# NOvA-T2K Joint Analysis Results

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Leona Woods Seminar, BNL

May 09, 2024

# Neutrino Oscillation

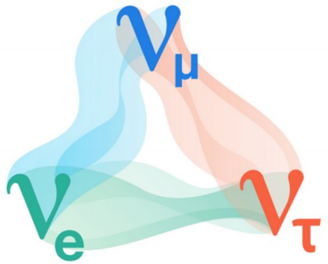
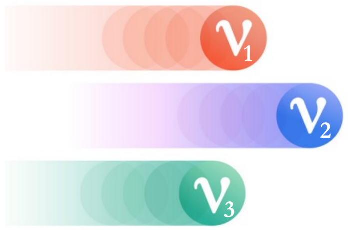


Image by Symmetry Magazine

Flavor Eigenstates

Mass Eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underset{\text{Mixing Matrix}}{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Quantum superposition of neutrino mass eigenstates leads to neutrino oscillation.

# Neutrino Oscillation

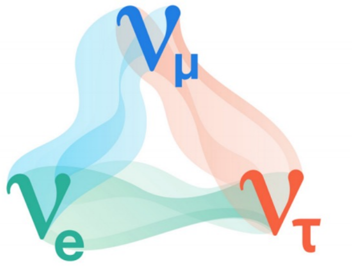


*Image by Symmetry Magazine*

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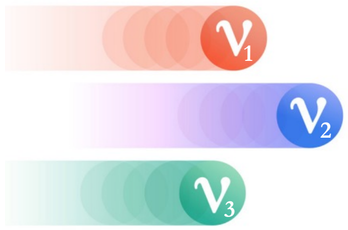
Mixing Matrix



Quantum superposition of neutrino mass eigenstates leads to neutrino oscillation.

Oscillation probability (2-flavor approx.)

$$P(\nu_\alpha \to \nu_\beta) \sim \underbrace{\boxed{\sin^2(2\theta)}}_{\text{Amplitude}} \sin^2\left(\underbrace{\frac{\boxed{\Delta m^2_{ij}} L}{4E}}_{\text{Frequency}}\right)$$

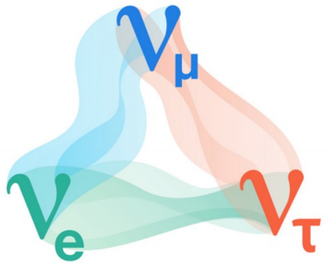
where $\Delta m^2_{ij} = m_i^2 - m_j^2$

**Experiment design:**
**L (baseline), E (Energy)**
**L/E optimized for maximum oscillation**

# Neutrino Oscillation

Flavor Eigenstates

Mass Eigenstates



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Mixing Matrix

$$\boxed{U_{\text{PMNS}}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

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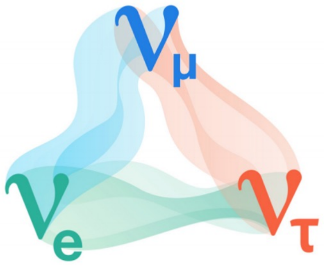
- Mass splitting ($\Delta m^2_{21}$, $\Delta m^2_{32}$) governs the frequency of the oscillation.
- Mixing angles ($\theta_{12}$ ,$\theta_{13}$ ,$\theta_{23}$) determine the magnitude of oscillation.
- $\delta_{CP}$ phase provides a measure of CP violation in neutrinos.

# Neutrino Oscillation



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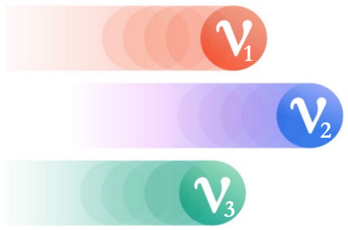

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Measured primarily from the following neutrino sources

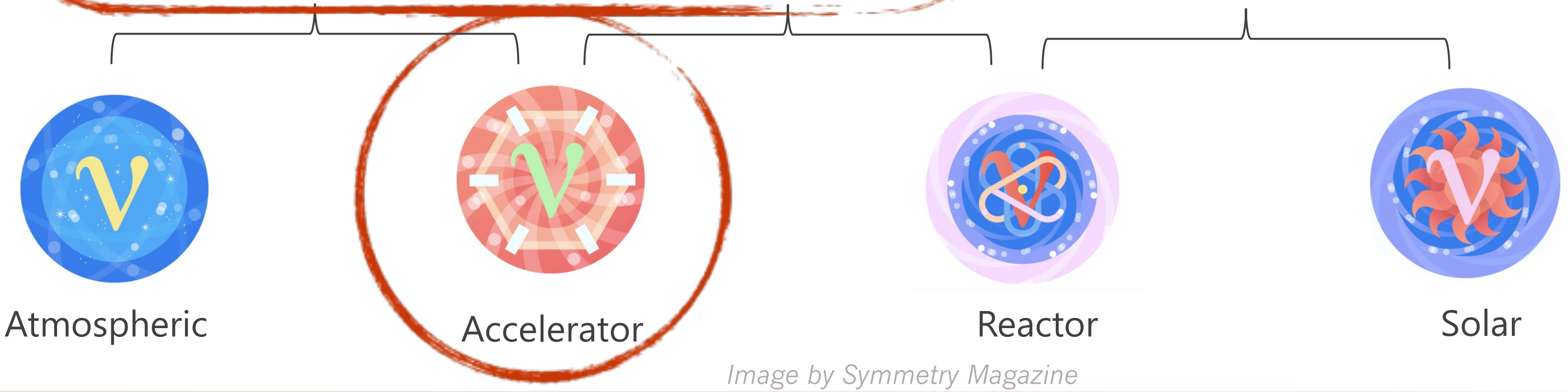


*Image by Symmetry Magazine*

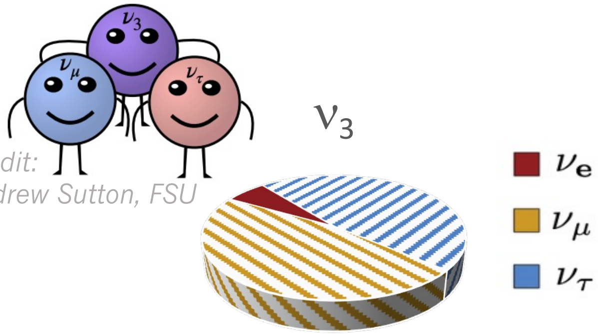
# Open Questions

- Long-baseline oscillation experiments offer a significant opportunity to address these fundamental physics questions

