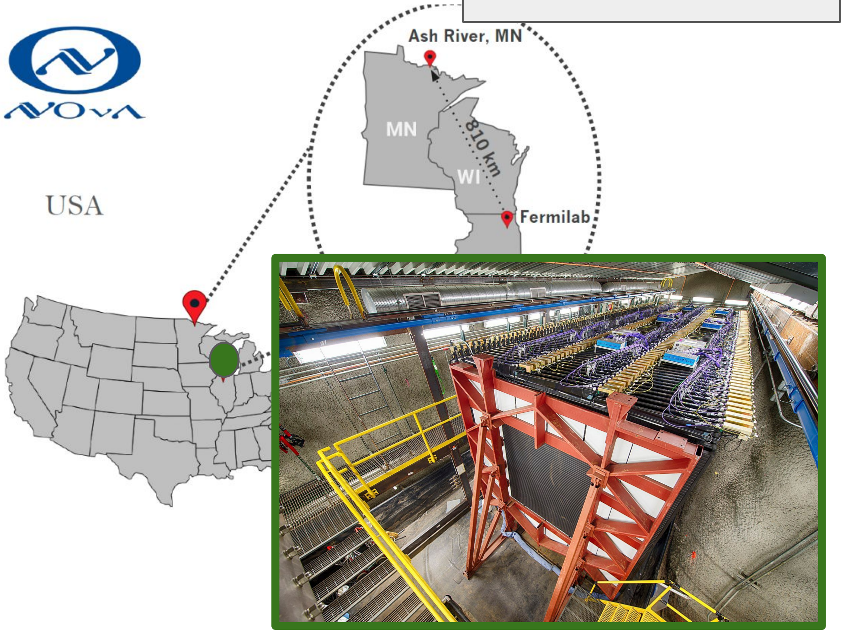
Key features:

- Accelerator-driven neutrino (or antineutrino beam) on one side of a country
  - J-PARC in Tokai
  - Main Injector (NuMI) at Fermilab

Accelerator based oscillation expts

Caption box



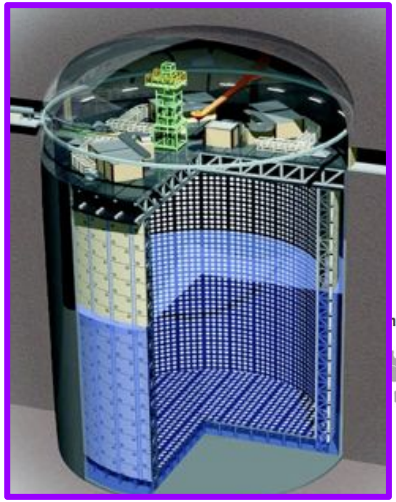


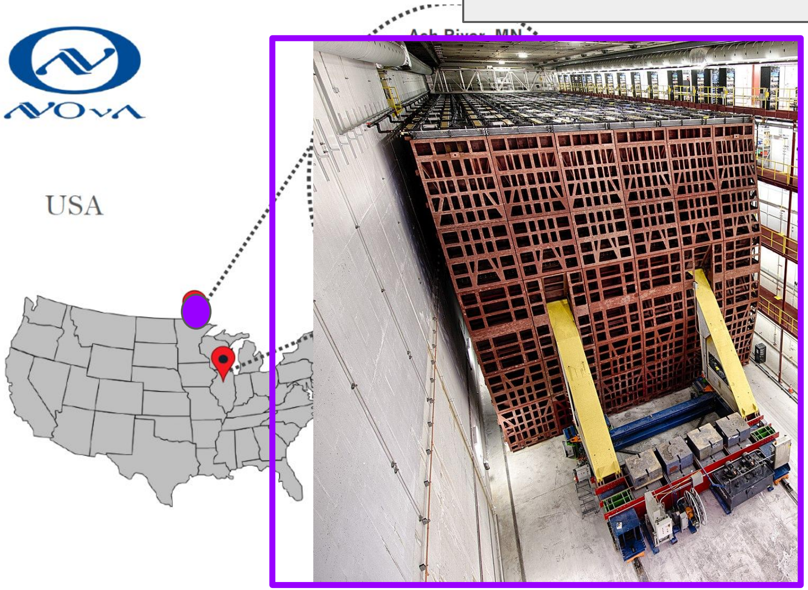
Key features:

- Accelerator-driven neutrino (or antineutrino beam)
- Detectors ‘near’ to the neutrino source
  - T2K suite of three detectors “on and off axis”, that is, the proton beam direction
  - NOvA “ND” is off axis

Accelerator based oscillation expts

Caption box

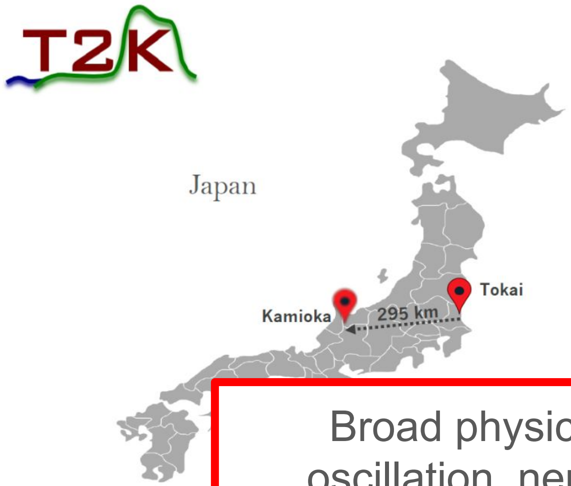




Key features:

- Accelerator-driven neutrino (or antineutrino beam) on one side of a country
- Detectors ‘near’ to the neutrino source
- ‘Far’ detectors hundreds of kilometers away
  - Enormous Water Cherenkov detector - Super-Kamiokande
  - Enormous liquid scintillator detector

Caption box



Broad physics programs: “three flavor” neutrino oscillation, neutrino cross sections, exotic physics searches

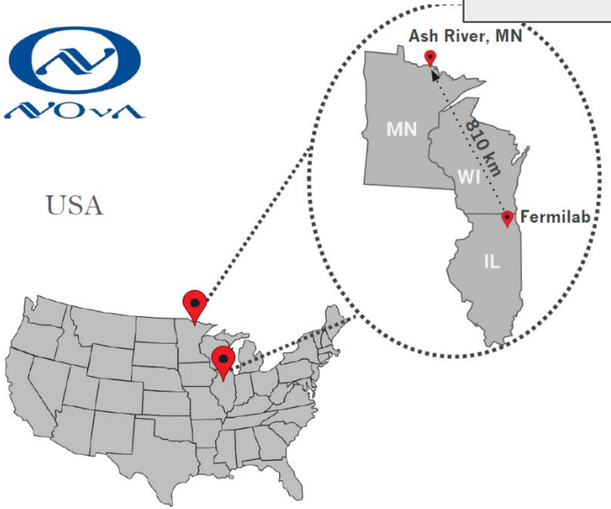
Topics shared with atmospheric neutrino, reactor and ‘short baseline’ neutrino experiments

Key features:

- Accelera… e of a country
- Detectors …
- ‘Far’ detectors hundreds of kilometers away

Caption box

Today's talk



Current landscape of neutrino oscillation

Recent results from T2K and NOvA, and T2K+NOvA, in a global context

What do we know about neutrino oscillation?

Caption box

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Flavor states Mass states

Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS)

If U is unitary, 3 mixing angles (θ_{12} θ_{23} θ_{13}) and one phase (δ_{CP})

What do we know about neutrino oscillation?

Caption box

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) + 2\sum_{i>j} \mathrm{Im}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\left(\frac{2.54\Delta m^2_{ij}L}{E}\right)$$

Probability to oscillate from flavor ν_α to ν_β and depends on:

- U elements (and therefore θ_{23}, δ_{CP}) and mass splitting Δm^2_{32}
- L - ‘Baseline’ - *T2K is 295km, NOvA is 810km*
- E - neutrino energy - *T2K peak energy is ~0.6 GeV, NOvA is ~2 GeV*

Open questions about neutrino oscillation

Caption box

Is CP-invariance violated in neutrino oscillations?

- $\delta_{CP} = 0, \pi$?

Is ν_3 mostly ν_μ or ν_τ? (θ_{23} "octant")

- $\sin^2(\theta_{23}) > 0.5$, < 0.5, or $\sin^2(\theta_{23}) = 0.5$?
- Is there an underlying symmetry to this matrix?

What is the neutrino mass ordering? (mass hierarchy)

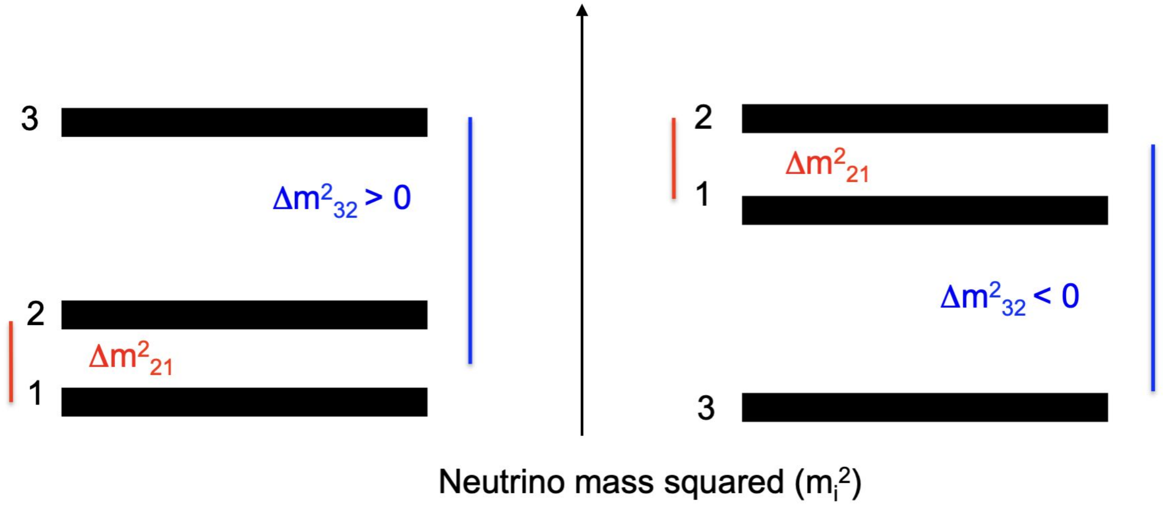
- Is ν_3 the heaviest?

André de Govêa:
"*Ultimate Goal:* ***Not Measure Parameters but Test the Formalism*** *(Over-Constrain Parameter Space)*"

Snowmass Neutrino Colloquium

Open questions about neutrino oscillation

Caption box

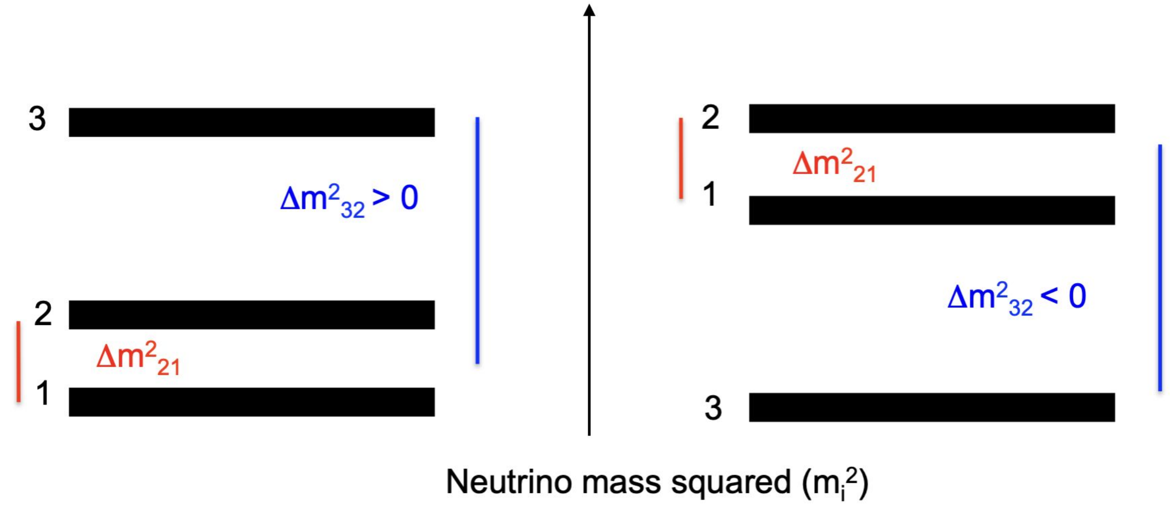


What is the neutrino mass ordering?
(mass hierarchy)

- Is ν_3 the heaviest?
- “Normal” mass ordering: $\Delta m^2_{32} > 0$
- “Inverted” mass ordering: $\Delta m^2_{32} < 0$

Open questions about neutrino oscillation

Caption box



What is the neutrino mass ordering? (mass hierarchy)

- Is ν_3 the heaviest?
- "Normal" mass ordering: $\Delta m^2_{32} > 0$
- "Inverted" mass ordering: $\Delta m^2_{32} < 0$

Sensitivity the mass ordering from interactions of ν_e (and electrons) in matter - *complementary to JUNO*

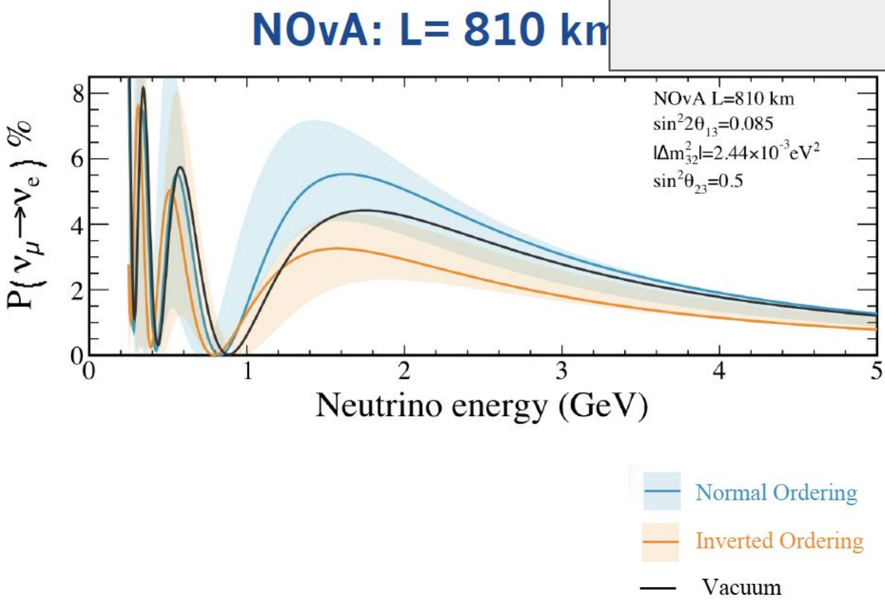
Mass ordering important to cosmology, and astrophysics, neutrinoless double beta decay

Probability depends on mass ordering, CP effect

Caption box

$\nu_\mu \rightarrow \nu_e$ appearance is sensitive to all open questions

Normal ordering enhances ν_e appearance and **inverted ordering** suppresses it



Probability depends on mass ordering, CP effect

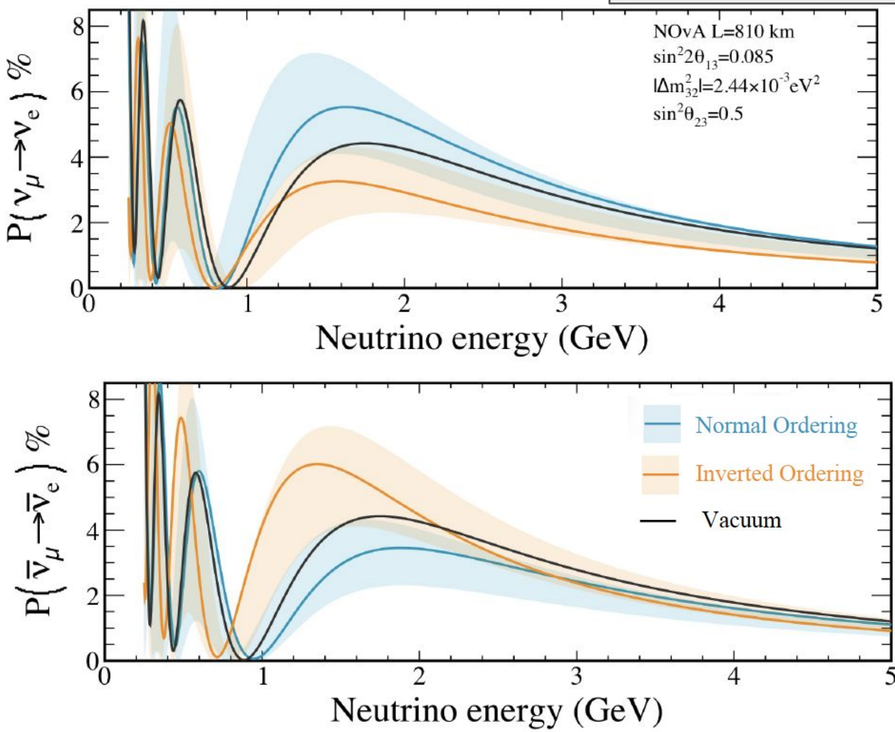
Caption box

$\nu_\mu \rightarrow \nu_e$ appearance is sensitive to all open questions

Normal ordering enhances ν_e appearance and **inverted ordering** suppresses it

The opposite is true for $\overline{\nu}_e$ appearance

NOvA: L= 810 km

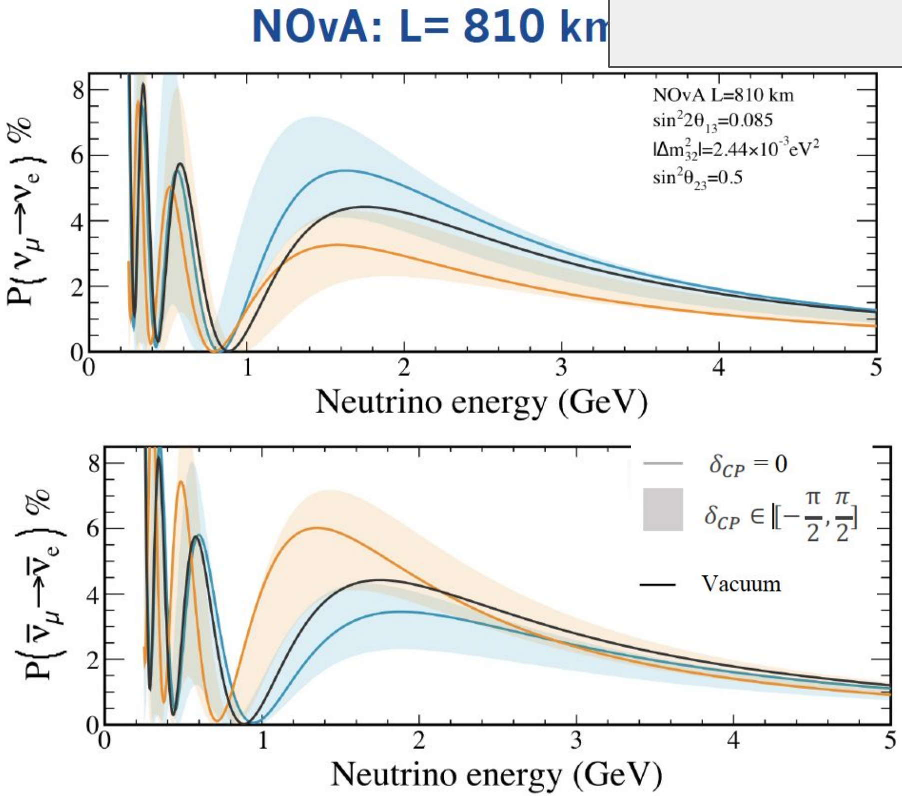


Probability depends on mass ordering, CP effect

Caption box

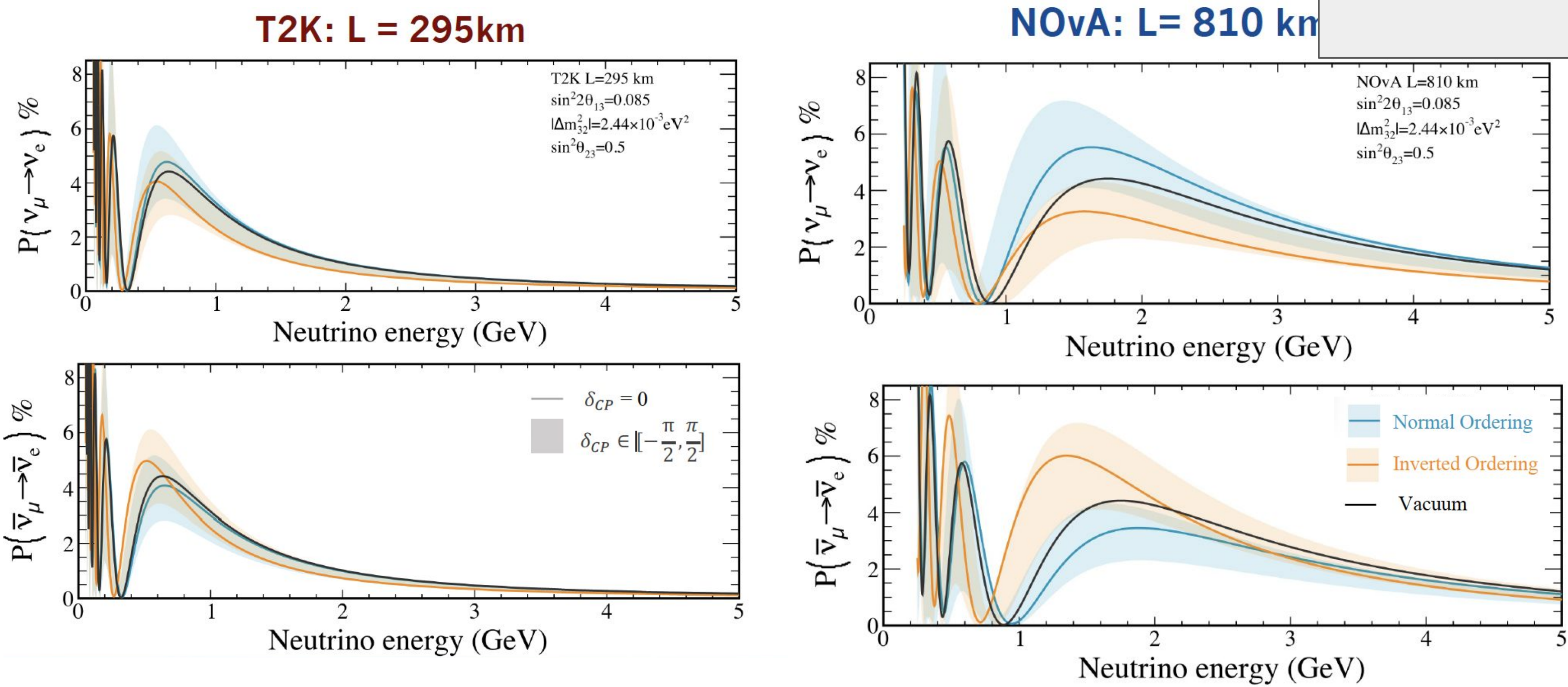
$\nu_\mu \rightarrow \nu_e$ appearance is sensitive to all open questions

CPV also enhances ν_e appearance and suppresses $\overline{\nu}_e$ appearance



Probability depends on mass ordering, CP effect

Caption box

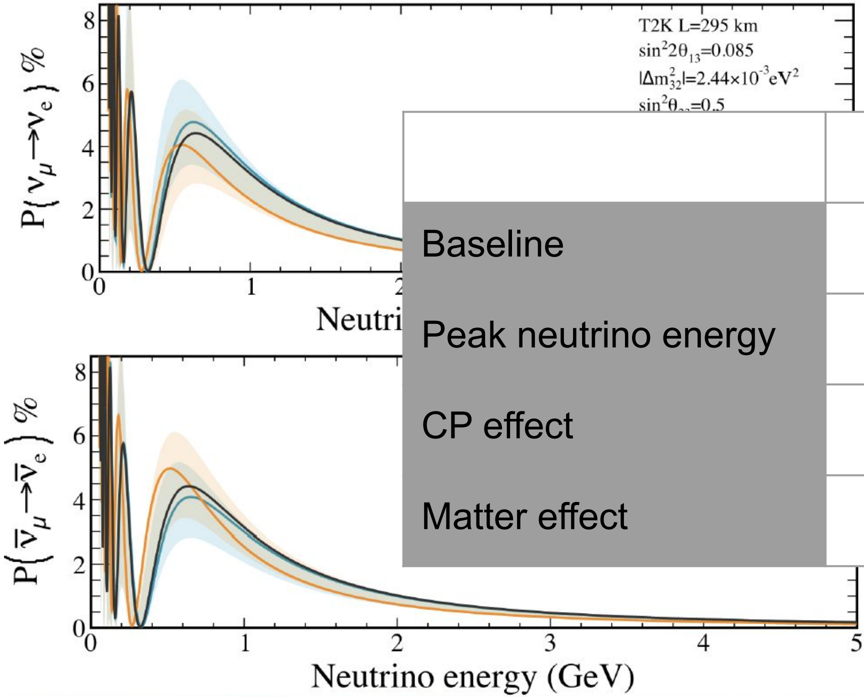


Baseline and energy change the oscillation probability - *T2K has a larger (relative) δ_{CP} effect*, *NOvA larger mass ordering effect*

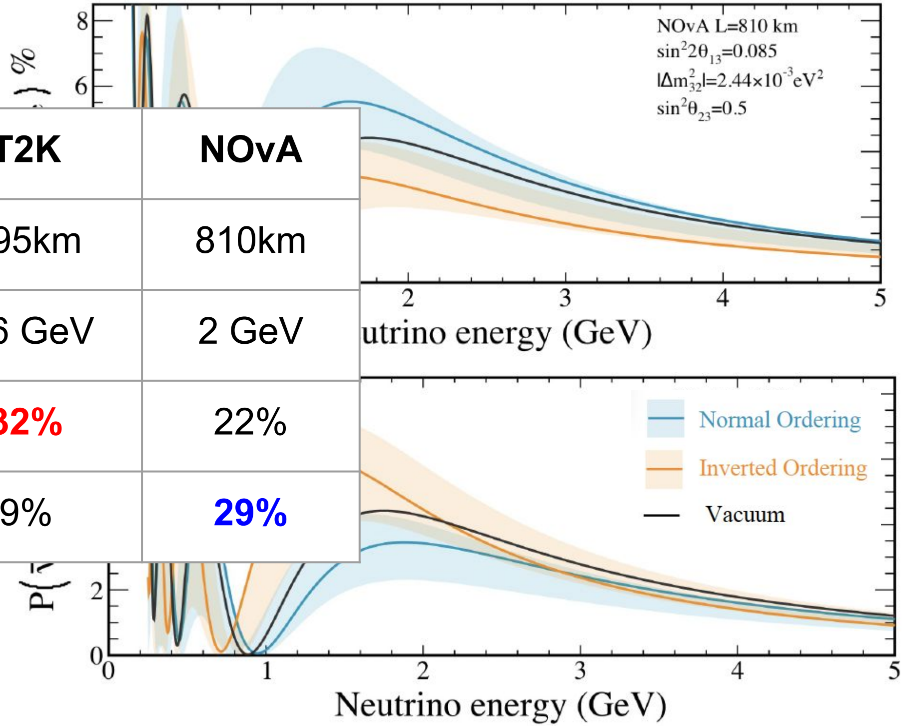
Probability depends on mass ordering, CP effect

Caption box

T2K: L = 295km



NOvA: L= 810 km

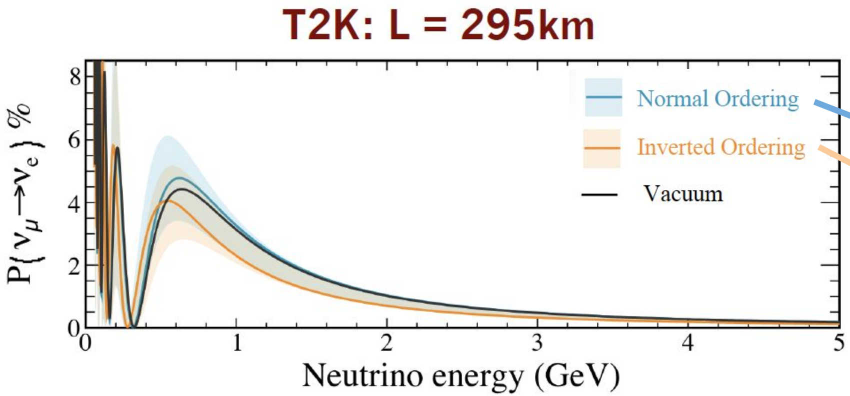


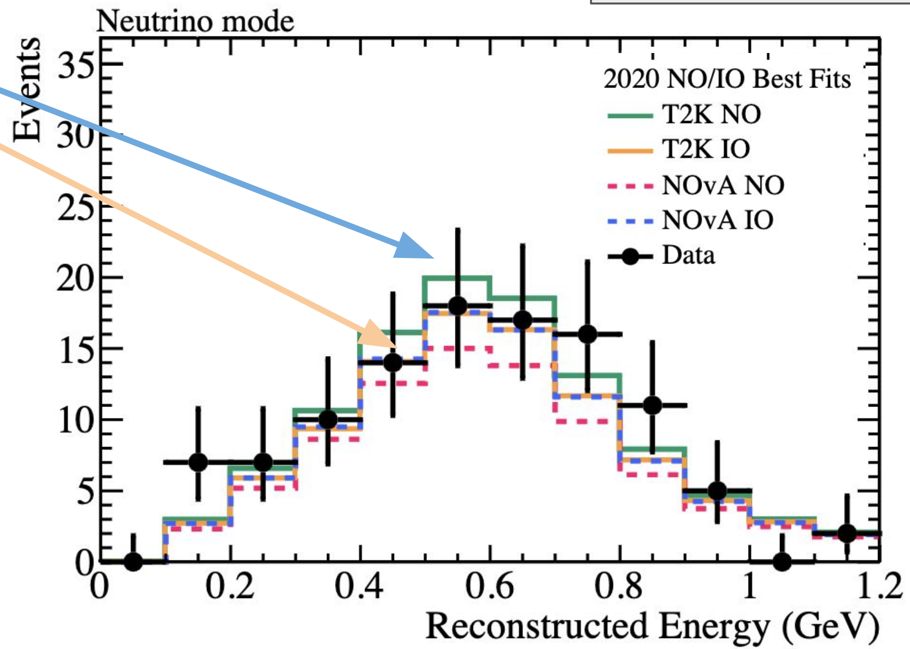
	T2K	NOvA
Baseline	295km	810km
Peak neutrino energy	0.6 GeV	2 GeV
CP effect	**32%**	22%
Matter effect	9%	**29%**

Baseline and energy change the oscillation probability - *T2K has a larger (relative) δ_{CP} effect*, *NOvA larger mass ordering effect*

Probabilities to reality: event rates

Caption box





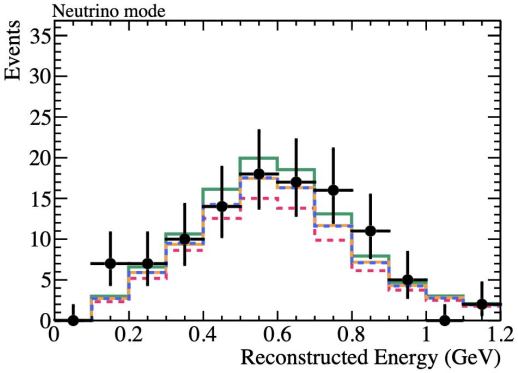
We determine oscillation parameters from event rates (at our 'far' detector)

- Example: one T2K ν_e event selection
- Uses neutrino source (flux, $\mathbf{\Phi}$), cross section ($\boldsymbol{\sigma}$), and detector (efficiency) models

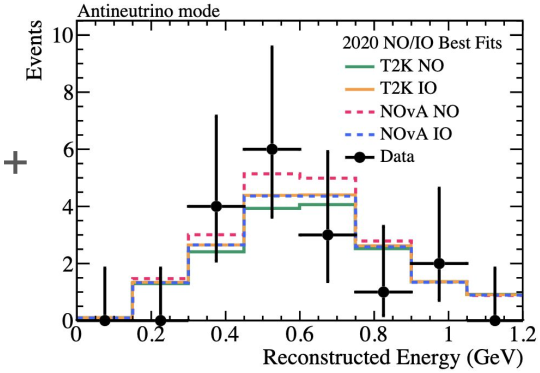
$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e)$$

Probabilities to reality: CP effect

Caption box



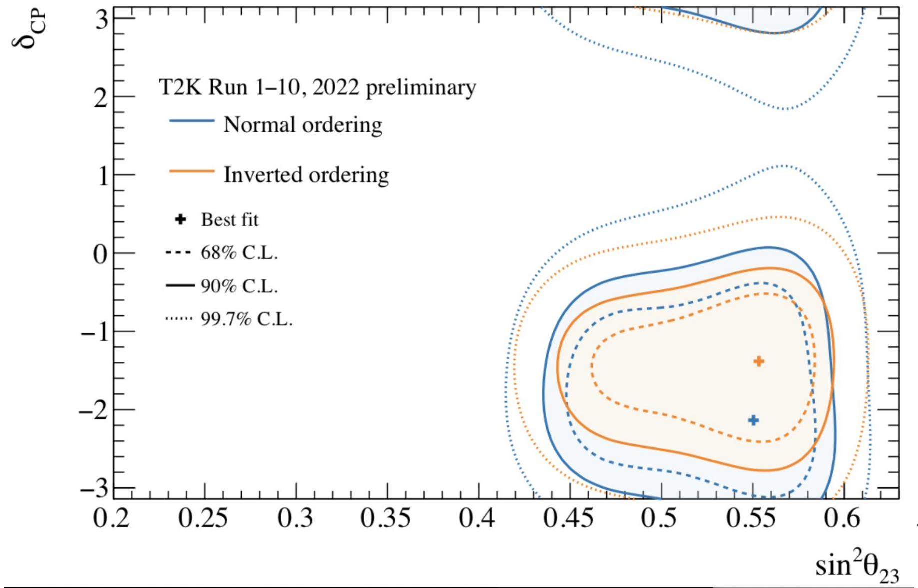
+



+ *additional* ν_e, ν_μ *samples*

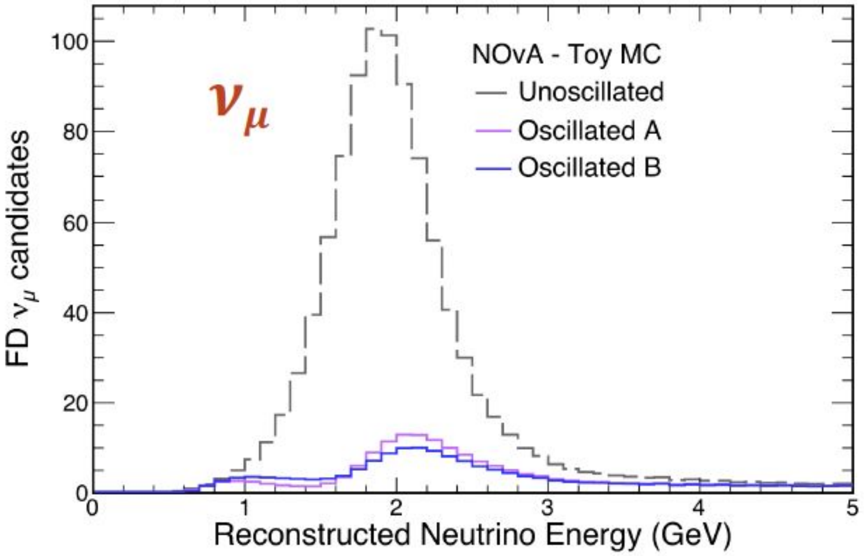
Event rates are used to infer oscillation parameters

- Example: T2K recent results on δ_{CP}
- Uses constraints from ν_μ disappearance - *next slide*



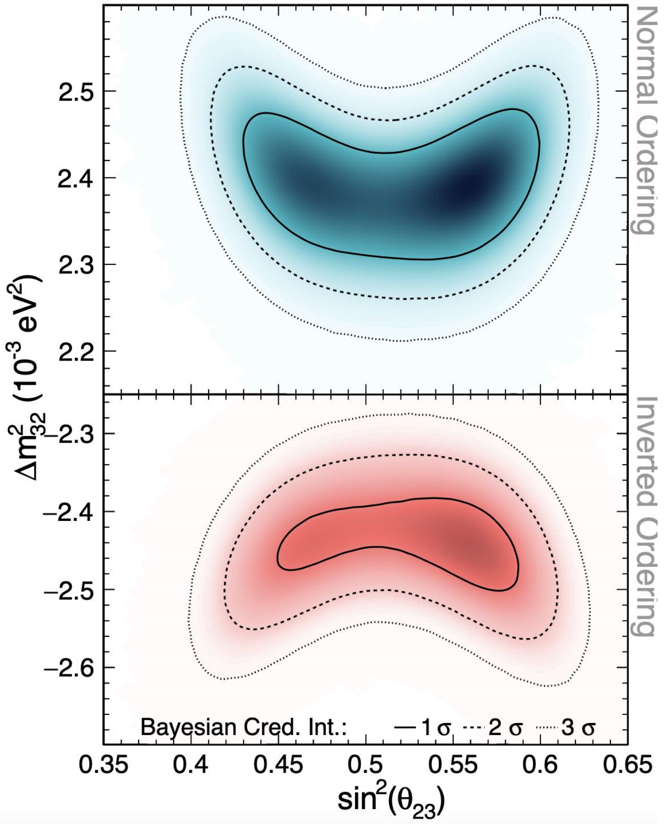
Probabilities to reality: mass splitting, octant

Caption box



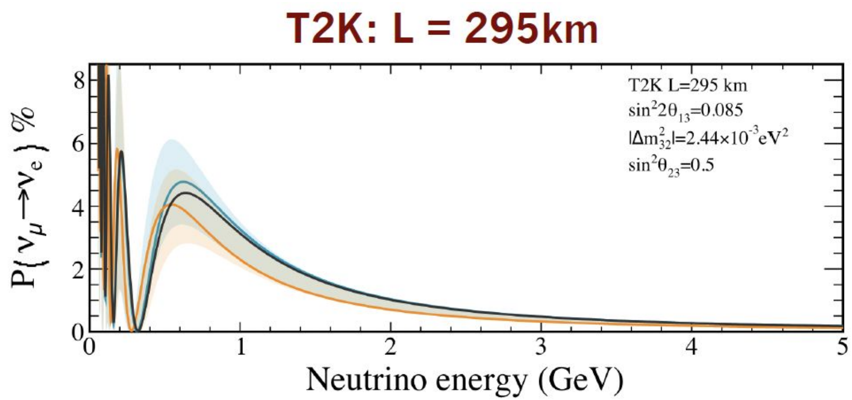
Event rates are used to infer oscillation parameters

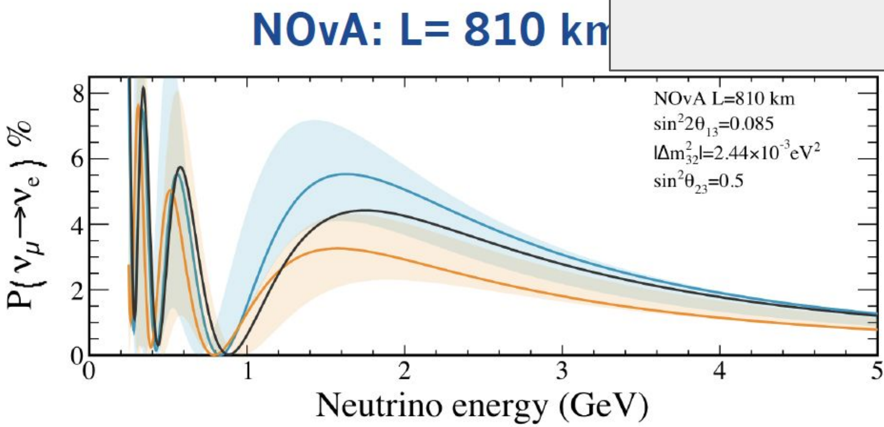
- Example: NOvA results on mass splitting and θ_{23} octant [arxiv - 2311.07835]