## 1. Is the $\theta_{23}$ mixing maximal?

Current Measured Value : $\theta_{23} \sim 45°$

Precision : $\sin^2\theta_{23} \sim 5\%$



*Credit: Andrew Sutton, FSU*

**If $\theta_{23}$ = 45° → $|U_{\mu3}| = |U_{\tau3}|$**

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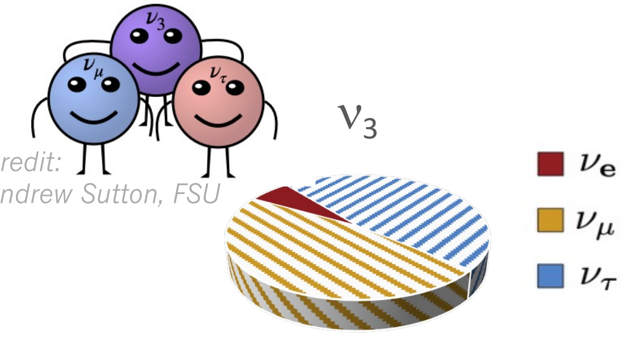
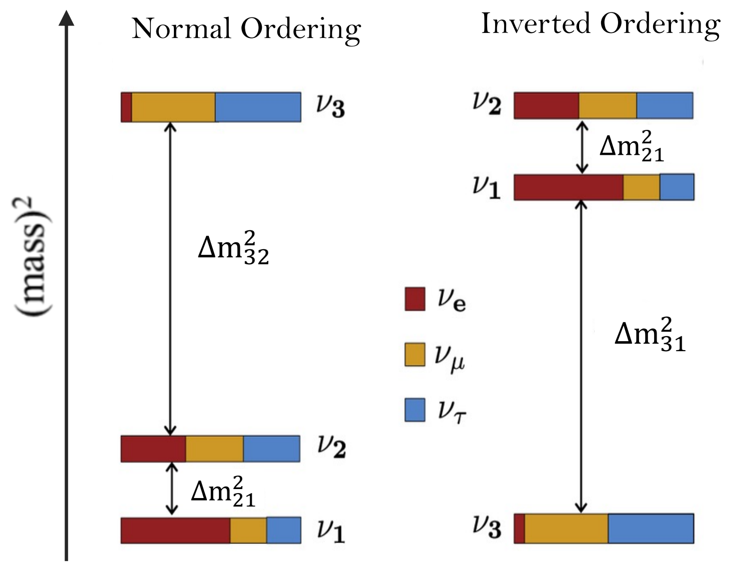


Credit:
Andrew Sutton, FSU

**If $\theta_{23} = 45°$ → $|U_{\mu 3}| = |U_{\tau 3}|$**

## 2. Which neutrino is the lightest?



**ν Mass Ordering (MO):**
**Normal or Inverted?**

Implications for 0νββ, cosmology

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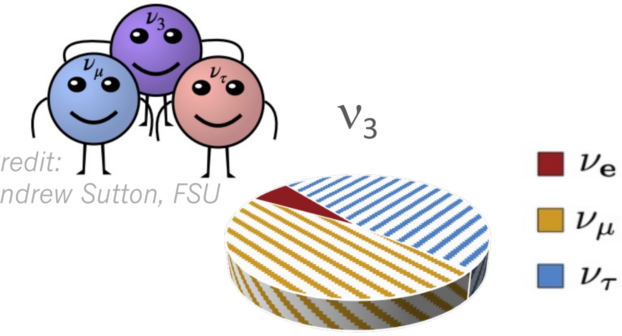

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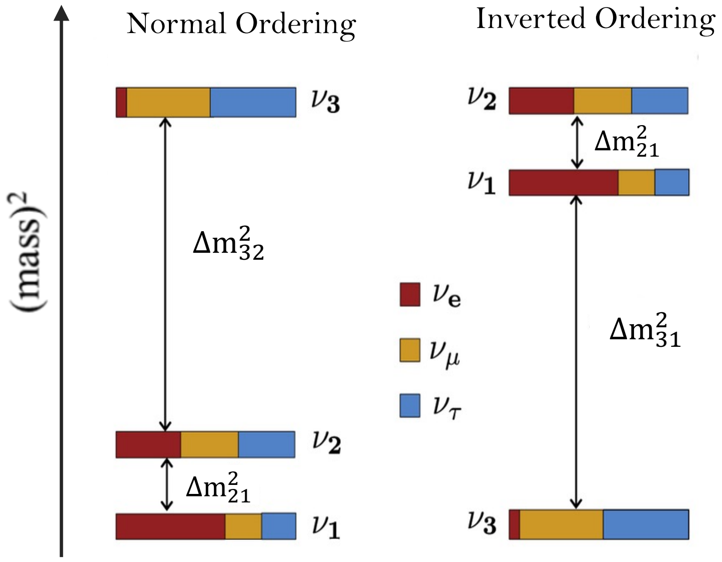
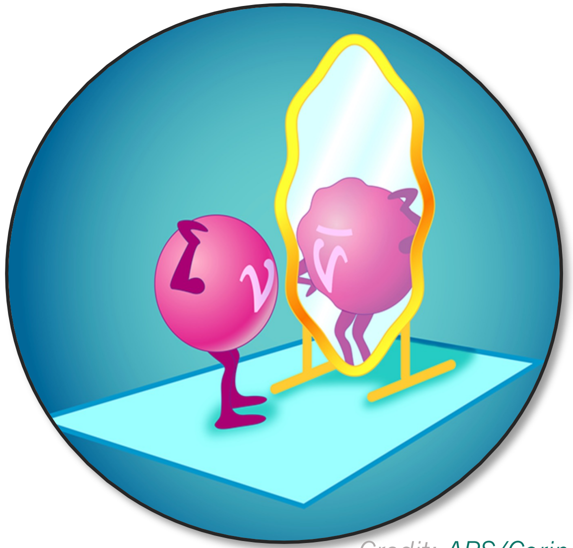