Disentangling neutrino oscillation

Caption box

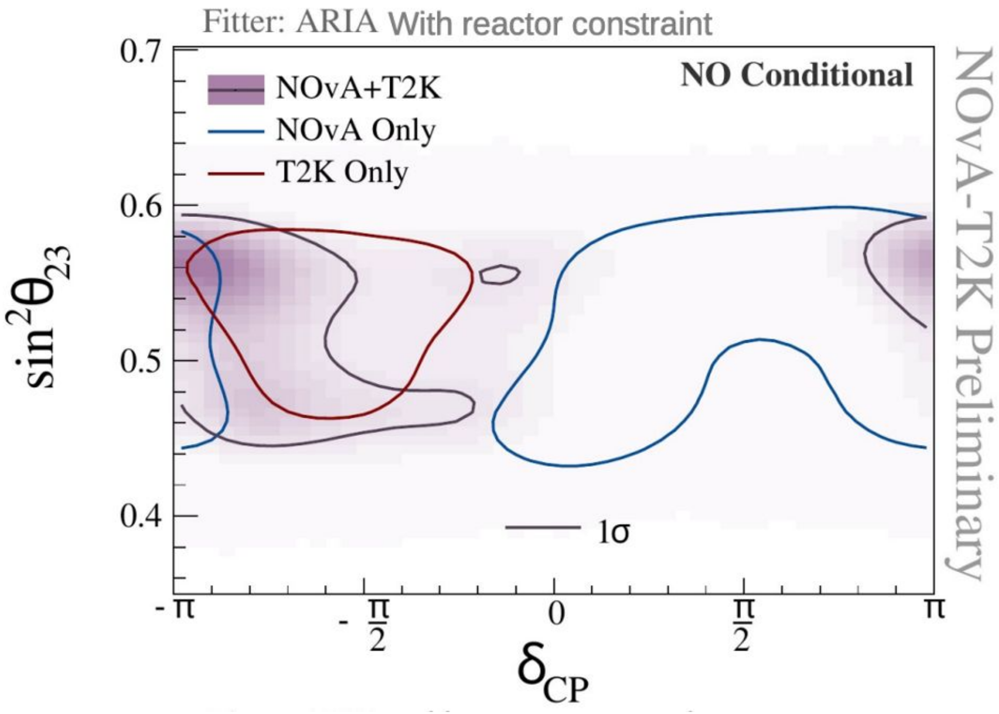




We can use different experimental conditions (L, E) to learn more about neutrino oscillation - *combinations of experiments break degeneracies in θ_{23}/mass ordering/CP*

Disentangling neutrino oscillation

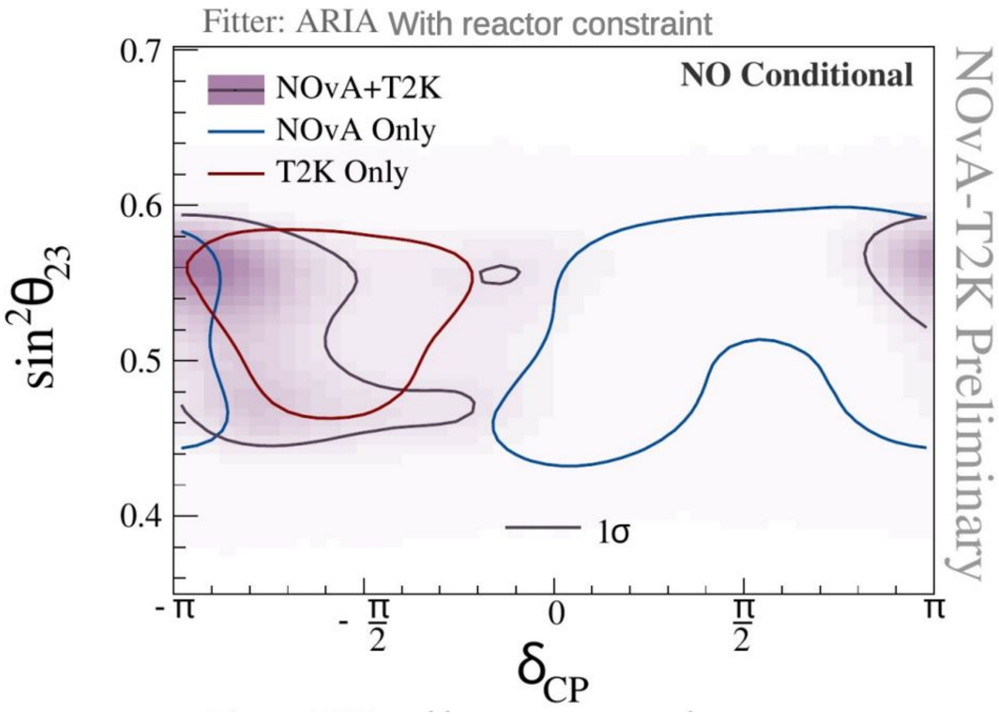
Caption box

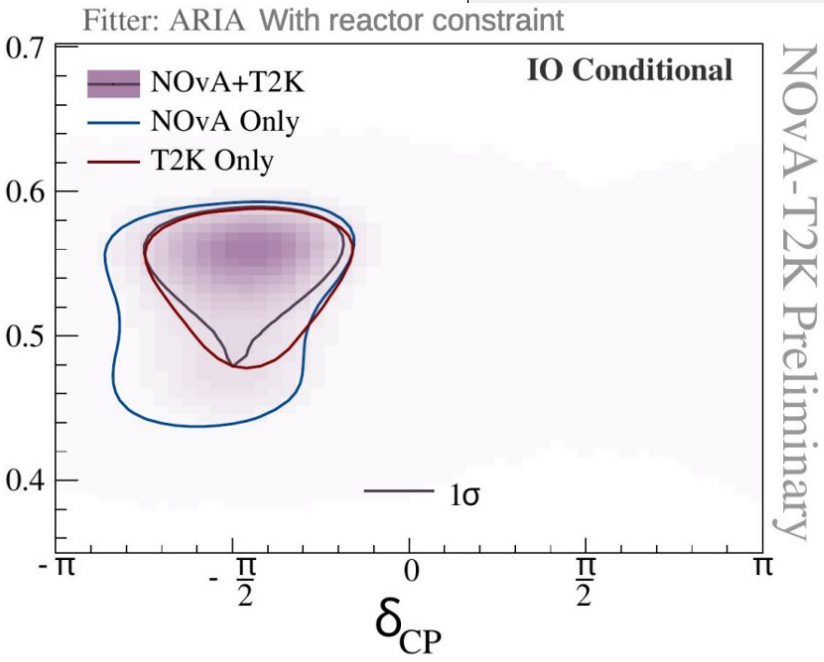


Example: in normal ordering, T2K and NOvA favor different oscillation values in θ_{23}/δ_{CP}

Disentangling neutrino oscillation

Caption box





Example: in normal ordering, T2K and NOvA favor different oscillation values in θ_{23}/δ_{CP}

In the inverted ordering however, the two experiments are consistent

T2K+NOvA joint fit overview

Caption box

Joint analysis of 2020 datasets includes:

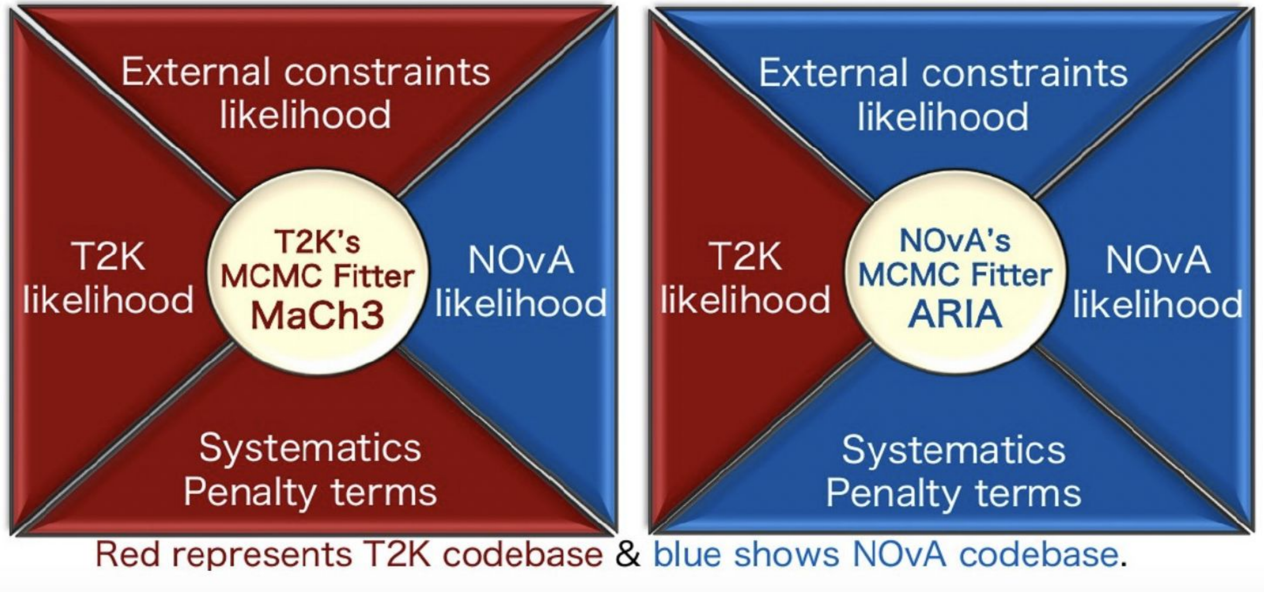
- Full energy reconstruction and detector response, detailed likelihood from each experiment
- Consistent statistical inference across the full dimensionality (Δm^2_{32} ,θ_{23}, θ_{13} mass ordering, δ_{CP})

Collaborations worked together on identifying detector, flux and cross section model commonalities, possible correlations

While accommodating different analysis approaches driven by different experimental designs

T2K+NOvA joint fit overview

Caption box



While accommodating different analysis approaches driven by different experimental designs

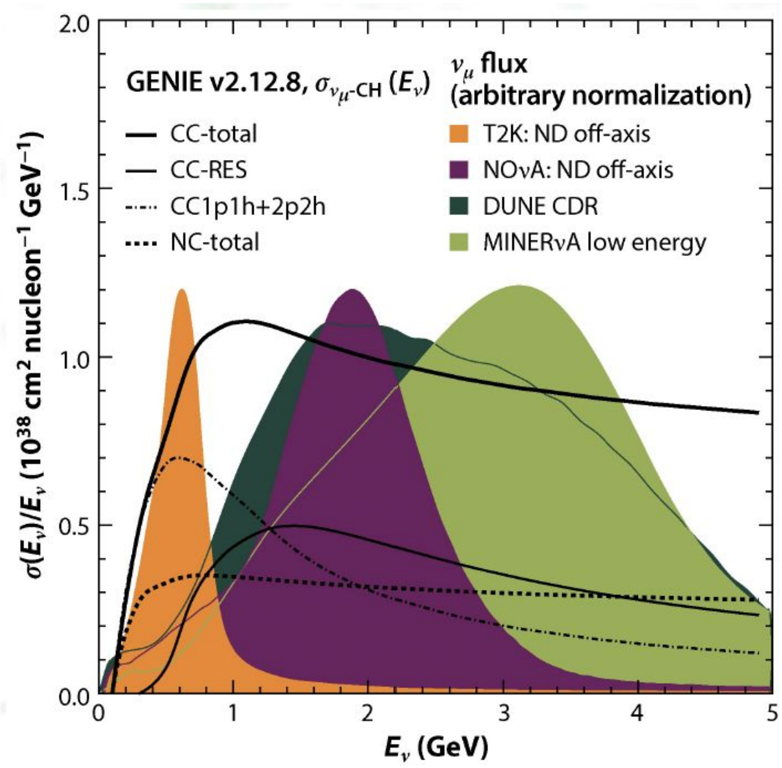
- The other experiment's likelihoods are integrated via a containerized environment.
- Individual experimental models, extrapolation are used

T2K+NOvA joint fit details

Caption box

Collaborations worked together on identifying detector, flux and cross section model commonalities, possible correlations

- No significant flux nor detector correlations expected
- The underlying physics of neutrino interactions is the same - *tests done to assess role of model and correlation choices*
- Correlation between key systematic [ν_e/ $\bar{\nu}_e$/ν_μ/ $\bar{\nu}_\mu$ σ] included



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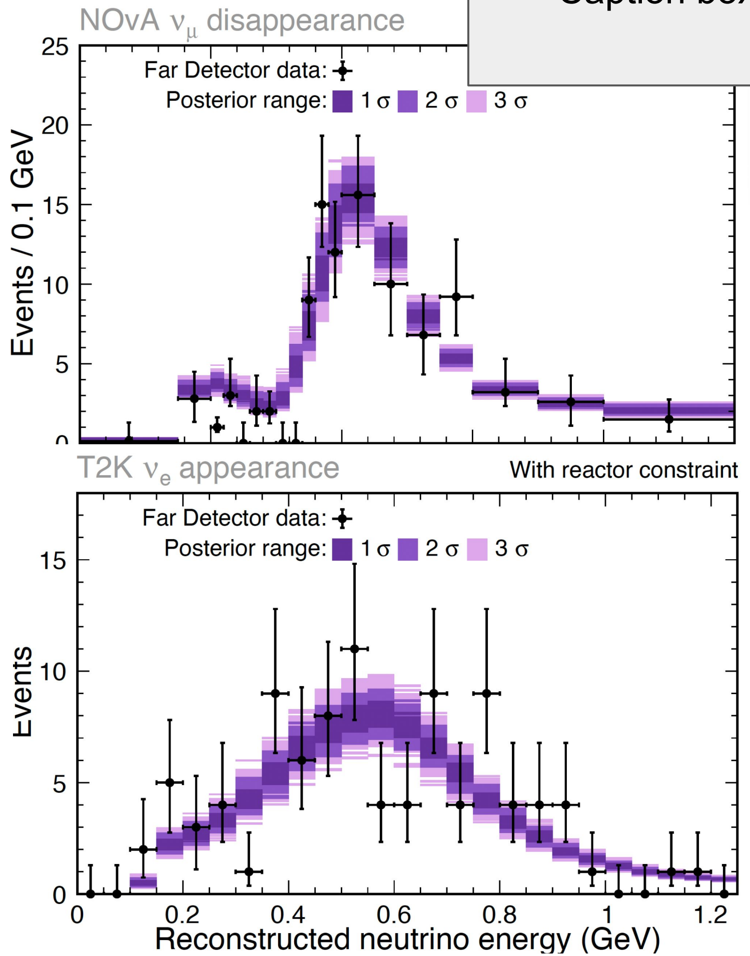
T2K+NOvA: goodness of fit

Caption box

- The data from both experiments is described well (p-value = 0.75) by the joint fit results
  - Individual experimental models are used with shared oscillation parameters

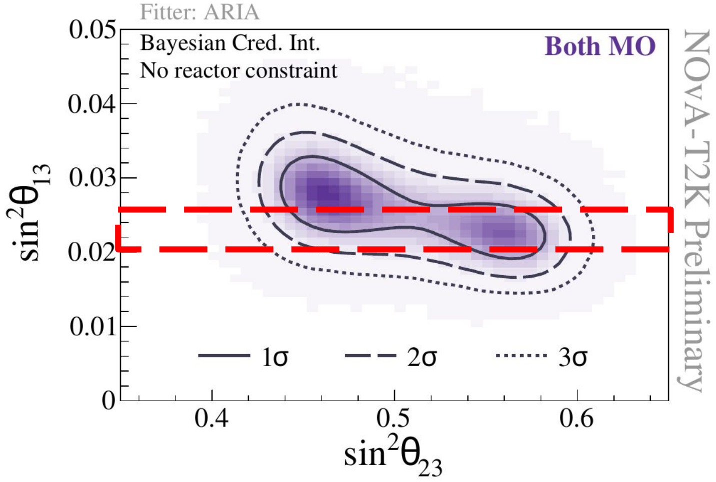
Channel	NOvA	T2K
ν_e	82	94 (ν_e) 14 ($\nu_e 1\pi$)
$\bar{\nu}_e$	33	16
ν_μ	211	318
$\bar{\nu}_\mu$	105	137



T2K+NOvA results: mixing angles

Caption box

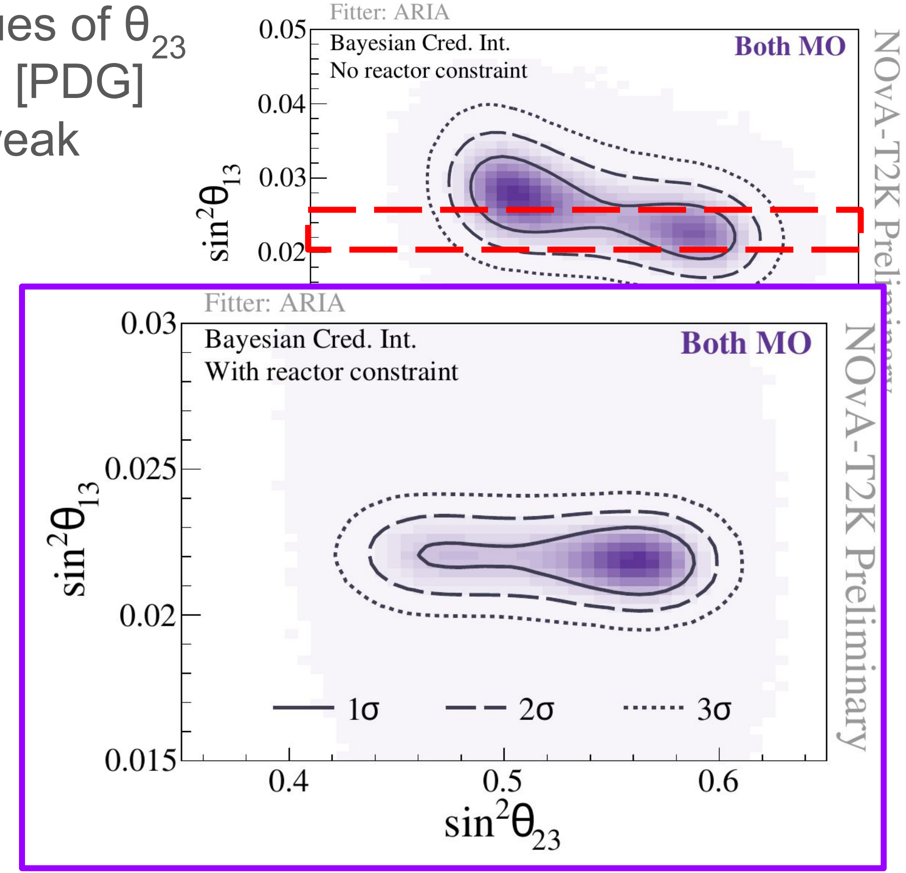
- Joint fit is consistent with reactor values of θ_{23}



T2K+NOvA results: mixing angles

Caption box

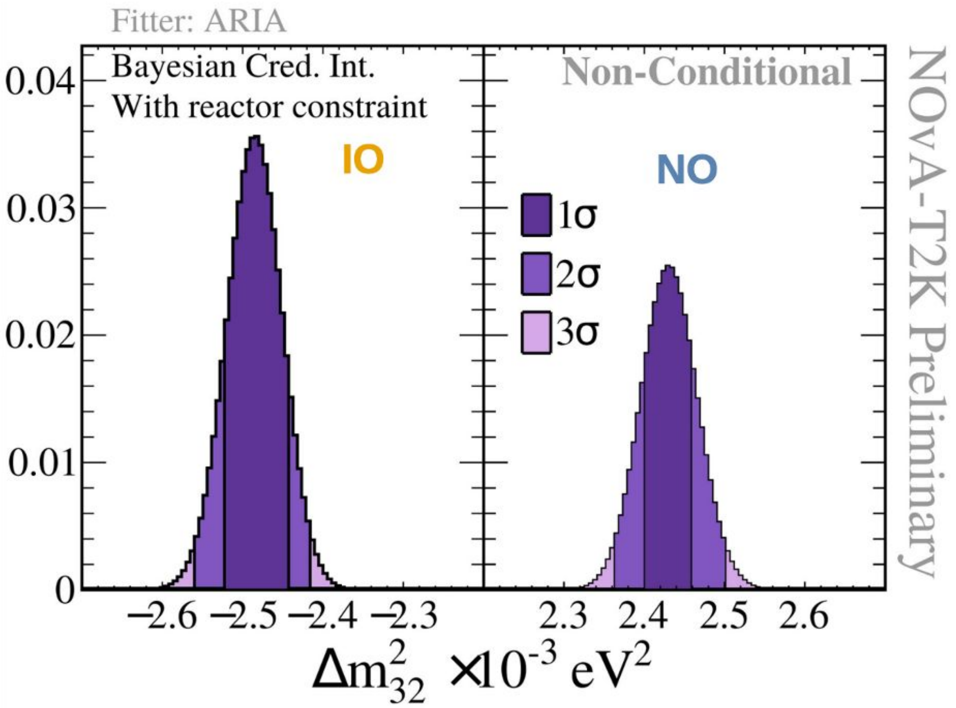
- Joint fit is consistent with reactor values of θ_{23}
- Using reactor experiment information [PDG] lifts θ_{23} degeneracy and provides a weak preference for the upper octant
- Without reactor (54% lower octant / 46% upper octant)
- With reactor (78% upper octant, 22% lower octant)



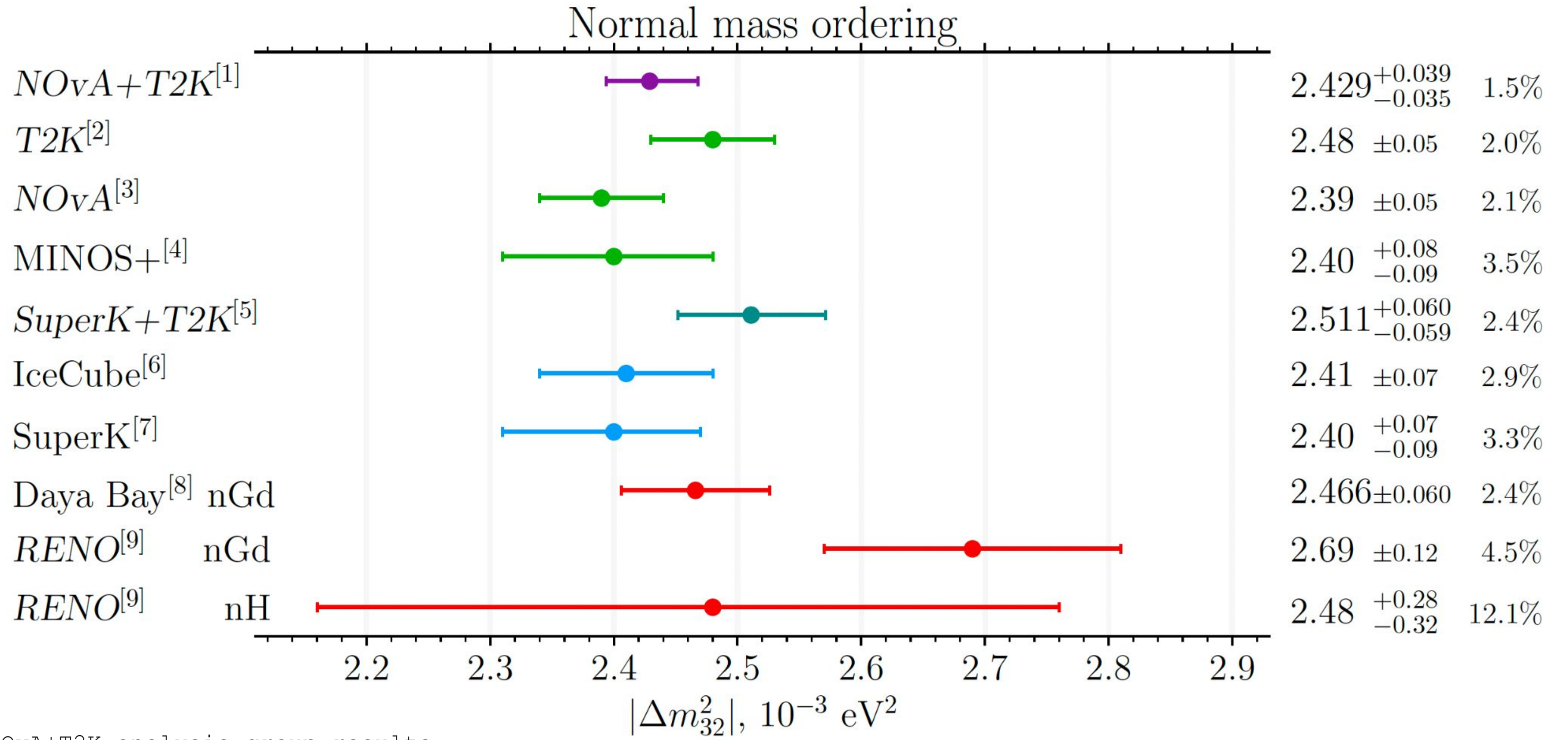
T2K+NOvA results: mass ordering, splitting

Caption box

- The experiments individually have preference for normal ordering
  - T2K p~0.81 for normal ordering
  - NOvA 1.0 σ for normal ordering
- The NOvA-T2K joint fit has no strong preference for ordering
  - Inverted ordering ~58%
  - Normal ordering ~42%

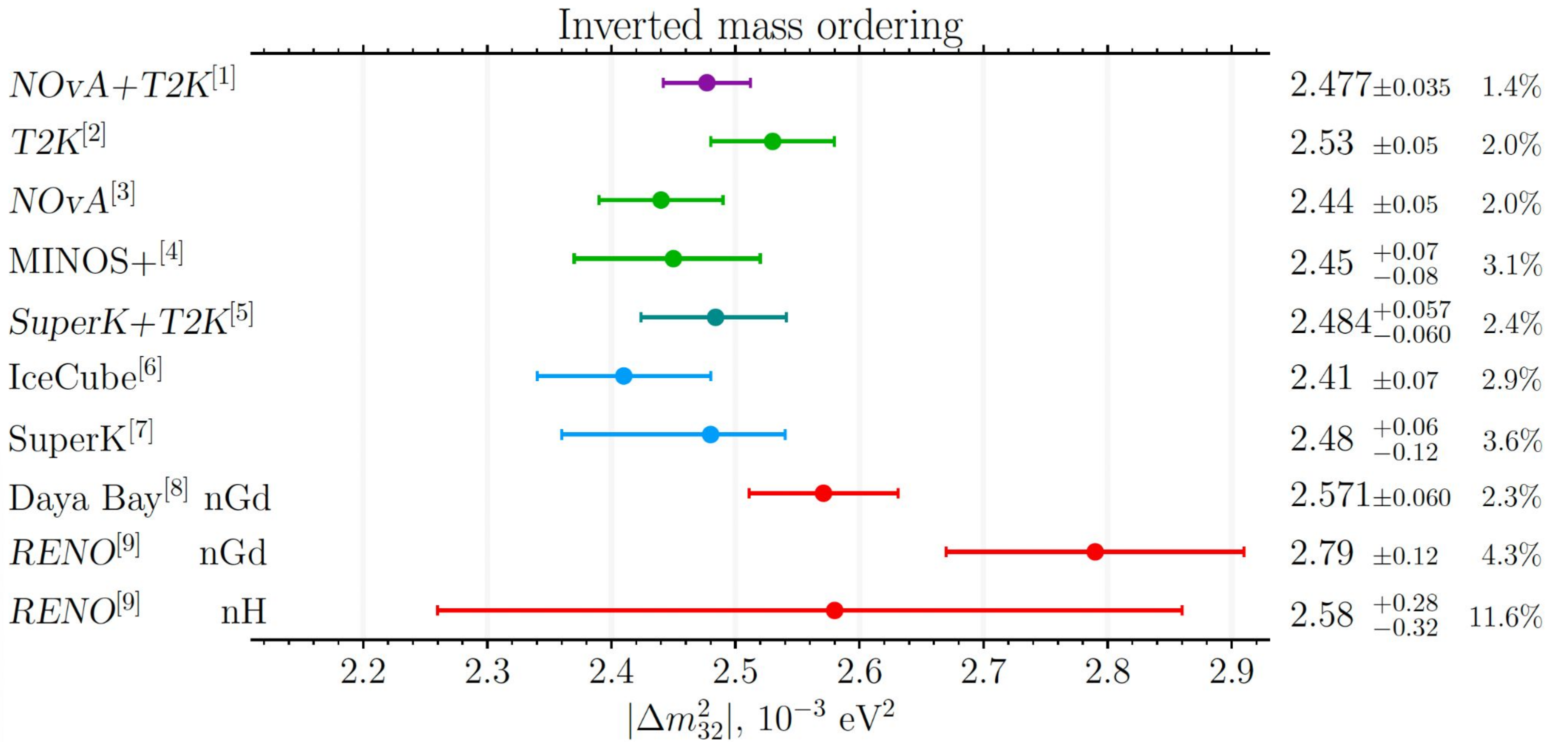


T2K+NOvA results in global landscape: mass splitting



[1] Joint NOvA+T2K analysis group results
[2] K.Abe et al. (T2K) Eur.Phys.J.C 83 (2023) 9, 782
[3] M.A.Acero et al. (NOvA) Phys.Rev.D 106 (2022) 3, 032004
[4] P. Adamson et al. (MINOS+), Phys. Rev. Lett. 125, 131802
[5] A. Eguchi, SuperK+T2K talk at NNN-2023, p. 65.
[6] R. Abbasi et al. (IceCube), Phys. Rev. D 108, 012014 (2023),
[7] T. Wester et al. (Super-Kamiokande), (2023), arXiv:2311.05105
[8] F. P. An et al. (Daya Bay), Phys. Rev. Lett. 130, 161802 (2023
[9] J. Yoo, RENO talk at Neutrino 2020, p. 13, p. 17.
[10] T. Bezerra Double CHOOZ talk Neutrino 2020, p. 20-21
[11] F. P. An et al. (Daya Bay), Phys.Rev.D 93 (2016) 7, 072011

T2K+NOvA results in global landscape: mass splitting



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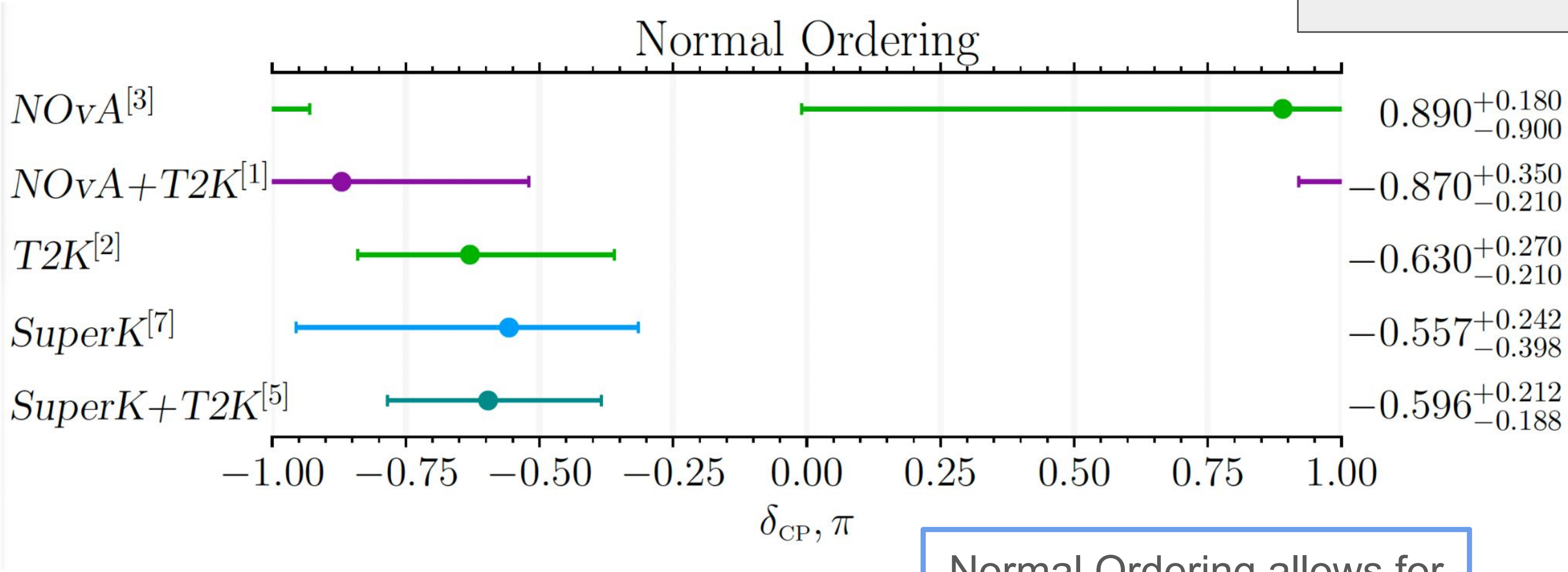
T2K+NOvA results in global landscape: δ_{CP}

Caption box



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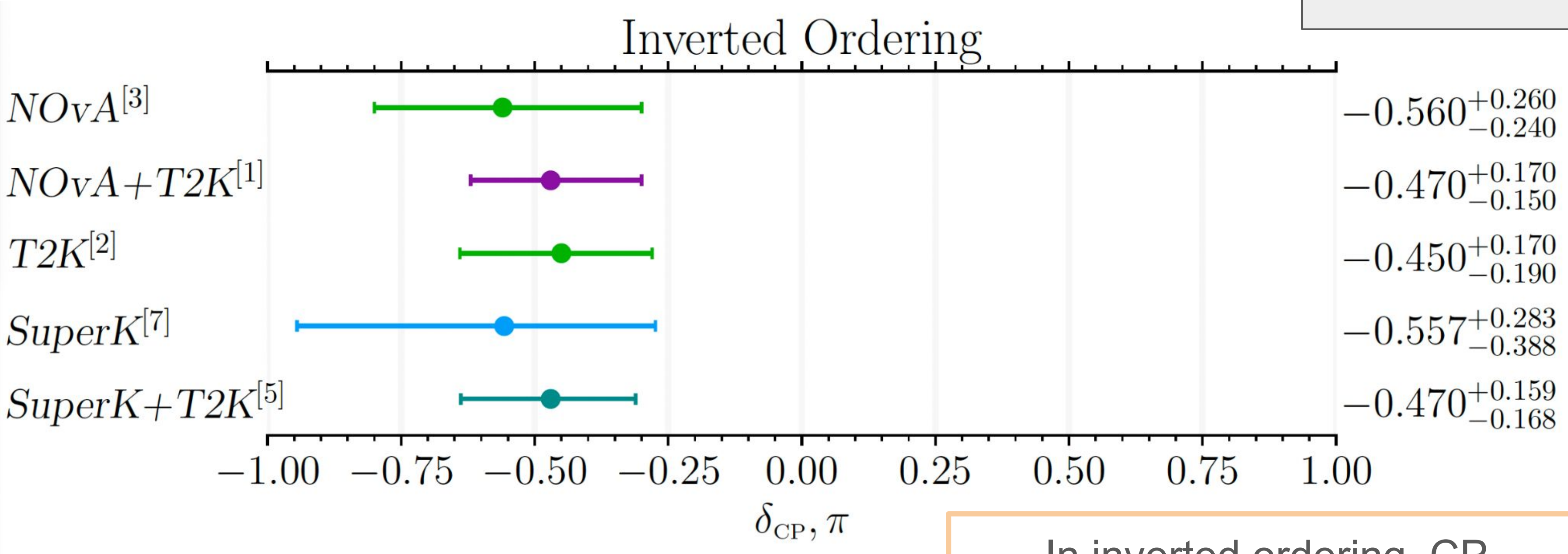
[5] A. Eguchi, SuperK+T2K talk at NNN-2023, p. 65.
[7] T. Wester et al. (Super-Kamiokande), (2023), arXiv:2311.05105

Normal Ordering allows for a broad range of δ_{CP} and $\delta_{CP} = \pi/2$ lies outside 3-sigma credible interval

T2K+NOvA results in global landscape: δ_{CP}

Caption box



In inverted ordering, CP conserving values lie outside the 3-sigma credible interval

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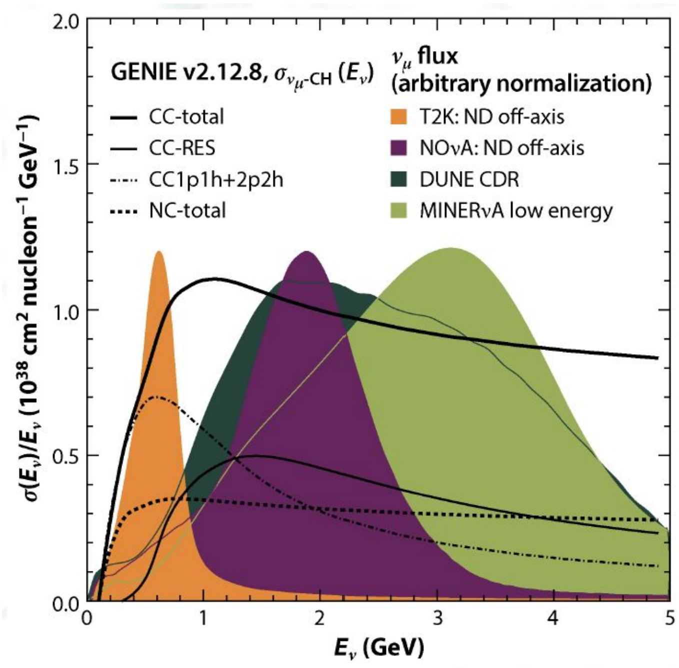
[7] T. Wester et al. (Super-Kamiokande), (2023), arXiv:2311.05105

The broader program: neutrino cross sections

Caption box

Energy regime: 0.1-20 Gev



Interesting physics

BSM: sterile neutrinos, light dark matter, NSI, precision tests of SM

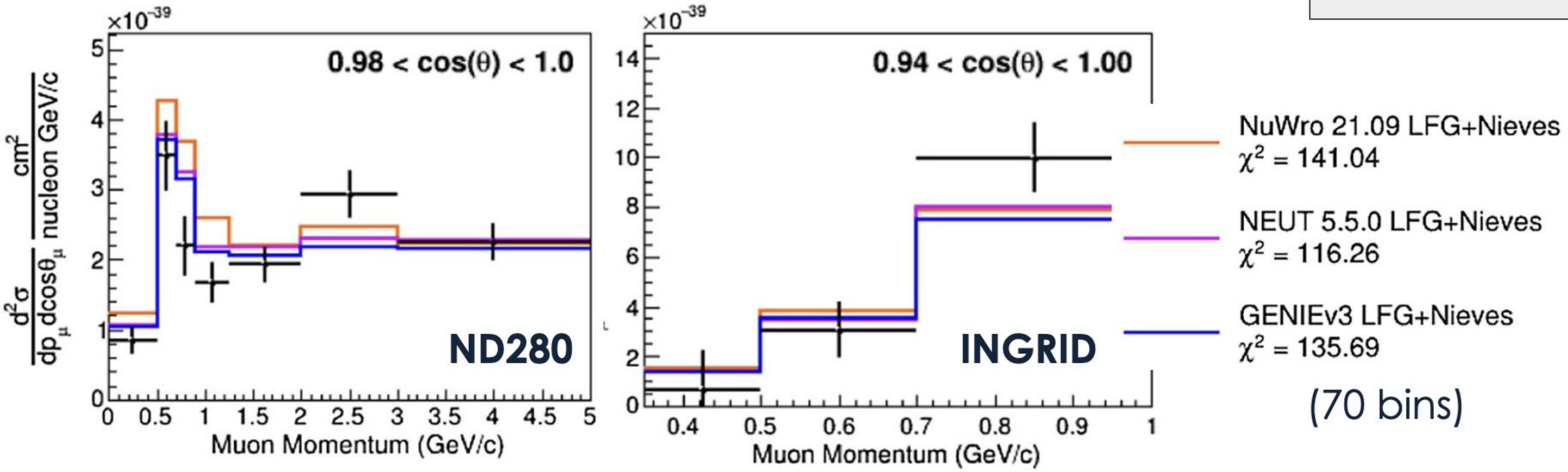
Three flavor oscillation: θ_{23} octant, mass hierarchy, CP violation.
Tests of neutrino mixing model

More BSM: proton decay

Cross section measurements allow us to iterate with theory and community on model development, completeness relevant to a broad set of physics programs