**ν Mass Ordering (MO): Normal or Inverted?**

Implications for 0νββ, cosmology

## 3. Is CP violated in leptons?

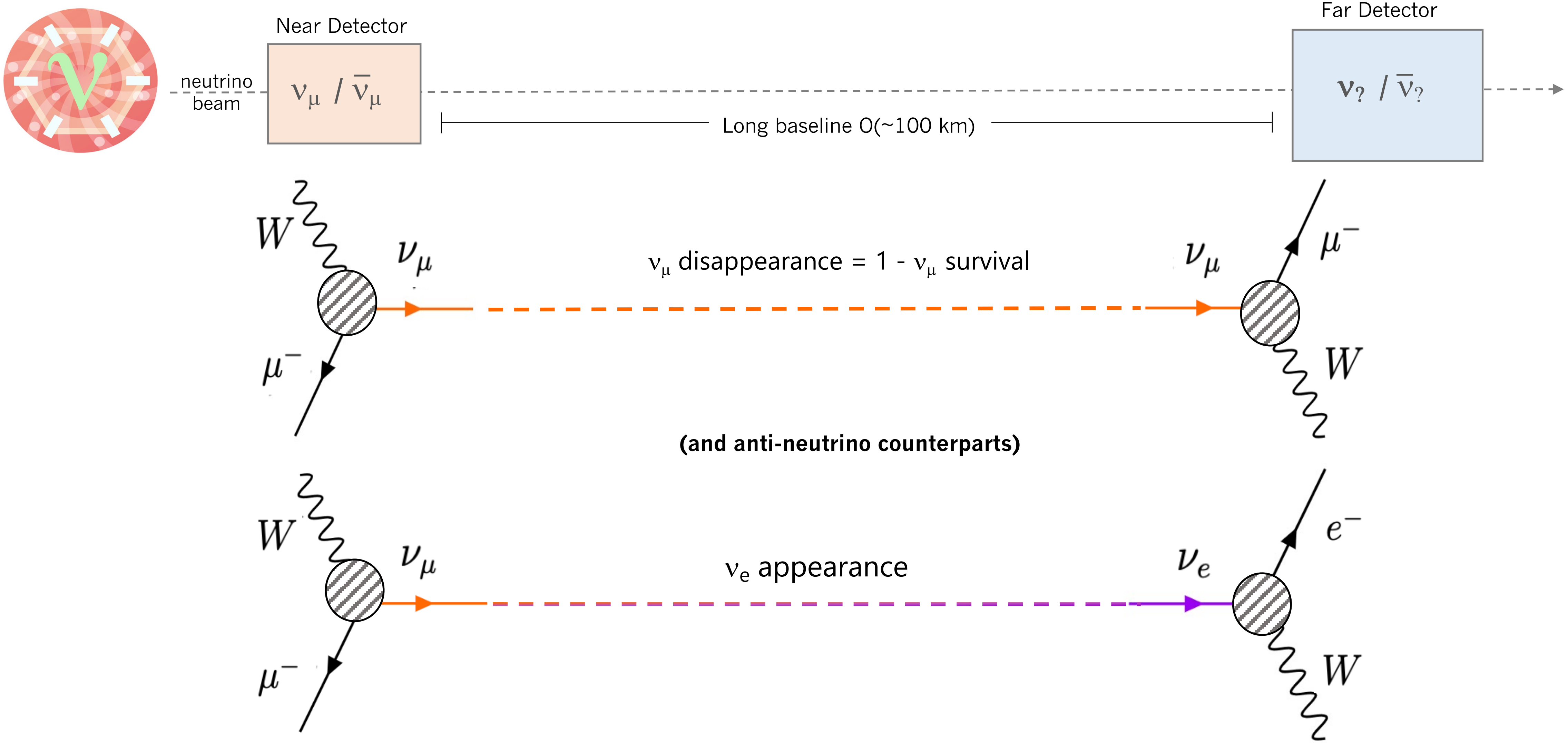


Credit: APS/Carin Cain

Do neutrinos and anti-neutrinos oscillate differently violating the CP symmetry?
**Is $\sin\delta_{CP} = 0$?**

**Both T2K and NOvA have extensive physics programs extending beyond 3-flavor neutrino oscillation. However, for the purposes of this joint-fit (and today's discussion), we will limit our scope to this.*

# Long-baseline Measurements



neutrino beam

Near Detector

$\nu_\mu$ / $\bar{\nu}_\mu$

Far Detector

$\nu_?$ / $\bar{\nu}_?$

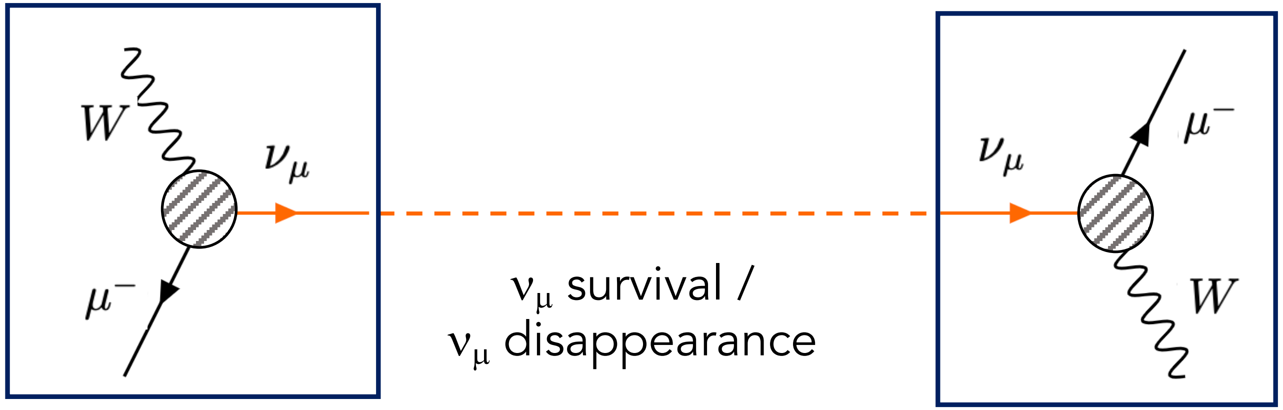
Long baseline O(~100 km)