The broader program: neutrino cross sections

Caption box



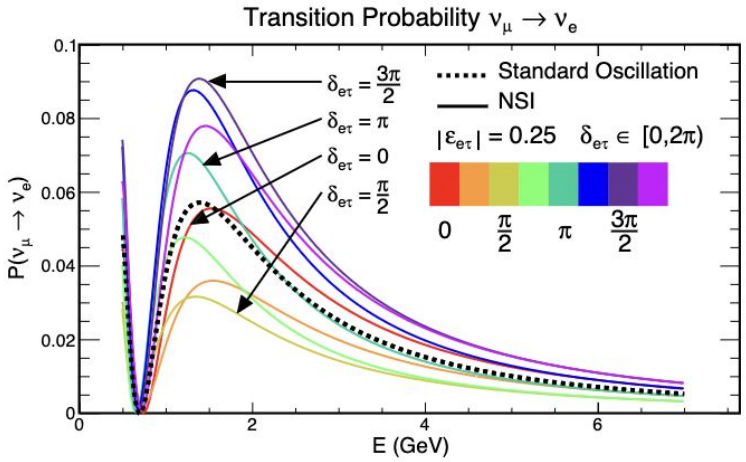
Recent example (T2K) using ND280 and INGRID near detectors [PRD108, 112009]

- Correlations in the neutrino source (flux) provide a strong constraint on models
- Difficulty in accommodating forward suppression at ND280 not seen at INGRID

The broader program: non-standard interactions (NSI)

Caption box

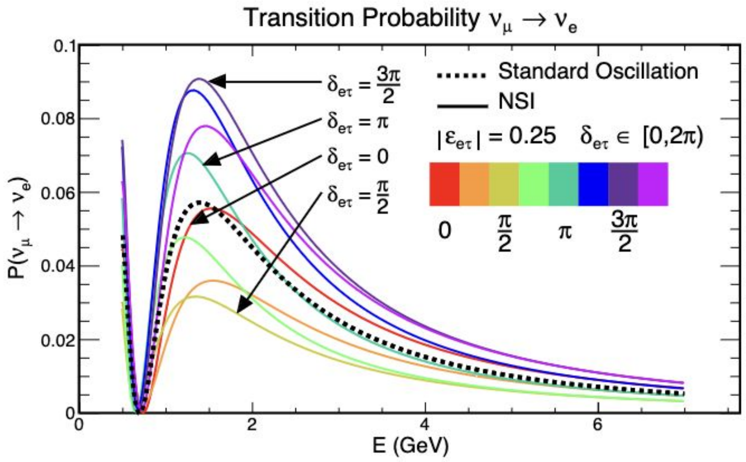
NSI would, like the mass ordering, modify the oscillation probability

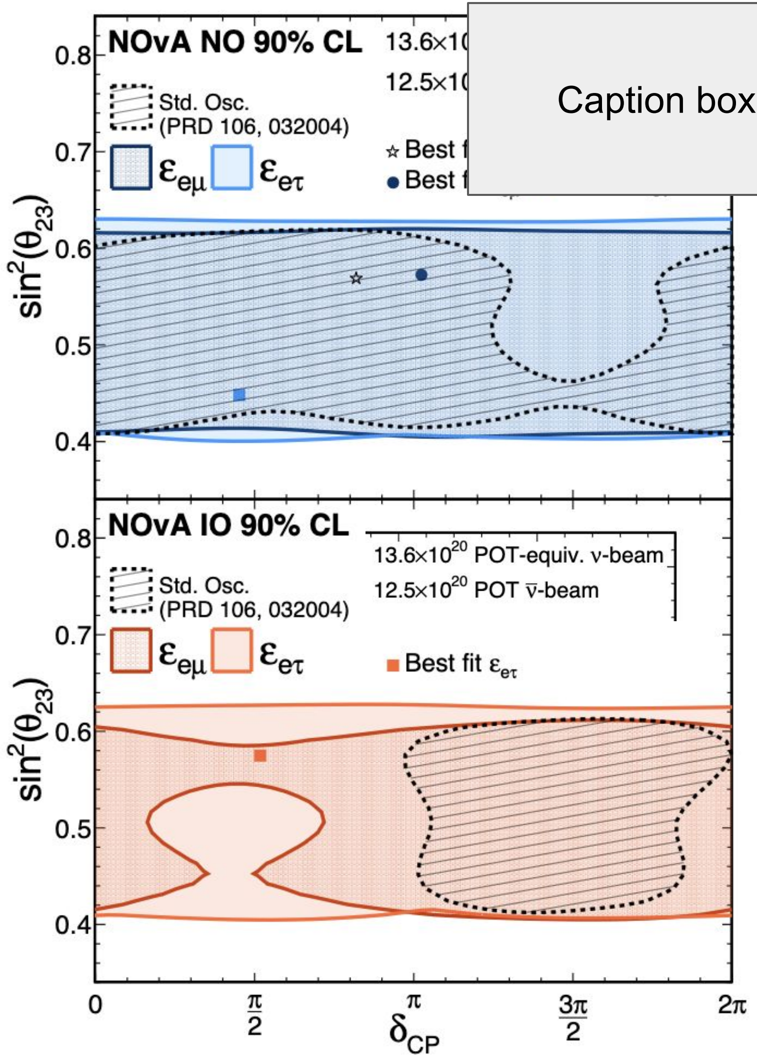


The broader program: non-standard interactions (NSI)

NSI would, like the mass ordering, modify the oscillation probability and the interpretation of (standard) oscillation parameters

- Example from NOvA [arxiv [2403.07266](https://arxiv.org/abs/2403.07266)]





Caption box

Summary

Caption box

T2K and NOvA are accelerator driven neutrino experiments:

- Experiments have led the discovery of CC ν_e and $\overline{\nu}_e$ appearance
- T2K, NOvA are complementary to each other and global (reactor, atmospheric) three flavor neutrino oscillation program
- Both experiments have rich cross section, exotic physics programs

A recent joint analysis effort of 2020 datasets from T2K and NOvA determined:

- No strong preference for the mass ordering
- Normal ordering allows for a wide range of δ_{CP} values; inverted ordering CP conserving values fall outside of the 3σ credible intervals

Outlook

Caption box

Both T2K and NOvA continue to collect data and improve individual analyses

- Data expected from both experiments expected to double in coming years before DUNE and Hyper-Kamiokande (next generation experiments) turn on
- T2K upgraded ND280 for better understanding of ν interactions; upgraded J-PARC accelerator (760kW!)
- NOvA is collecting more anti-neutrino data and has already doubled neutrino data
- Please see poster session and talks in the neutrino track

T2K and NOvA have produced their first joint analysis of data from both experiments

- Established collaboration and knowledge sharing; scope and timeline are being explored for subsequent joint analyses

Caption box

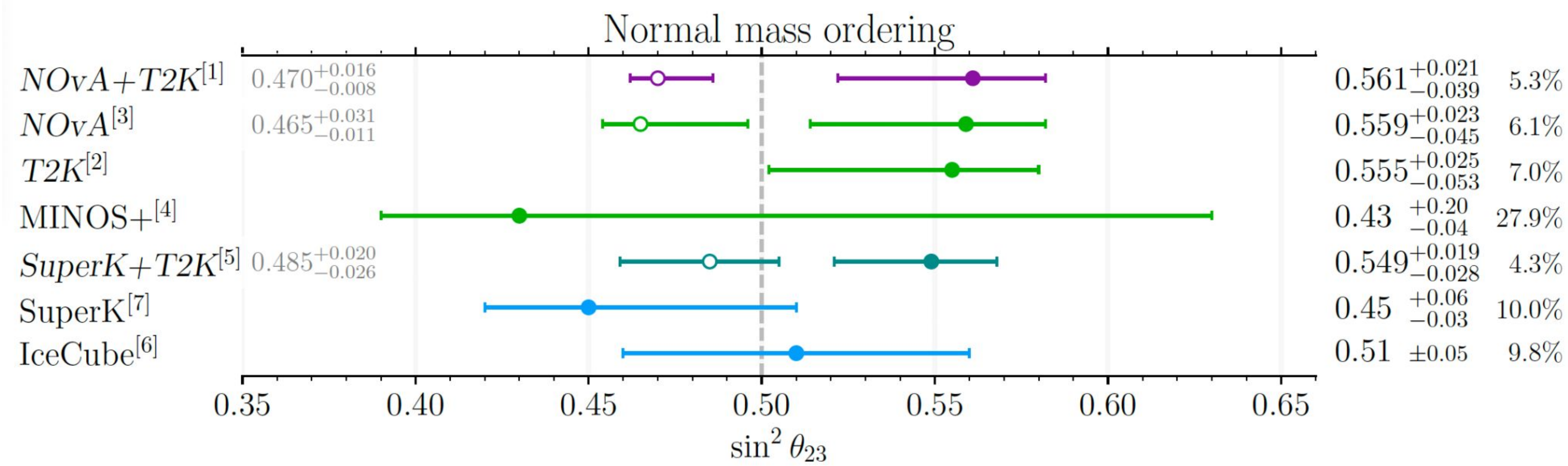
Thanks to both collaborations!

Speaker supported by DOE award - DE-SC0015903

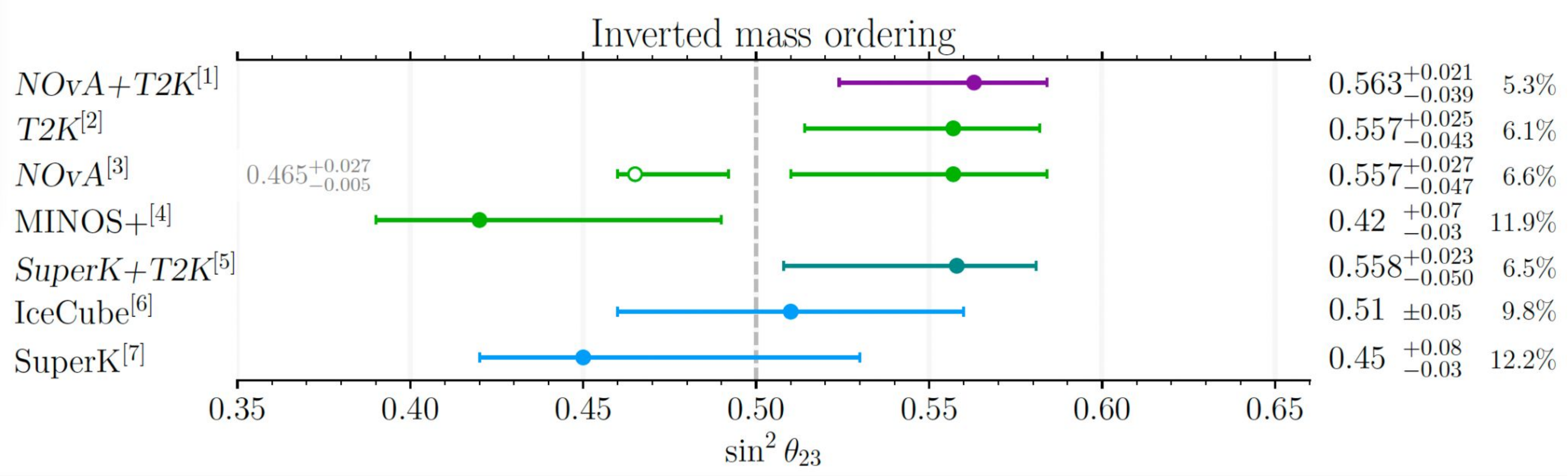
Backup

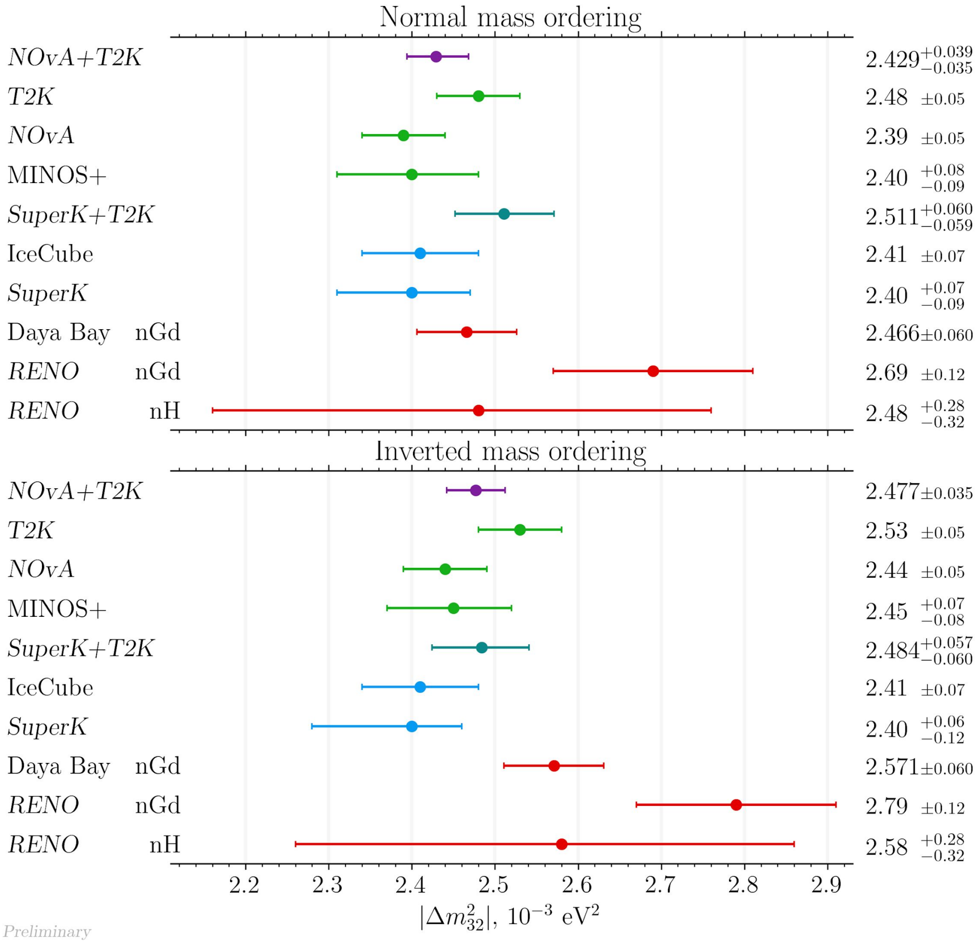
Some backup slides helpfully prepared by J. Walsh

T2K+NOvA results:



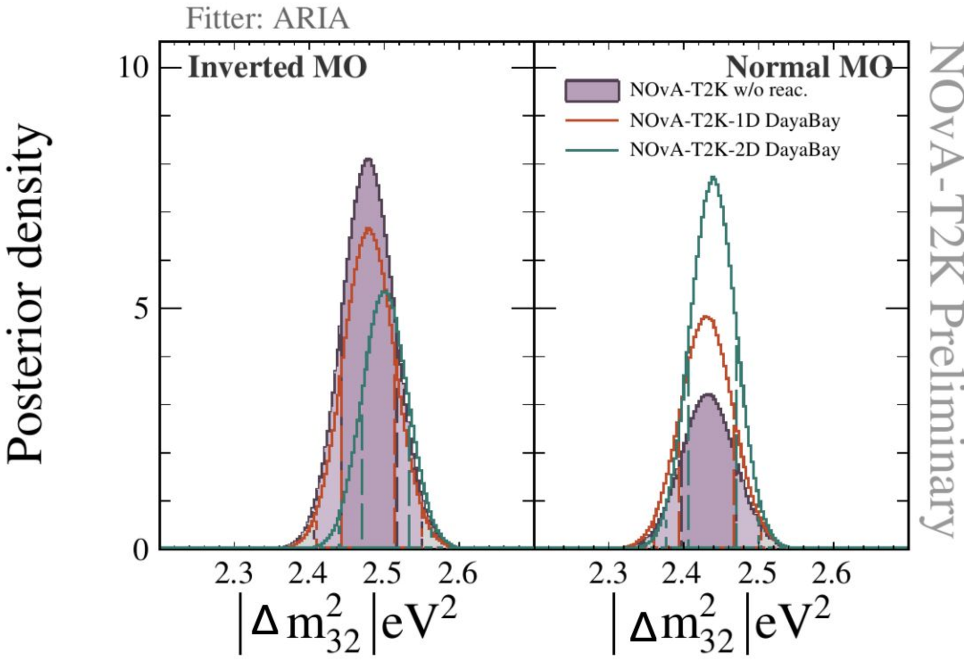
T2K+NOvA results:




Normal mass ordering
NOvA+T2K 2.429 +0.039 −0.035
T2K 2.48 ±0.05
NOvA 2.39 ±0.05
MINOS+ 2.40 +0.08 −0.09
SuperK+T2K 2.511 +0.060 −0.059
IceCube 2.41 ±0.07
SuperK 2.40 +0.07 −0.09
Daya Bay nGd 2.466 ±0.060
RENO nGd 2.69 ±0.12
RENO nH 2.48 +0.28 −0.32
Inverted mass ordering
NOvA+T2K 2.477 ±0.035
T2K 2.53 ±0.05
NOvA 2.44 ±0.05
MINOS+ 2.45 +0.07 −0.08
SuperK+T2K 2.484 +0.057 −0.060
IceCube 2.41 ±0.07
SuperK 2.40 +0.06 −0.12
Daya Bay nGd 2.571 ±0.060
RENO nGd 2.79 ±0.12
RENO nH 2.58 +0.28 −0.32
2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9
$|\Delta m^2_{32}|$, 10^{-3} eV^2
Preliminary

2D DayaBay constraint

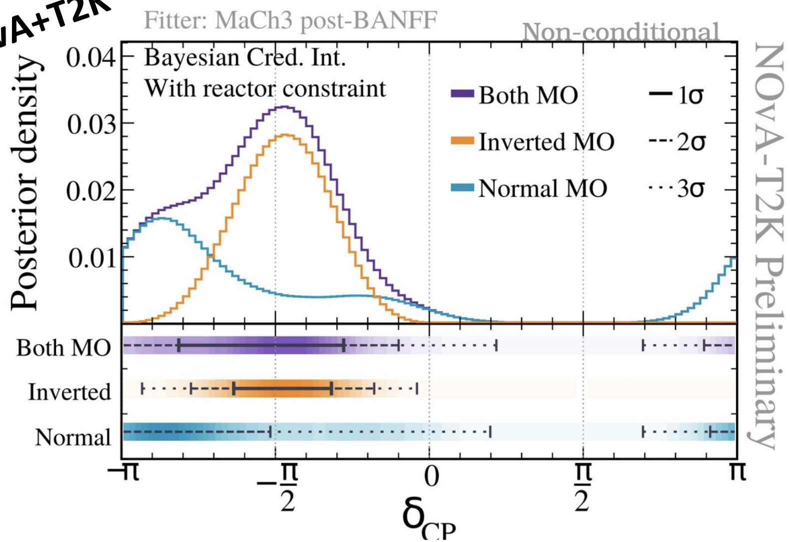
	No Reactor Constraint	**1D** Reactor Constraint	**2D** Reactor Constraint
Mass Ordering	2.45 71% : 29% (IO : NO)	1.38 58% : 42% (IO : NO)	1.44 59% : 41% (NO/IO)
Octant	1.17 54% : 46% (LO : UO)	3.58 78% : 22% (UO : LO)	3.219 76% : 24% (UO : LO)



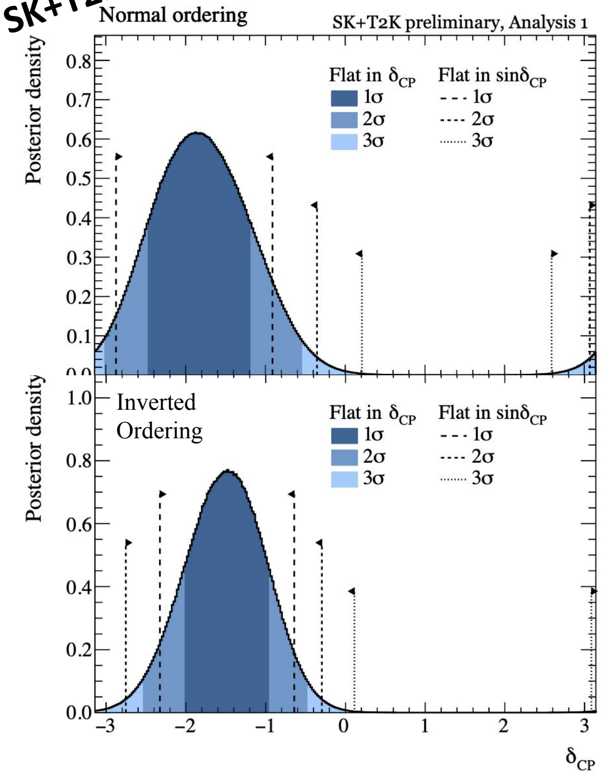
Comparison of both joint results

A. Eguchi NNN23

NOvA+T2K



SK+T2K



	NOvA+T2K		SK+T2K	
	Lower Octant	Upper Octant	Lower Octant	Upper Octant
Normal Ordering	12.6%	29.8%	36.7%	53.3%
Inverted Ordering	9.2%	48.3%	2.2%	7.8%
B(NO/IO) or B(IO/NO)	1.38 for IO		8.98 for NO	
B(UO/LO)	3.58		1.57	