$\nu_\mu$ disappearance = 1 - $\nu_\mu$ survival

**(and anti-neutrino counterparts)**

$\nu_e$ appearance

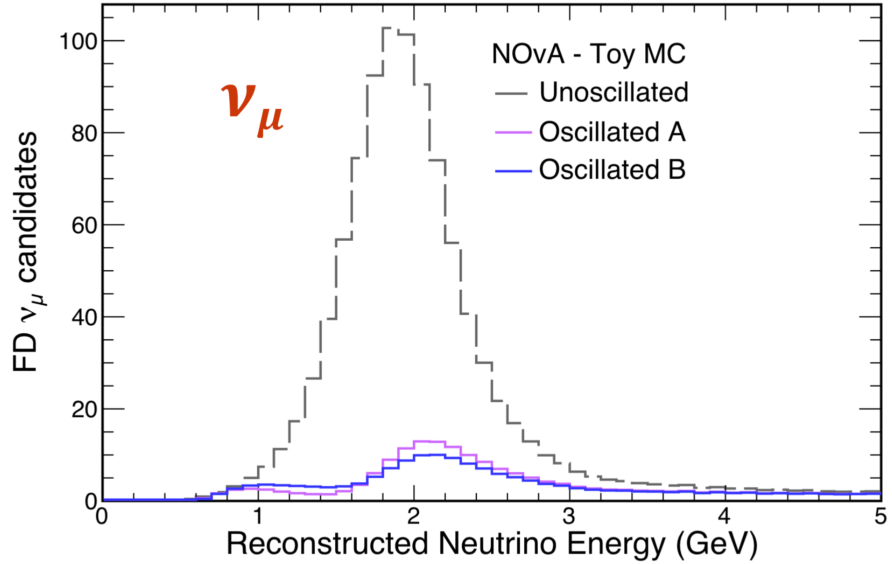
# $\nu_\mu$ disappearance channel

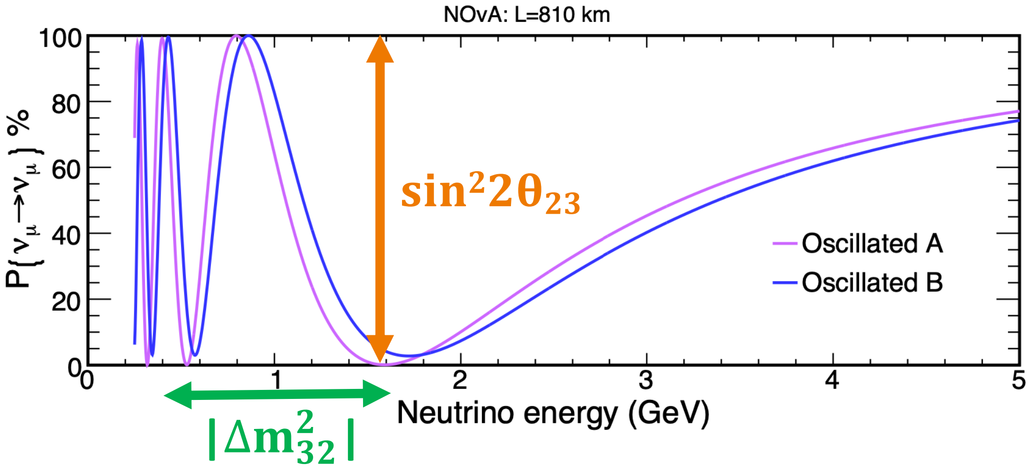


$\nu_\mu$ survival /
$\nu_\mu$ disappearance

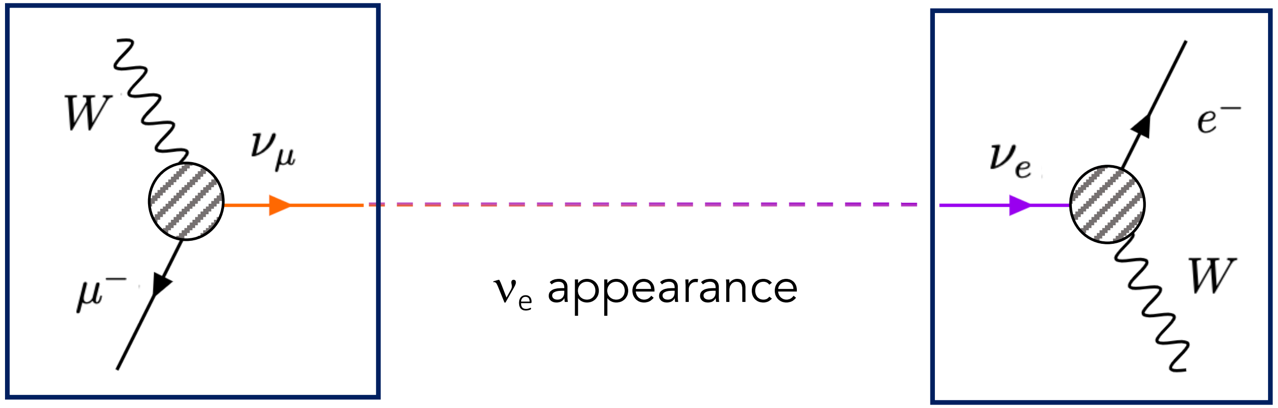
$$P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu\right) \approx 1 - \boxed{\sin^2 2\theta_{23}}\, \sin^2\left(\boxed{\Delta m^2_{32}}\frac{L}{4E}\right)$$

- Leading order dependence on $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$
- If $\sin^2 2\theta_{23} = 1$, then maximal $\nu_\mu$ disappearance.



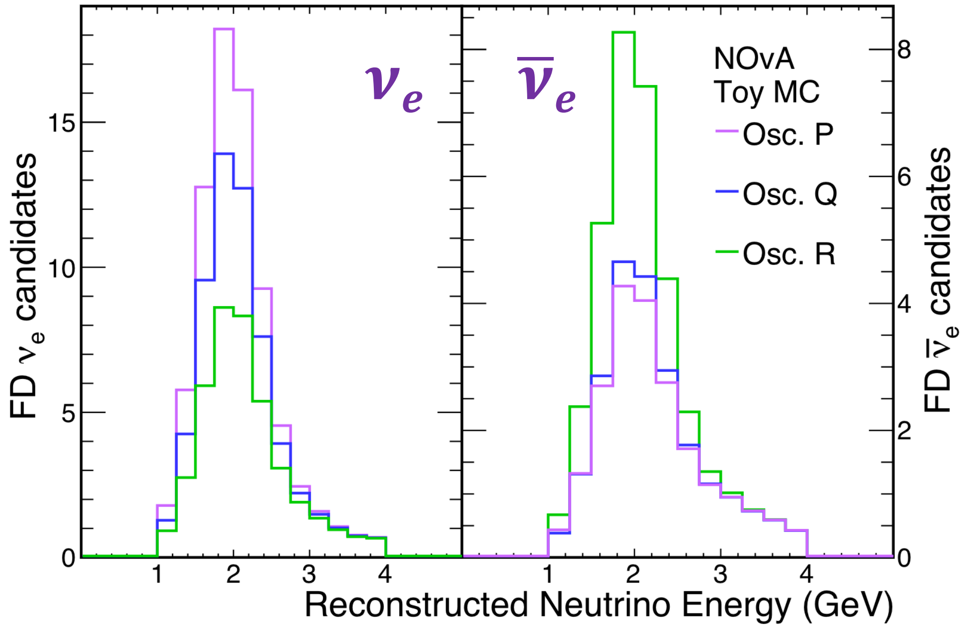


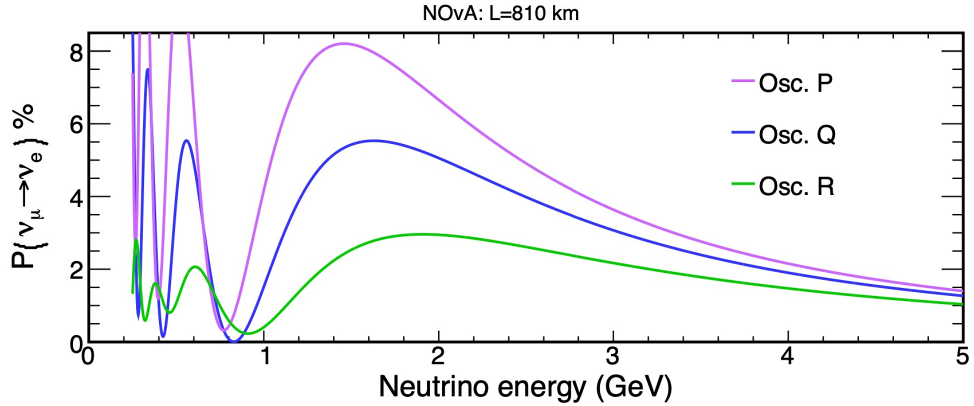
# $\nu_e$ appearance channel



$\nu_e$ appearance

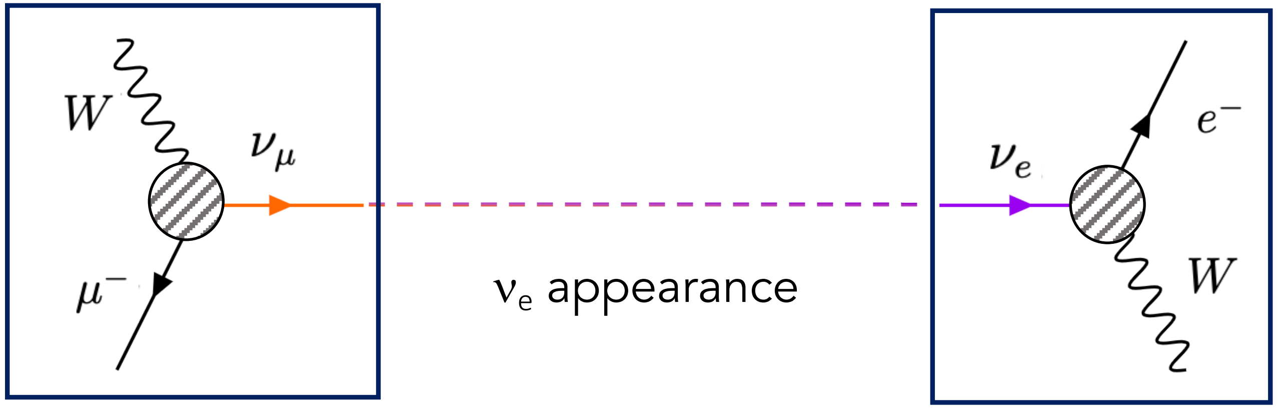
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31} \times \frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

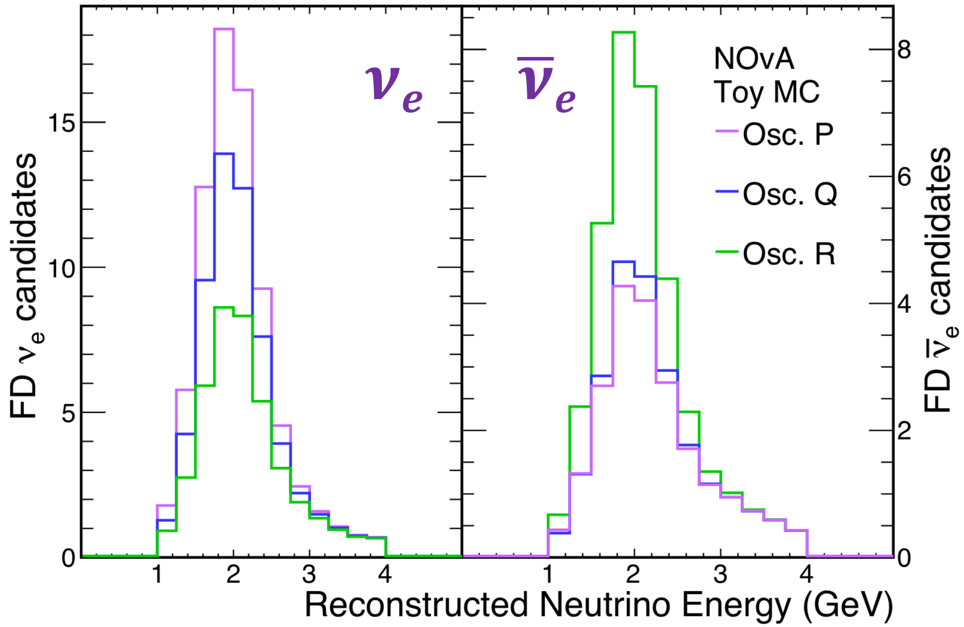




- Complicated dependence on multiple parameters of interest.

# $\nu_e$ appearance channel



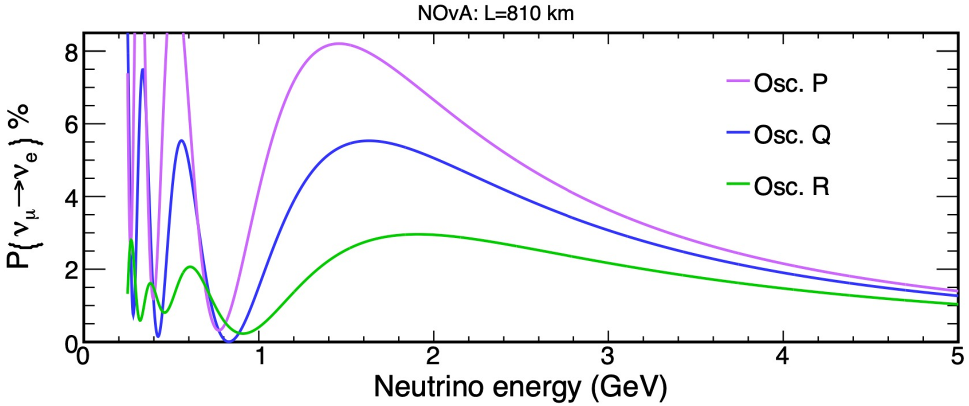


$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq$

Mixing angles — Maximal Mixing (octant of $\theta_{23}$ )