Both results contain the same T2K data and PDG reactor constraint and so have an expected correlation and should not be combined

Super-K + T2K joint result

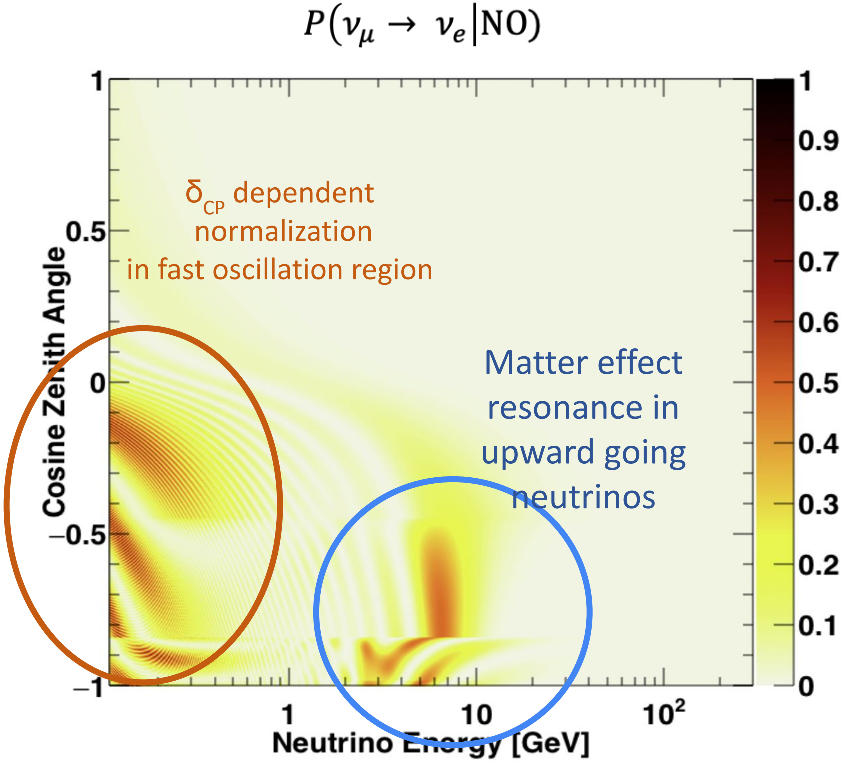
Another analysis combined beam and atmospheric neutrino data from the Super-Kamiokande and T2K experiments

Atmospheric neutrinos have sensitivity to different mass ordering and CPV effects

Super-K is the T2K far detector:

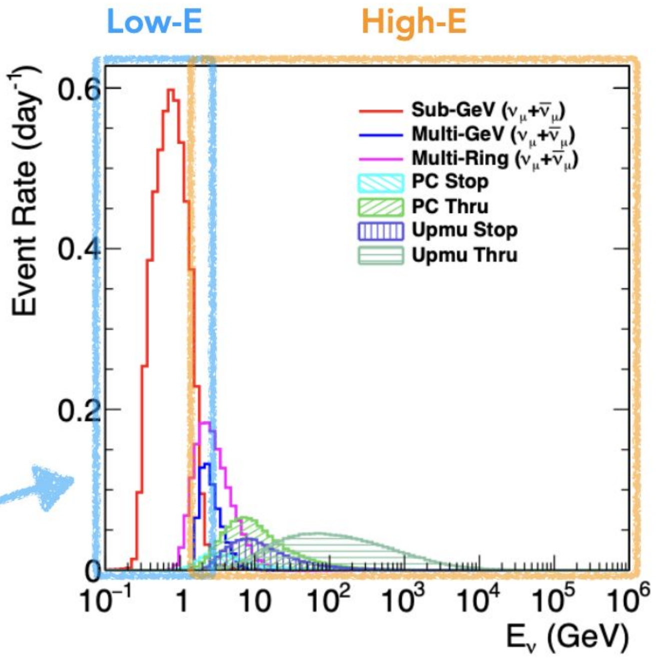
Same detector

Shared modelling and analysis infrastructure



A. Eguchi, NNN2023, SK+T2K combined analysis

- SK atmospheric covers a wider range of energies than T2K.
  - Use different models for low-energy and high-energy samples.



Use a common cross-section model with T2K

	Low-energy sub-GeV atm + beam	**High-energy** multi-GeV atm
CCQE	T2K model with ND280 constraint, correlated in low-E/highE (except for high-Q^2)	
	high-Q^2 params w/ND280	high-Q^2 params w/o ND
	add ν_e/ν_μ ratio unc. (CRPA)	
2p2h	T2K model w/ND280	SK model (100% error) + T2K-style shape
Resonant	T2K model w/ND280 + new pion momentum dial + NC1π0 uncertainties	SK model for 3 dials common with T2K, use more recent larger T2K priors
DIS	T2K model w/ND280	SK model
ν_τ	SK model (25% norm on top of other syst) for other systematics checked that we have no numerically unstable values	
FSI	T2K model w/ND280	T2K model w/o ND280 should be mostly same as SK model
SI	T2K model, correlated in low-E/high-E only applied to FC and PC for atm, PN not applied to atm	

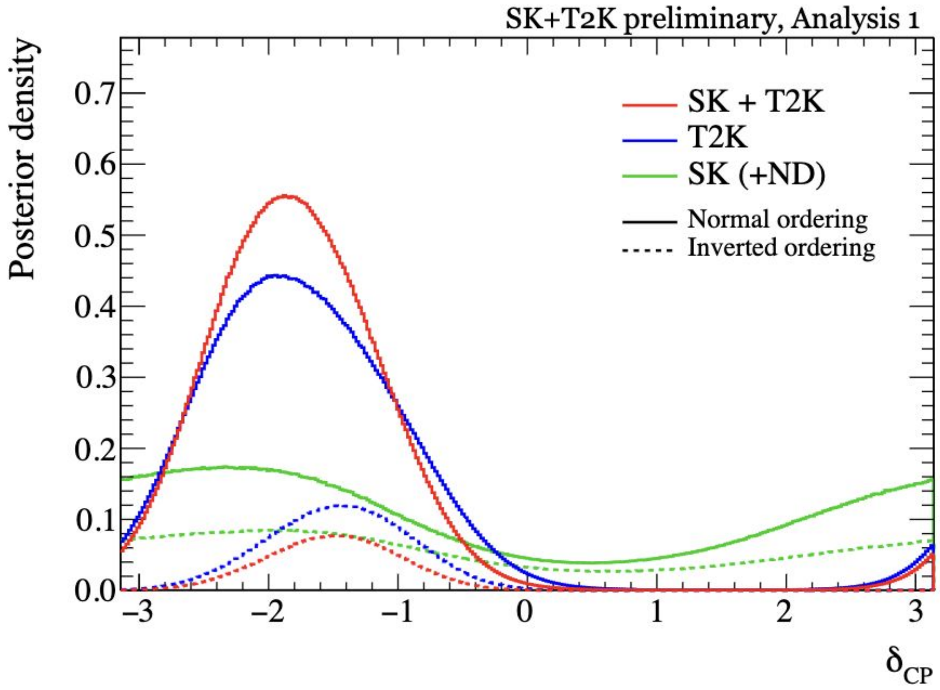
- SK atmospheric covers a wider range of energies than T2K.
  - Use different models for low-energy and high-energy samples.

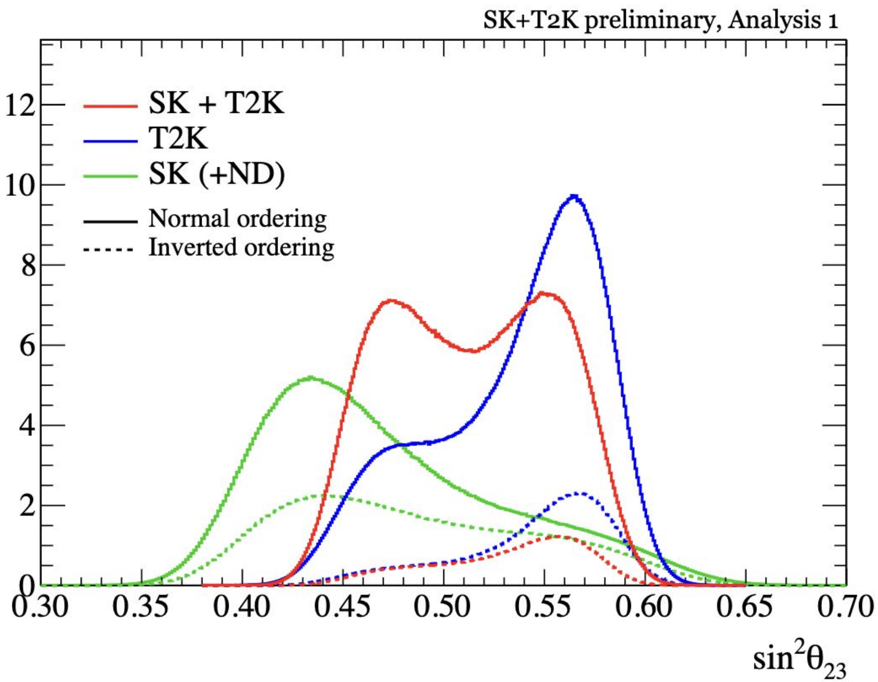
- **Low energy** (beam and atmospheric Sub-GeV samples)
  - Use the T2K model [ref] as the base which is **constrained by the T2K near detector**.
  - Some extra parameters are added to cover important uncertainties for the atmospheric analysis.

- **High energy** (rest of atmospheric samples)
  - Use a modified SK model [ref] including additional systematics uncertainties.

	Low-energy sub-GeV atm + beam	**High-energy** multi-GeV atm
CCQE	T2K model with ND280 constraint, correlated in low-E/highE (except for high-Q^2)	
	high-Q^2 params w/ND280	high-Q^2 params w/o ND
	add ν_e/ν_μ ratio unc. (CRPA)	
2p2h	T2K model w/ND280	SK model (100% error) + T2K-style shape
Resonant	T2K model w/ND280 + new pion momentum dial + NC1π0 uncertainties	SK model for 3 dials common with T2K, use more recent larger T2K priors
DIS	T2K model w/ND280	SK model
ν_τ	SK model (25% norm on top of other syst) for other systematics checked that we have no numerically unstable values	
FSI	T2K model w/ND280	T2K model w/o ND280 should be mostly same as SK model
SI	T2K model, correlated in low-E/high-E only applied to FC and PC for atm, PN not applied to atm	

SK+T2K combined results - *shown at NNN*





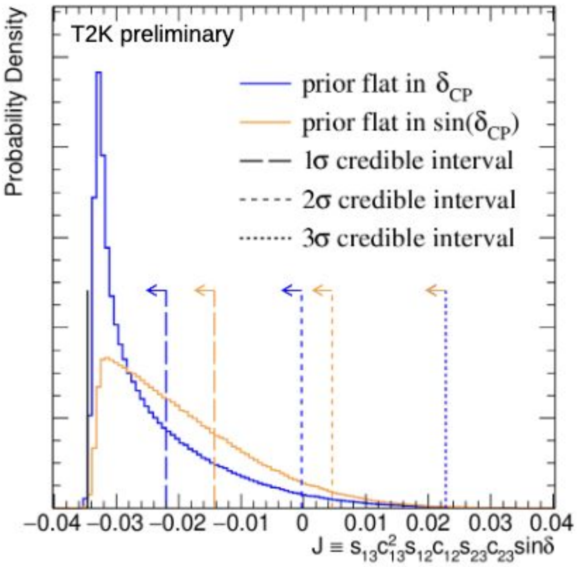
Combined results are consistent with T2K-only results in δ_{CP} - *publication in preparation*

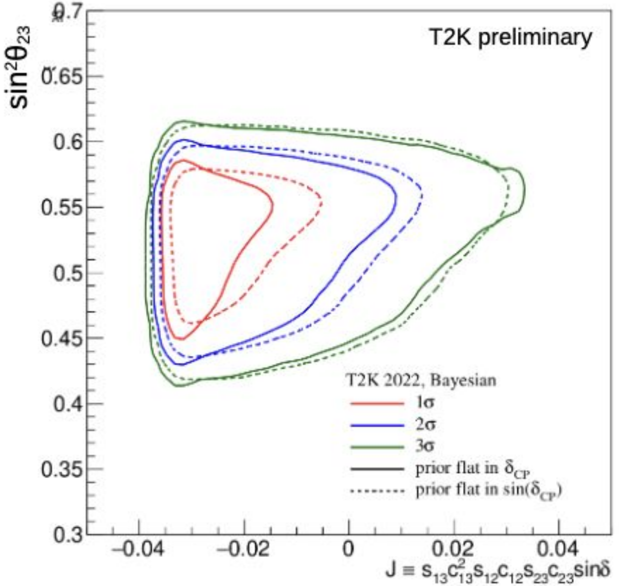
- Weak preference for normal mass ordering MO (Bayes factor is ~9.0, 1.6σ)
- Different experimental preferences in θ_{23} octant is resolved in joint fit

New oscillation result
Jarlskog invariant

C. Bronner, Neutrino 2022

- Can search for potential CP violation by looking at the posterior probability and credible intervals for J_{CP}
- Results depend on the metric in which we assume the prior for δ to be uniform





Marginalized over mass ordering hypotheses
Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

Now available for T2K, NOvA and T2K+NOvA and T2K+SK

Fake Data Studies

Test for out-of-model effects which could bias results

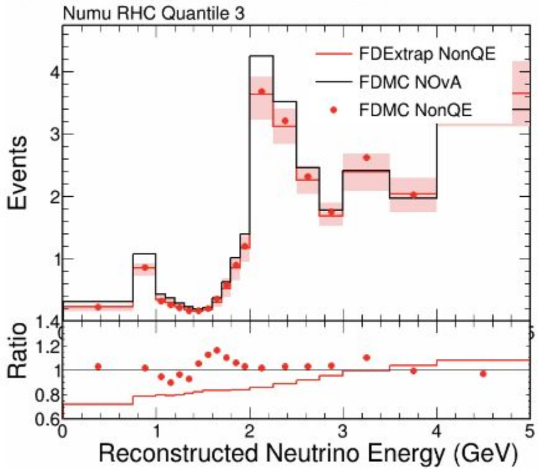
Generate “fake data” – a modified set of the nominal MC to include variations not deliberately included inthe uncertainty model

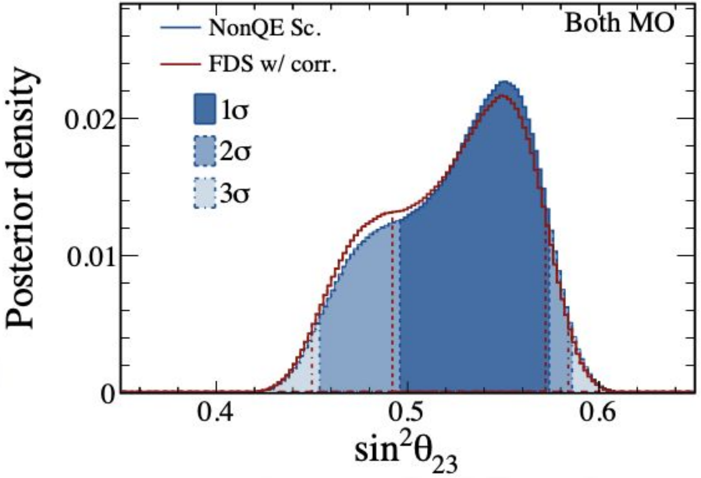
Fit T2K model to fake data at ND280 - use post-ND280 constrained flux+xsec model to fit SK fake data in joint fit

Use NOvA ND to build tuned response templates for NOvA FD in joint fit

Check shifts in credible interval positions and sizes are not large relative to systematic uncertainty contribution

Perform this procedure at key several different oscillation parameter combinations of interest



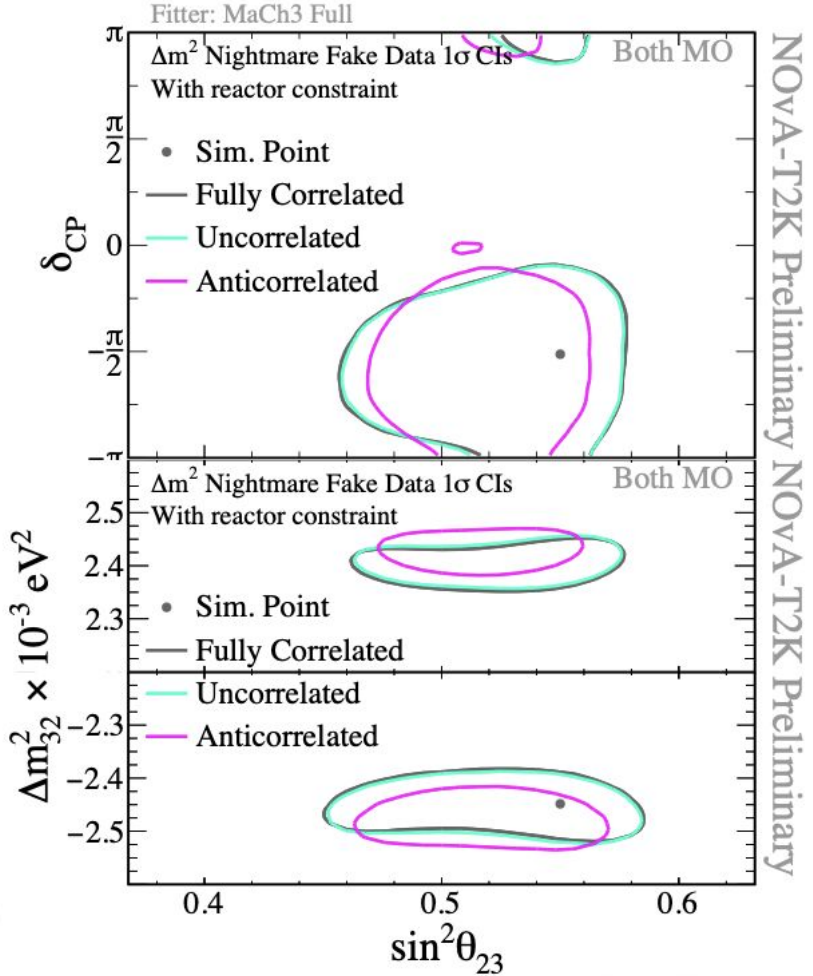


Correlation Studies

Test for impact of missing cross-experiment correlations or erroneously implementing correlations between parameters

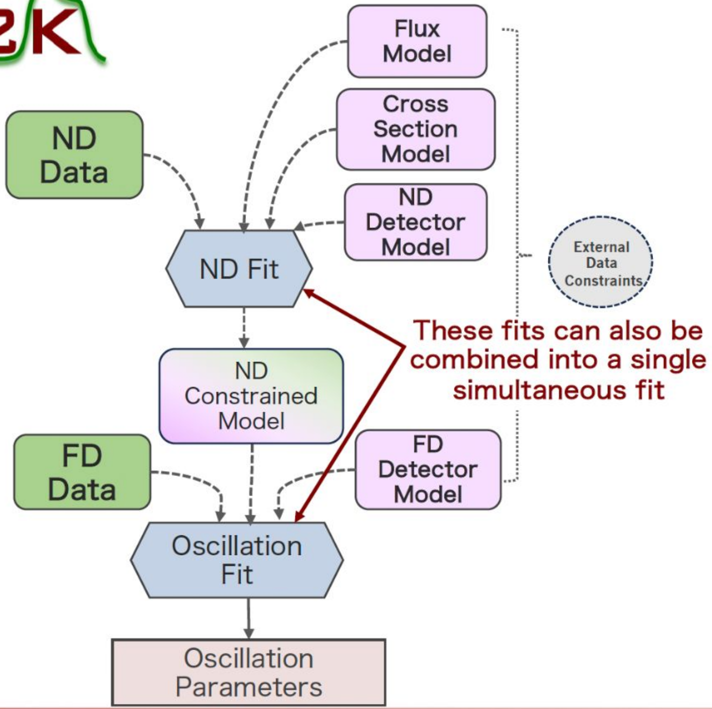
Construct “nightmare parameters” which take parameters known to have strong correlations with the oscillation parameters and enhance their impact

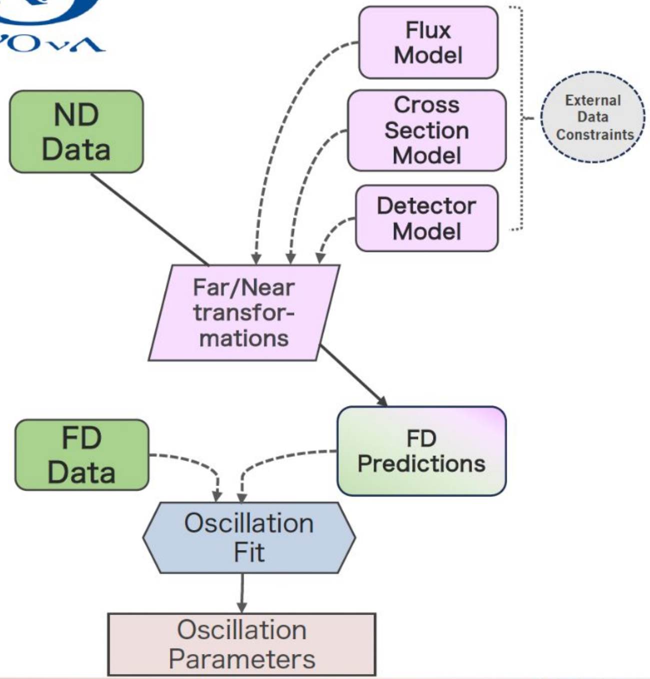
Fit fake data sets where these parameters are moved together are fit under the assumption of correlation or anticorrelation



Analysis Strategy

- The experiments have different analysis approaches driven by contrasting detector designs.