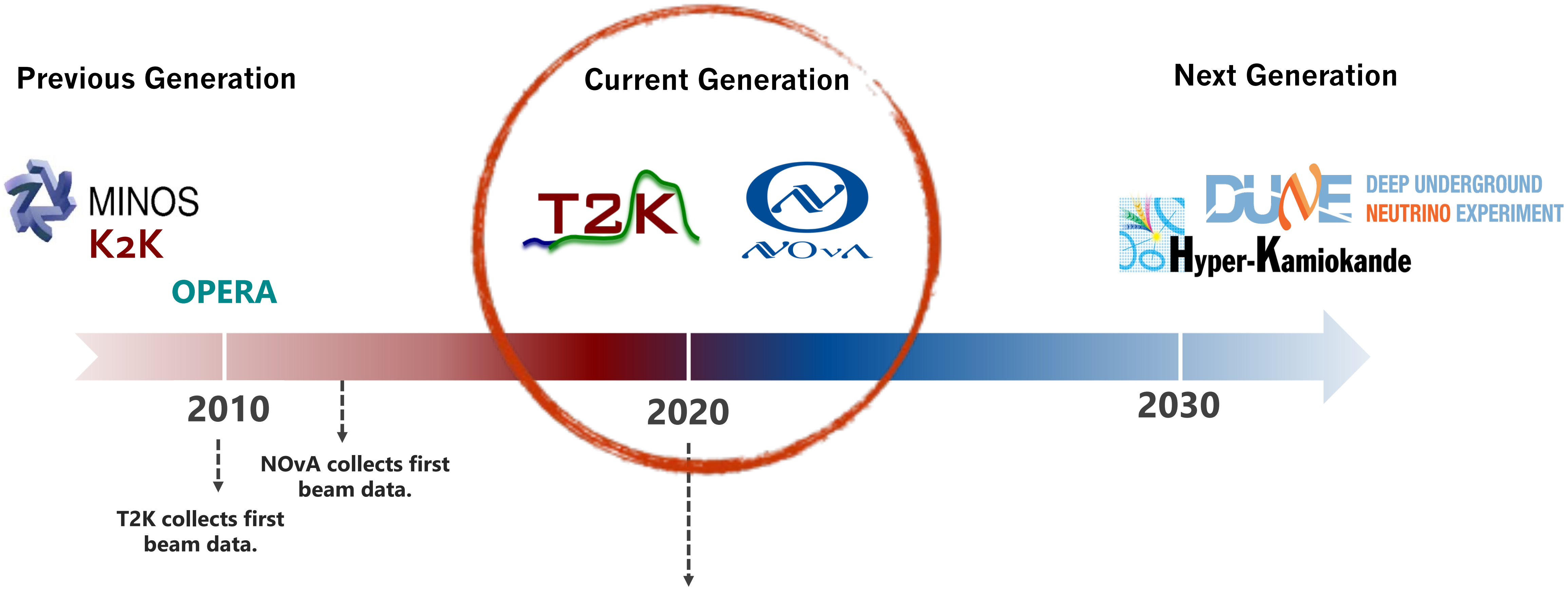
Matter effect* — Mass Ordering (sign of $\Delta m^2_{32}$ )

CP Phase $\delta_{CP}$ — CP violation



- Opposite impact of matter effect and $\delta_{CP}$ for $\nu_e$ vs $\bar{\nu}_e$ appearance probability.
- *Matter effect: $\nu_e$'s interact with the electrons in the Earth modifying oscillation probability.

# Long-baseline oscillation experiments



**Previous Generation**

MINOS
K2K
OPERA

**Current Generation**

T2K
NOvA

**Next Generation**

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT
Hyper-Kamiokande

2010

2020

2030

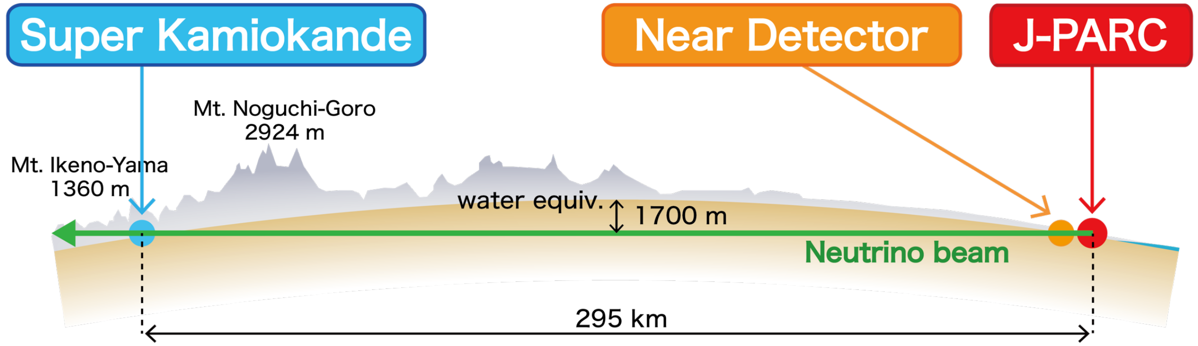
**T2K collects first beam data.**

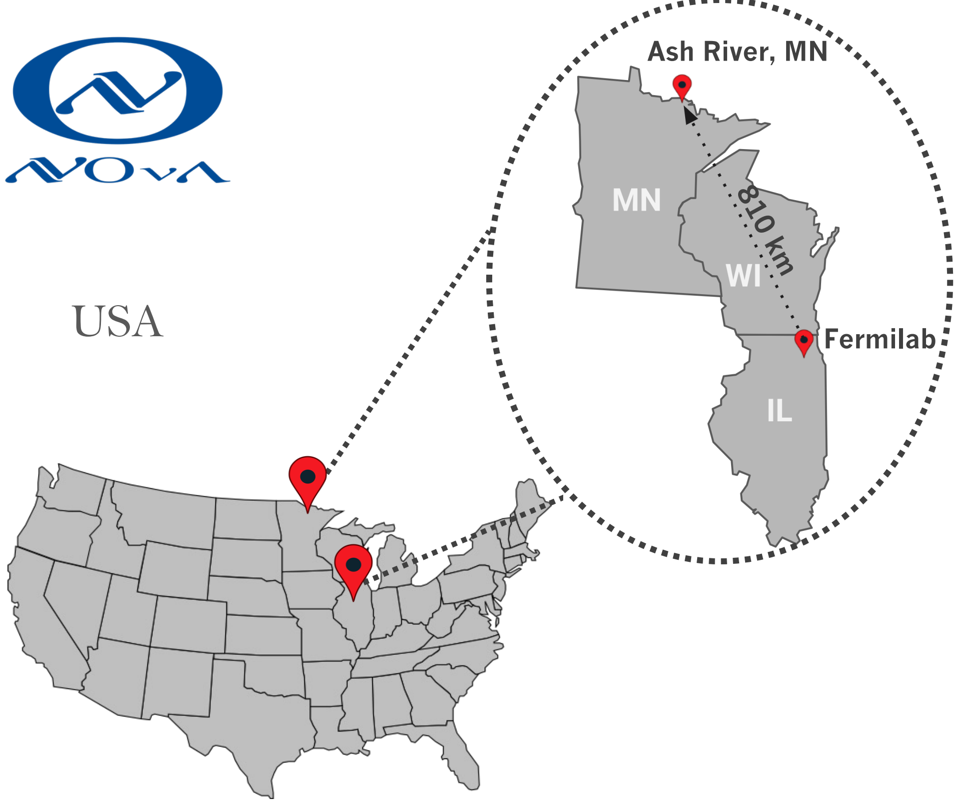
**NOvA collects first beam data.**

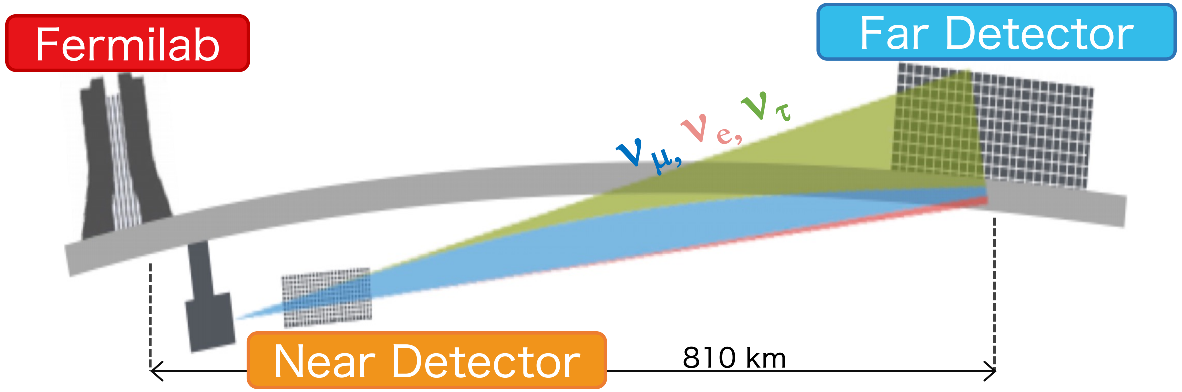
**Published dataset[1,2] until 2020 by both experiments. Today's results uses this dataset!**

[1] T2K: Eur. Phys. J. C (2023) 83:782 (2023)
[2] NOvA: Phys. Rev D 106, 032004 (2022) (Frequentist) and arXiv:2311.07835 (Bayesian)


Japan
Kamioka
Tokai
295 km


Super Kamiokande
Near Detector
J-PARC
Mt. Noguchi-Goro
2924 m
Mt. Ikeno-Yama
1360 m
water equiv.
1700 m
Neutrino beam
295 km