T2K analysis reminder - *analysis flow*

Refine, revisit and test models

Flux model

E.g. beam monitors, external data

Cross section model

E.g. theory, external data

Inputs from theory, external and in-situ data

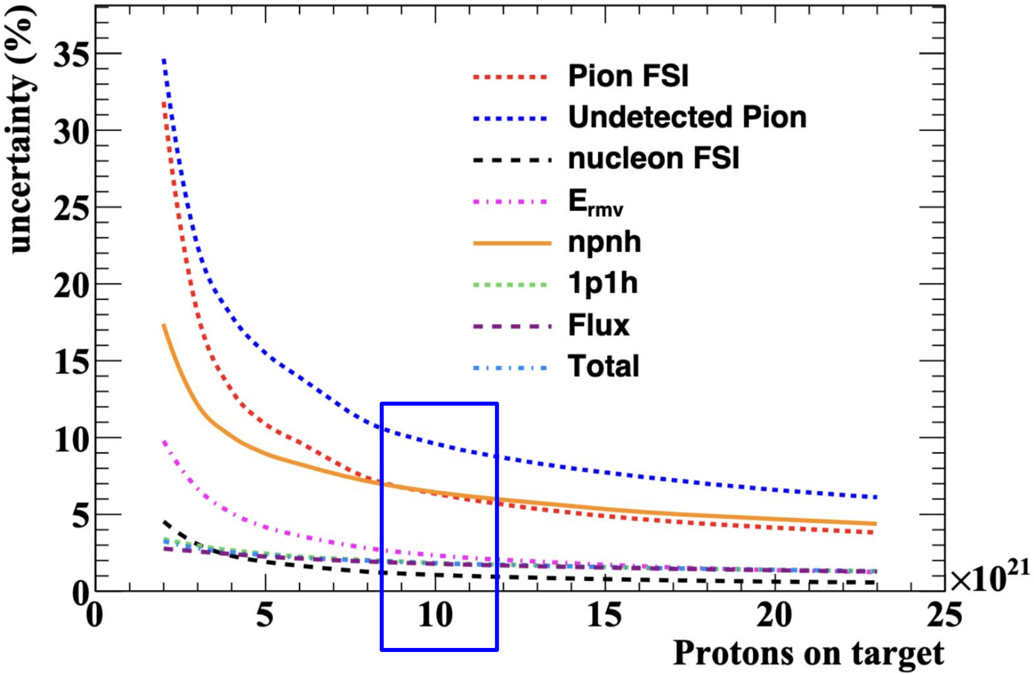
$$N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}$$

Improved prediction, reduced uncertainties

$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e)$$

We determine oscillation parameters from event rates (at our ‘far’ detector, SK)

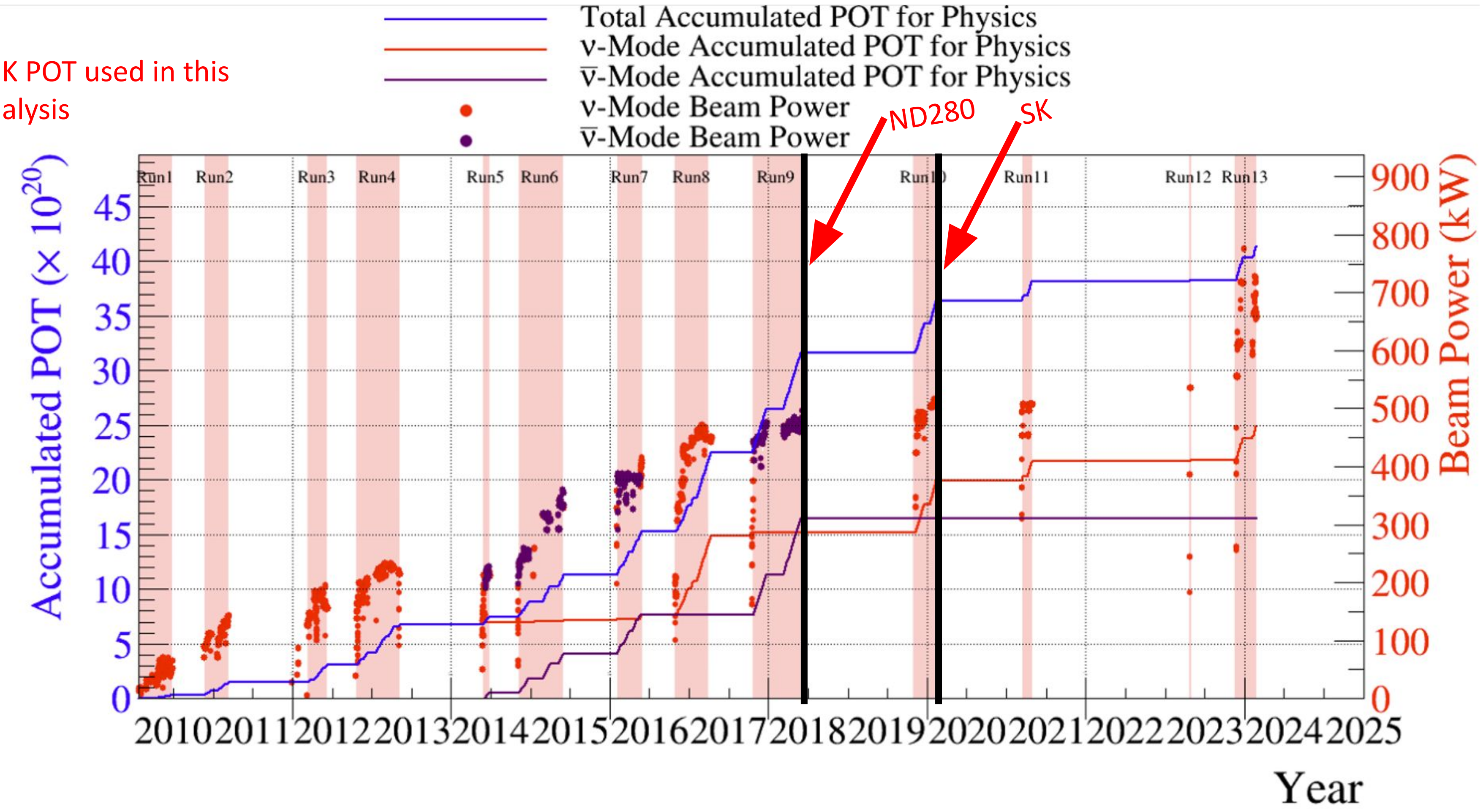
- Uses neutrino source (flux, Φ), cross section (σ), and detector (efficiency) models
- Models built from theory, beam monitors and key external measurements
- Model tested against near detector data



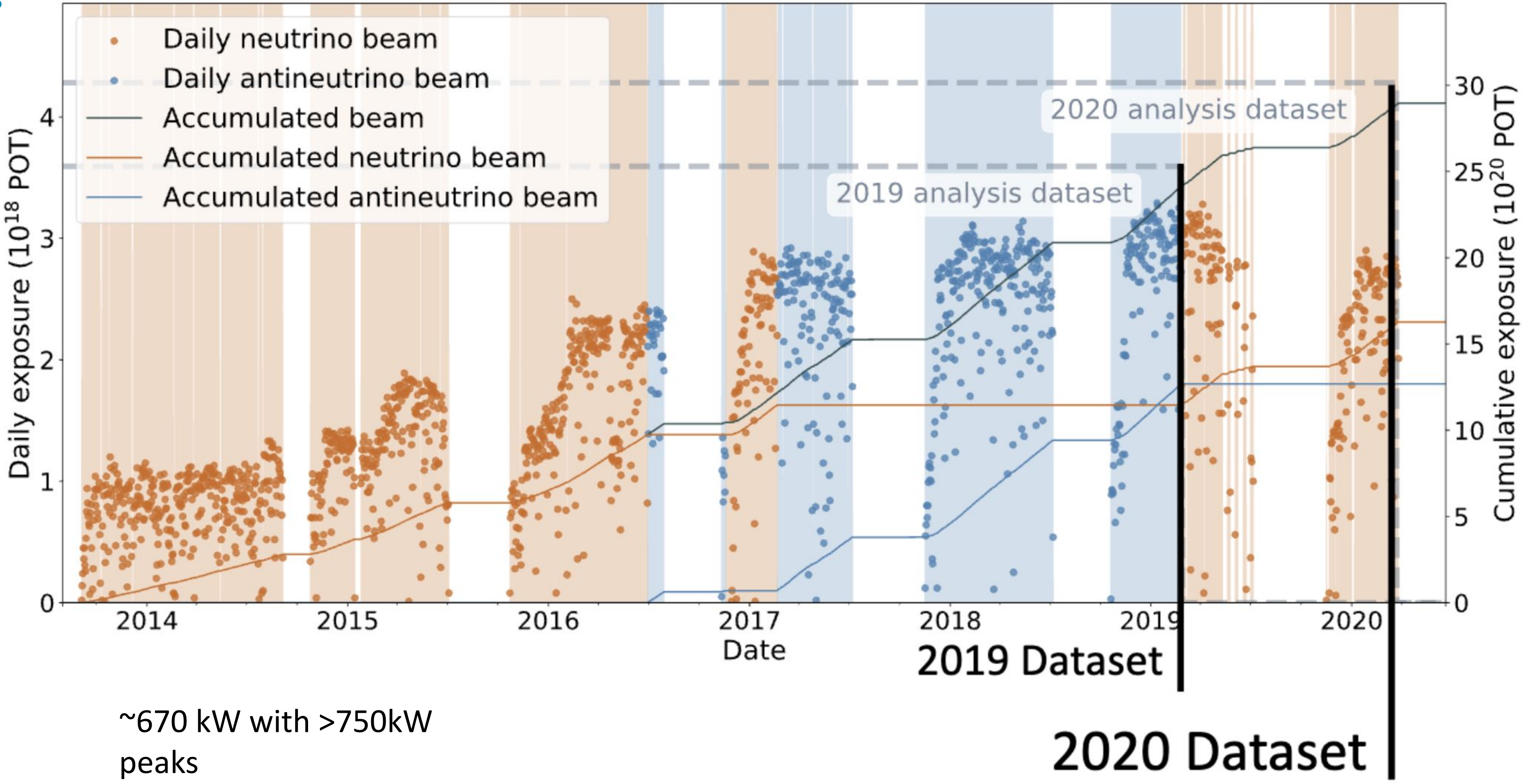
Phys.Rev.D 105 (2022) 3, 032010

2108.11779 [hep-ex]

T2K POT used in this analysis

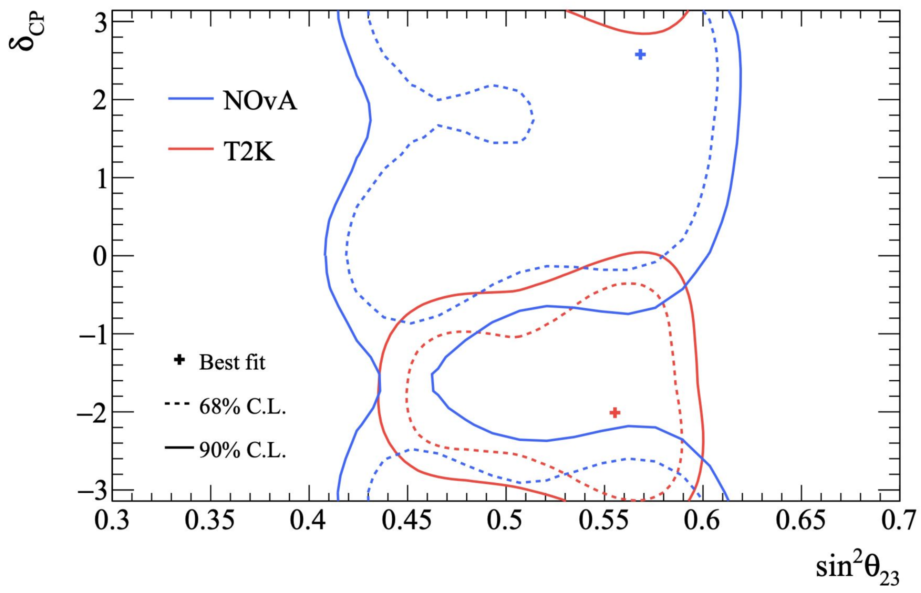


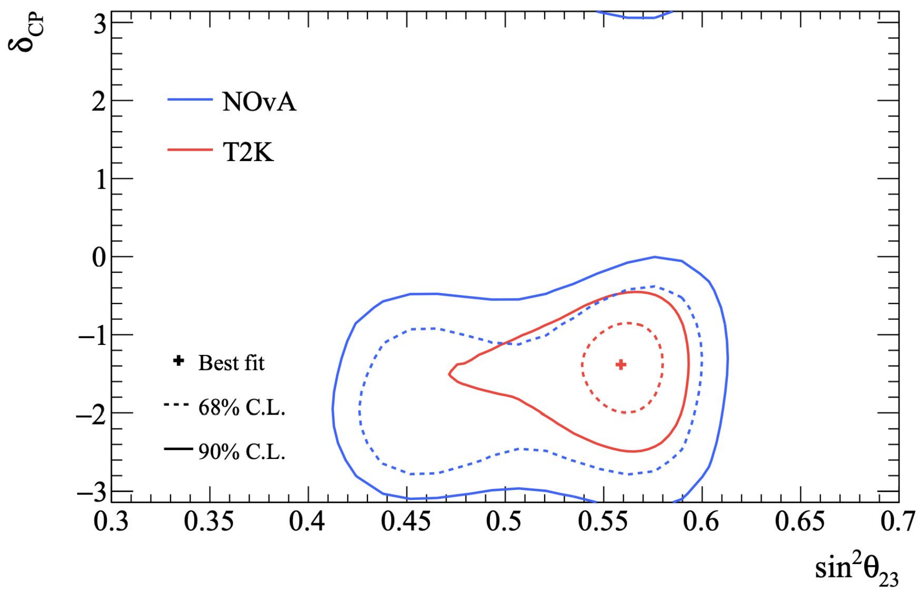
NOvA POT used in this analysis



~670 kW with >750kW peaks

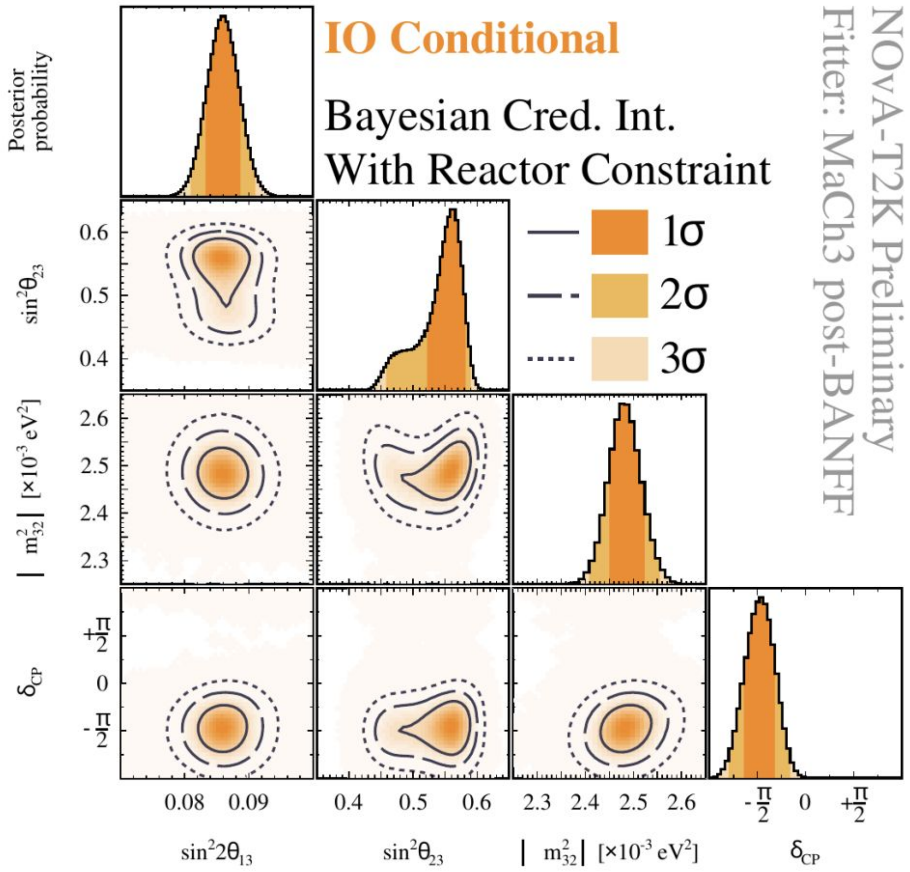
2020 Individual Results



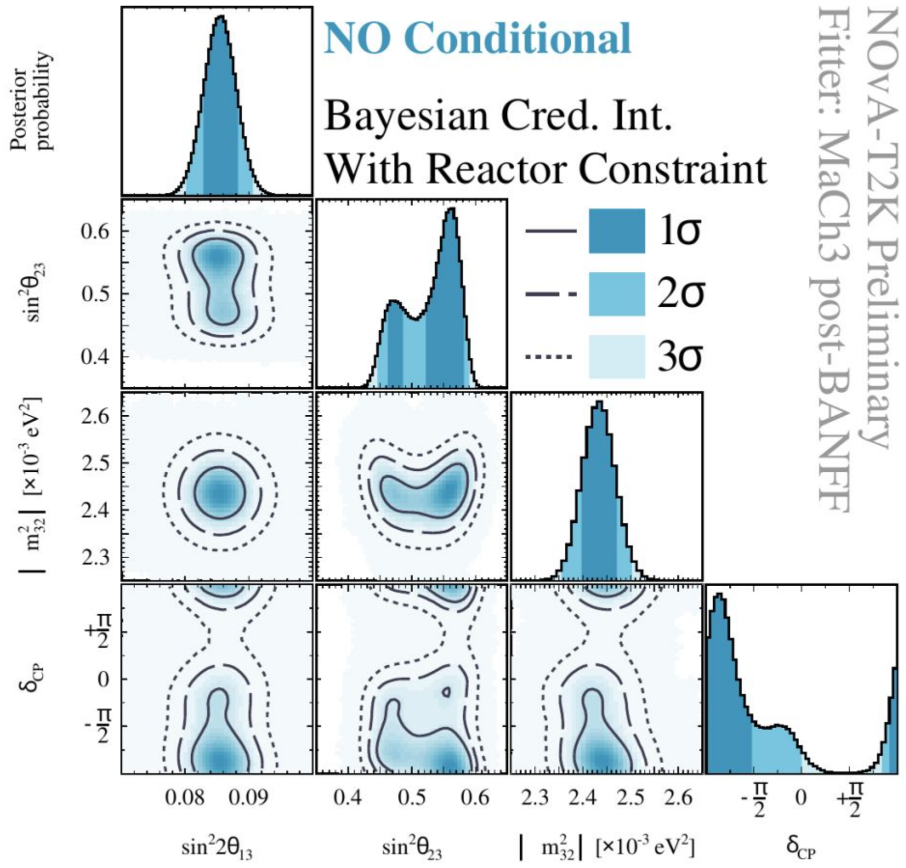


NOvA and T2K similarities and differences

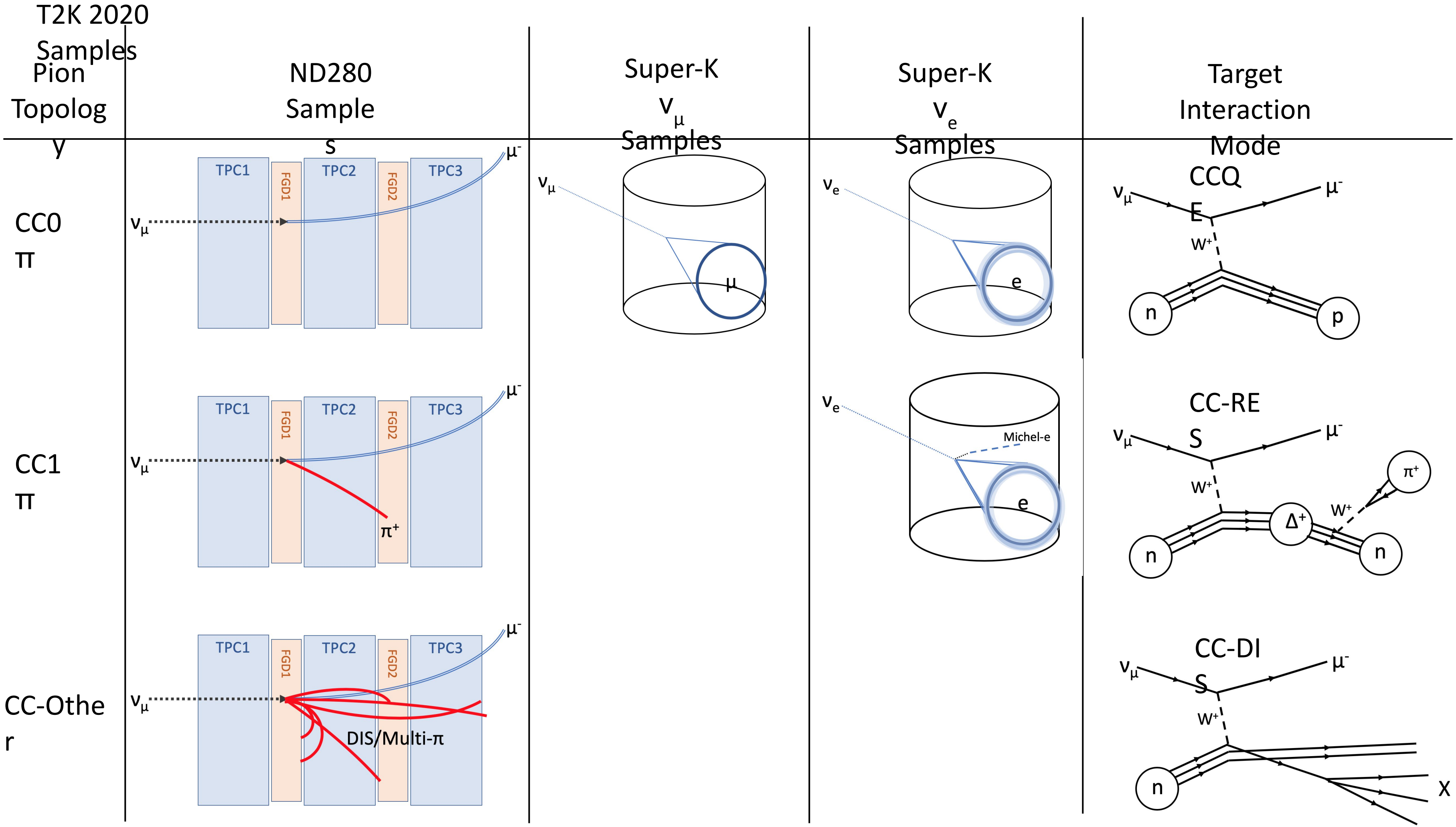
	T2K	NOvA
Baseline	295 km	810 km
Beam spectrum peak	0.6 GeV	2 GeV
Interactions	Mostly QE, 2p2h and RES backgrounds	Mixture of QE, 2p2h, RES, DIS etc
Near Detector target	Plastic scintillator with some water	Organic liquid scintillator
Far Detector Target	Water	Organic liquid scintillator
Near Detector principle	Magnetized Plastic Scintillator and Gaseous Argon TPC tracker	Segmented Liquid Scintillator Tracker
Far Detector principle	Water Cherenkov Under a mountain ~1km rock overburden	Segmented Liquid Scintillator Tracker Sits on surface
Near-to-far extrapolation	Fit model to ND data and propagate best-fit model parameters and uncertainties	Large overlap in systematics allows for direct cancellation and use of ND-tuned model to build FD predictions
Neutrino energy estimator	Lepton Kinematics (Assume elasticity)	Sum of lepton and hadronic energy (Momentum by range and calorimetry)



IO Conditional
Bayesian Cred. Int.
With Reactor Constraint
1σ
2σ
3σ
NOvA-T2K Preliminary
Fitter: MaCh3 post-BANFF
Posterior probability
$\sin^2\theta_{23}$
$|\Delta m^2_{32}|$ [$\times10^{-3}$ eV^2]
δ_{CP}
$\sin^2 2\theta_{13}$



NO Conditional
Bayesian Cred. Int.
With Reactor Constraint
1σ
2σ
3σ
NOvA-T2K Preliminary
Fitter: MaCh3 post-BANFF
Posterior probability
$\sin^2\theta_{23}$
$|\Delta m^2_{32}|$ [$\times10^{-3}$ eV^2]
δ_{CP}
$\sin^2 2\theta_{13}$


T2K 2020 Samples
Pion Topology
ND280 Samples
Super-K νμ Samples
Super-K νe Samples
Target Interaction Mode
CC0π
CC1π
CC-Other
TPC1
FGD1
TPC2
FGD2
TPC3
νμ
μ-
π+
DIS/Multi-π
μ
νe
e
Michel-e
CCQE
CC-RES
CC-DIS
W+
n
p
Δ+
π+
X

T2K 2020
Samples

Topology	Target Mode	ND280 Samples	SK Samples
CC0pi	CCQE (+2p2h)		
CC1pi	CCRes		
CCOther			

SK Cannot distinguish between ν and $\bar{\nu}$ in most cases

ND280
Total of 18 samples

Split by reco pion topology for ν-beam and $\bar{\nu}$-beam
Dedicated samples for ν events in $\bar{\nu}$-beam

Larger ν cross section in matter leads to larger wrong-sign contamination for $\bar{\nu}$-beam

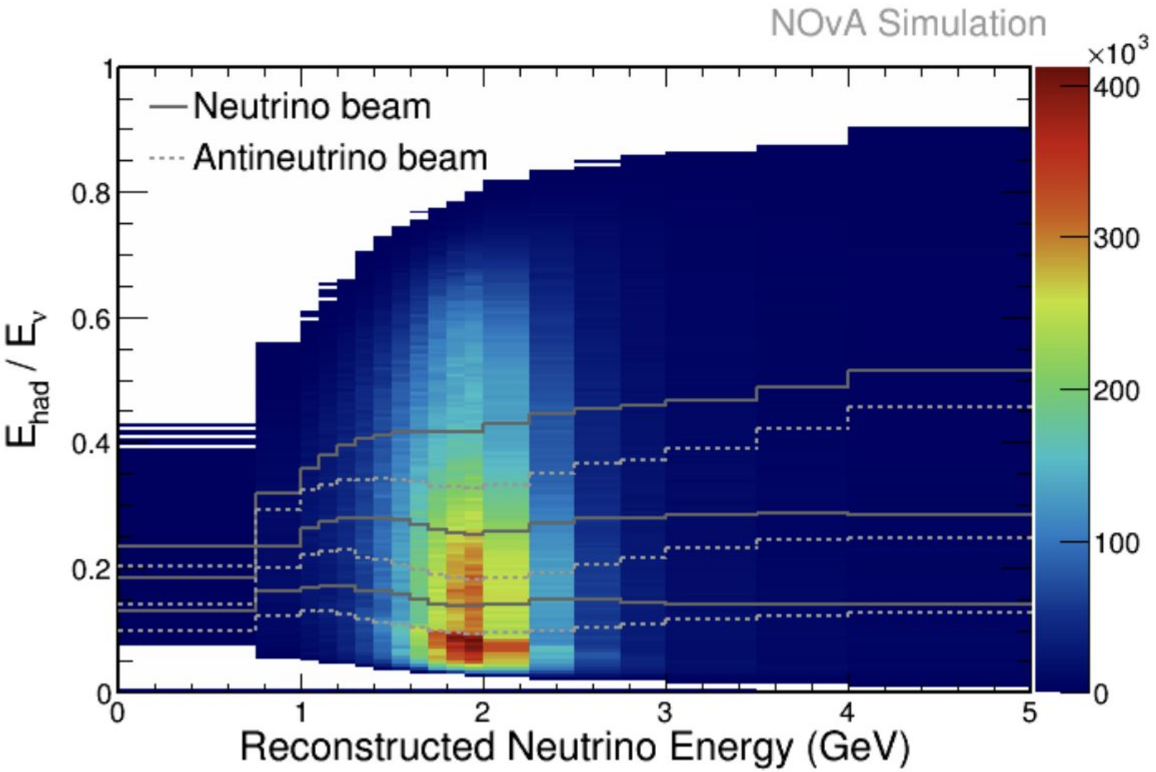
SK
total of 5 samples
4 single rings samples for each mixing channel
Dedicated sample to tag low-p_{π} CC1π events from decay to Michel Electron

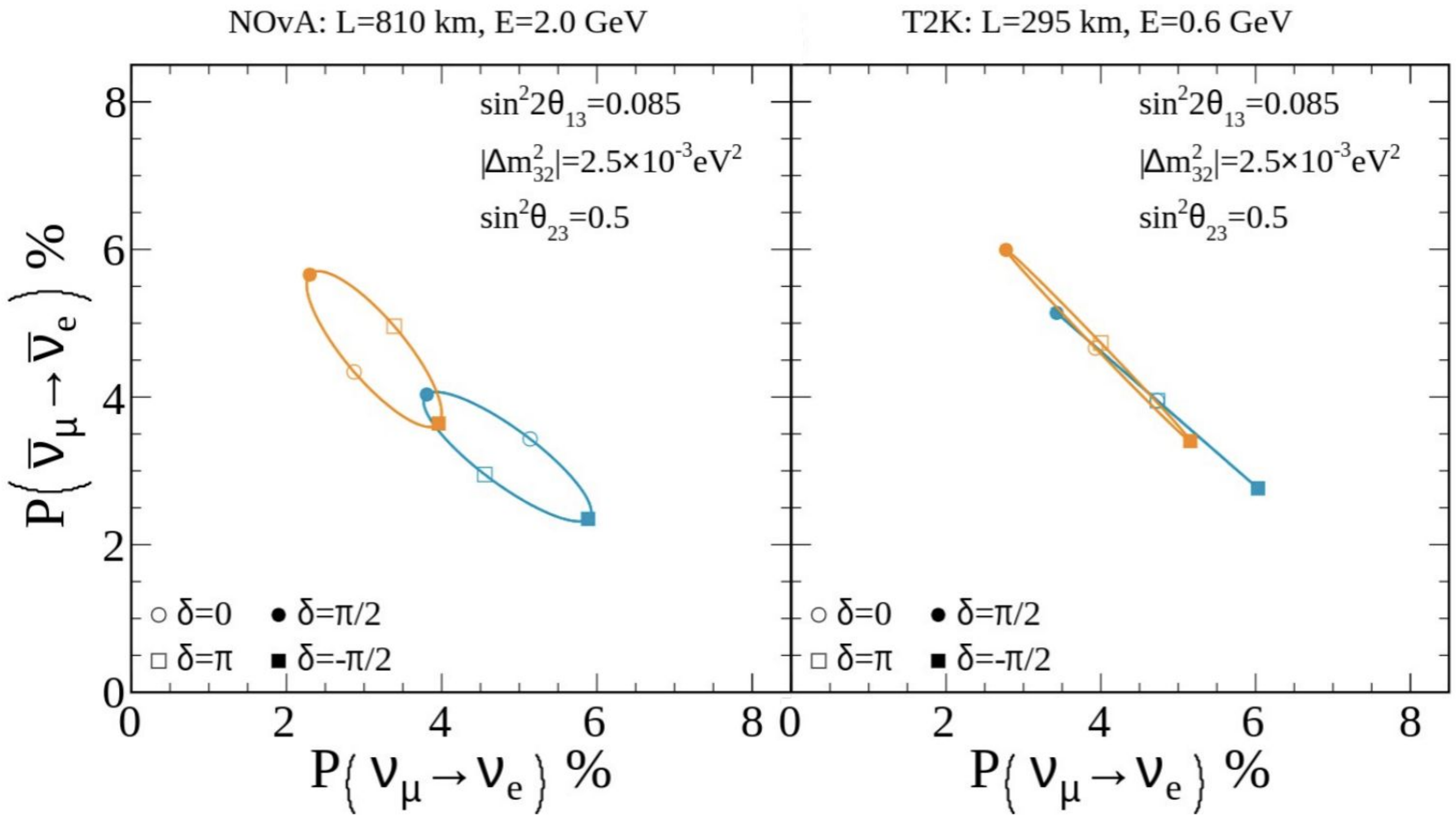
T2K 2022 split ν-beam CC0pi events at ND280 by presence of reconstructed ejected proton as well as a dedicated CC-photon sample to constrain potential ν_e backgrounds, and an additional multi-ring ν_{μ} sample at SK targeting CC1pi events

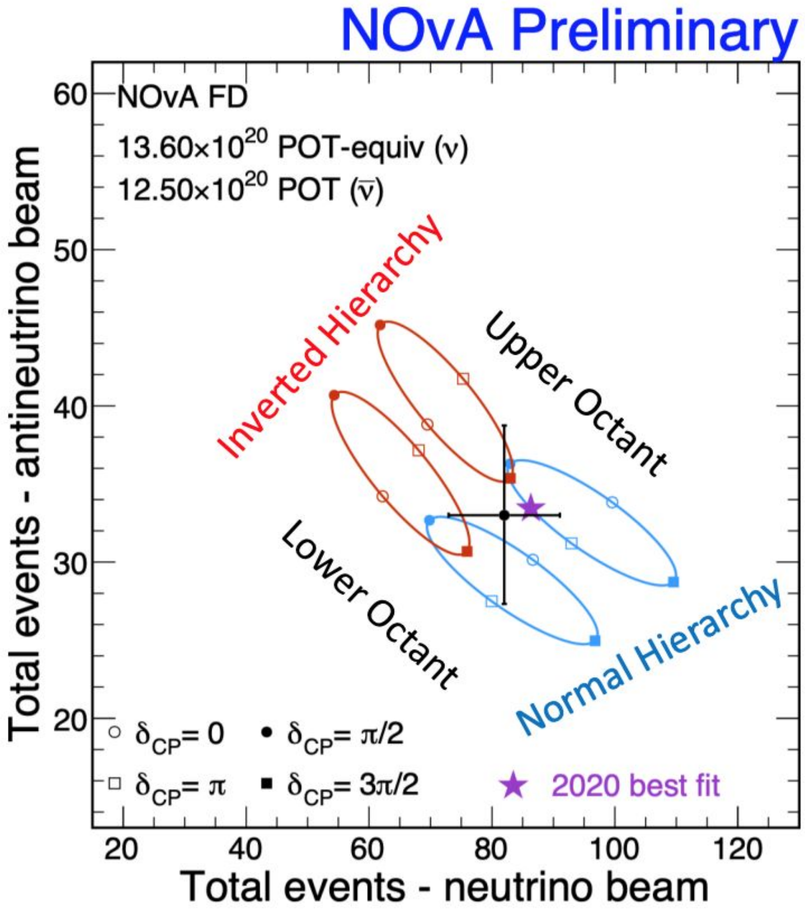
NOvA Hadronic Energy Quartiles

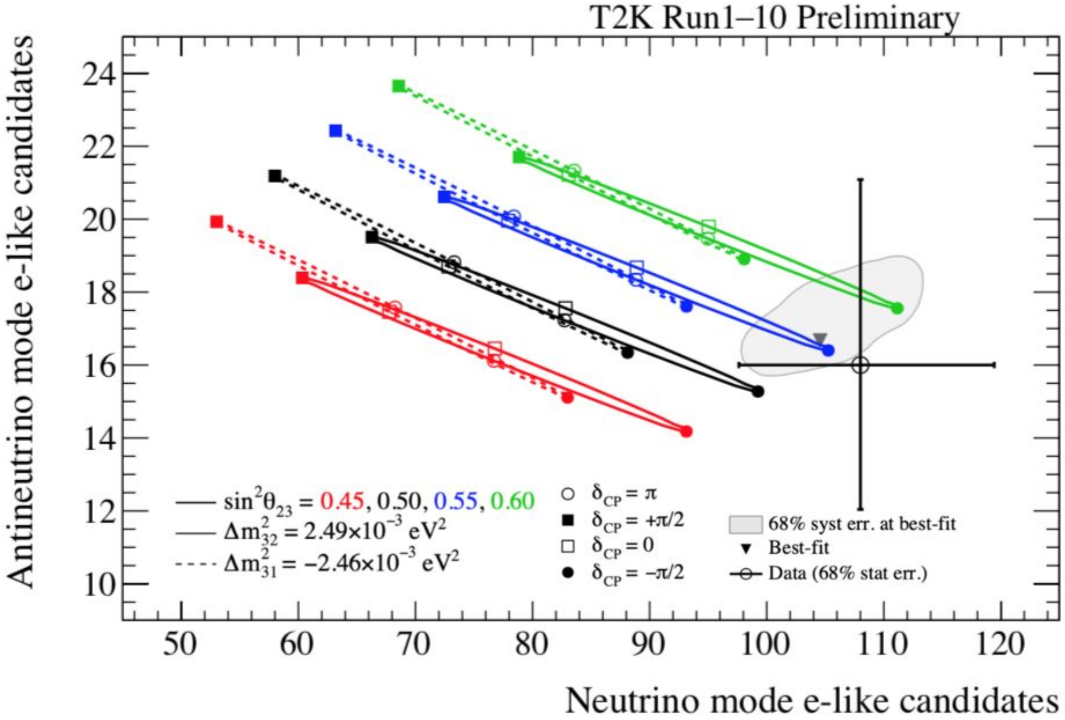
NOvA data split by relative fraction of hadronic energy in total neutrino energy estimator

Done separately for nu/nubar




NOvA: L=810 km, E=2.0 GeV
T2K: L=295 km, E=0.6 GeV
sin²2θ13=0.085
|Δm²32|=2.5×10⁻³eV²
sin²θ23=0.5
sin²2θ13=0.085
|Δm²32|=2.5×10⁻³eV²
sin²θ23=0.5
P(ν̄μ → ν̄e) %
P(νμ → νe) %
P(νμ → νe) %
δ=0
δ=π/2
δ=π
δ=-π/2
δ=0
δ=π/2
δ=π
δ=-π/2
0
2
4
6
8
0
2
4
6
8
0
2
4
6
8


NOvA Preliminary
NOvA FD
13.60×10^20 POT-equiv (ν)
12.50×10^20 POT (ν̄)
Inverted Hierarchy
Upper Octant
Lower Octant
Normal Hierarchy
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
2020 best fit
Total events - antineutrino beam
Total events - neutrino beam
20
30
40
50
60
80
100
120


T2K Run1–10 Preliminary
Antineutrino mode e-like candidates
Neutrino mode e-like candidates
sin²θ23 = 0.45, 0.50, 0.55, 0.60
Δm²32 = 2.49×10⁻³ eV²
Δm²31 = −2.46×10⁻³ eV²
δCP = π
δCP = +π/2
δCP = 0
δCP = −π/2
68% syst err. at best-fit
Best-fit
Data (68% stat err.)
10
12
14
16
18
20
22
24
50
60
70
80
90
100
110
120

The Jarlskog prior dependence

With reactor constraint