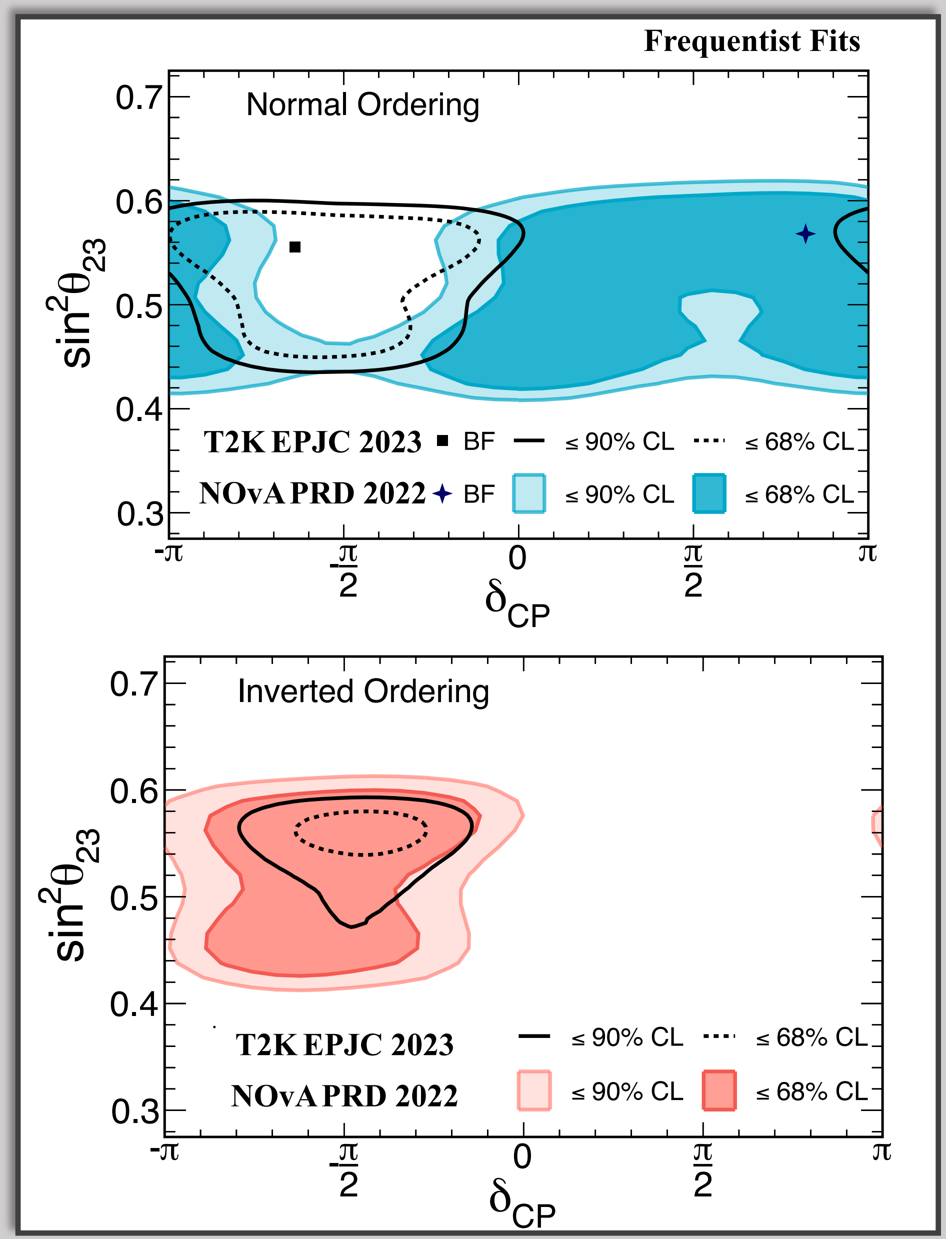

USA
Ash River, MN
MN
WI
810 km
Fermilab
IL


Fermilab
Far Detector
$\nu_\mu, \nu_e, \nu_\tau$
Near Detector
810 km

# Why NOvA-T2K joint analysis?

# Why NOvA-T2K joint fit?

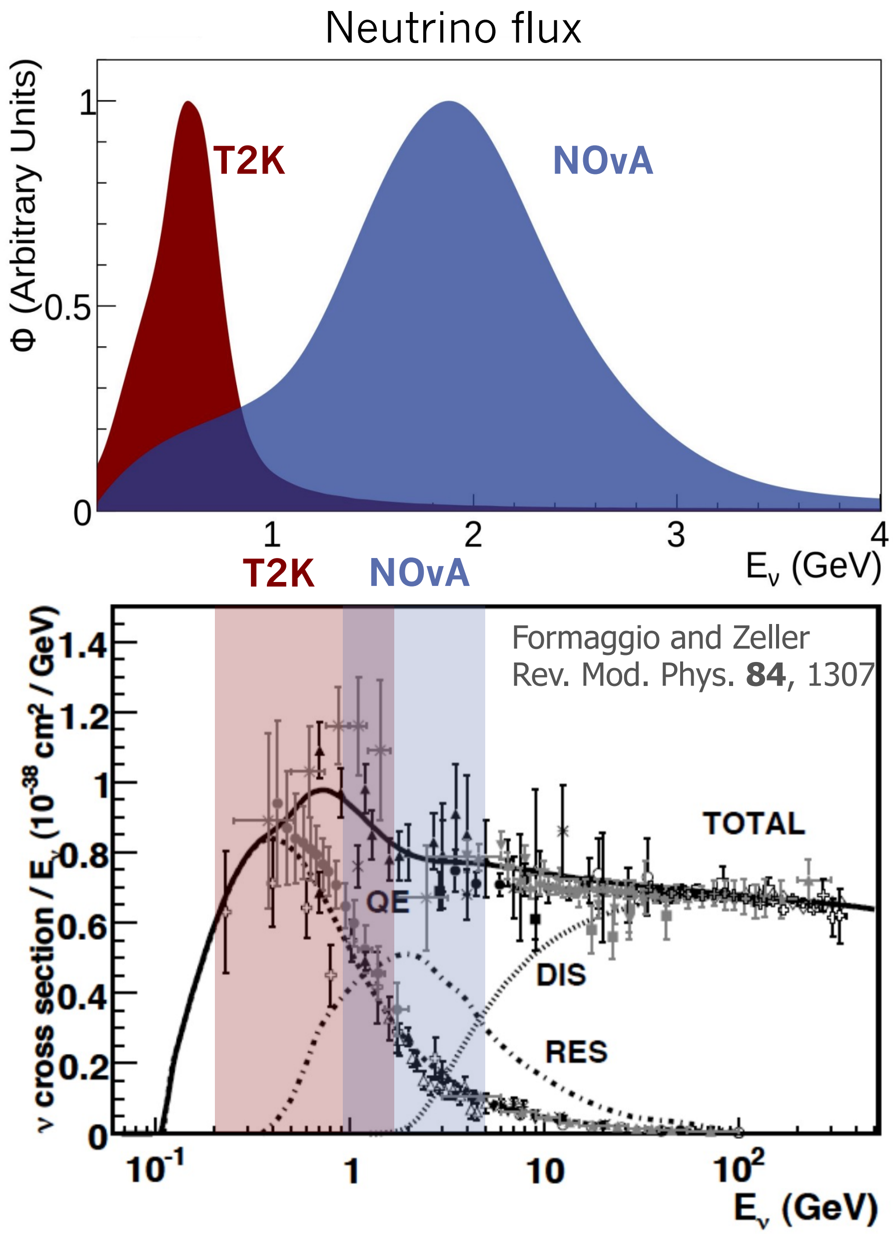
- The complementarity between the experiments provides the power to **break degeneracies.**
- Full implementation of:
  - ❑ **Energy reconstruction and detector response**
  - ❑ **Detailed likelihood** from each experiment
  - ❑ Consistent **statistical inference across the full dimensionality**
- In-depth review of:
  - ❑ **Models, systematic uncertainties and possible correlations**
  - ❑ **Different analysis approaches** driven by contrasting detector designs



**Results from NOvA and T2K from 2020 datasets**

# Beamlines

- Both experiments are located off-axis to receive a narrow-band, highly pure muon (anti-)neutrino beam.
  - **T2K:** beam from J-PARC, peaks at **0.6 GeV** neutrino energy.
  - **NOvA:** beam peaks at **2 GeV** and is delivered from **Fermilab's NuMI**.
- The **difference in neutrino beam energy** leads to qualitatively **different neutrino interactions**
  - **T2K**: primarily Quasi-Elastic and 2p2h interactions
  - **NOvA**: mix of Quasi-Elastic, 2p2h, Resonant and DIS interactions

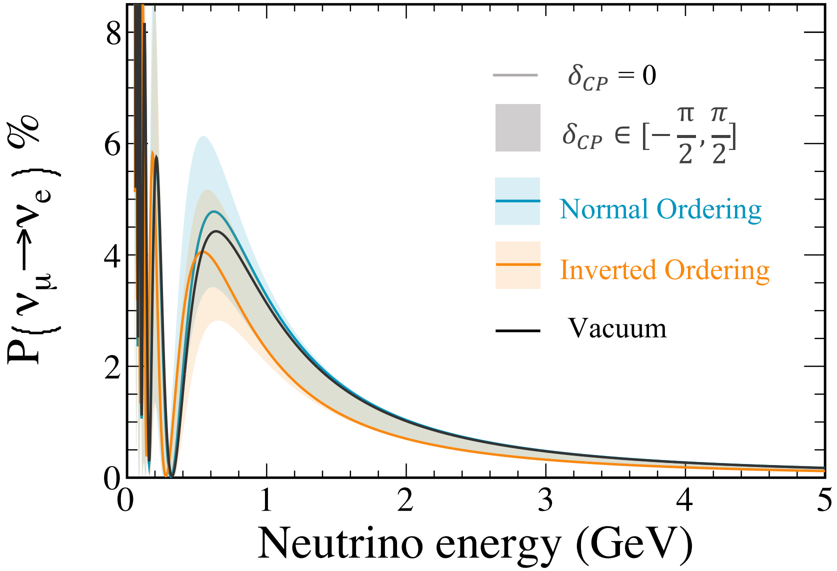


Formaggio and Zeller
Rev. Mod. Phys. **84**, 1307

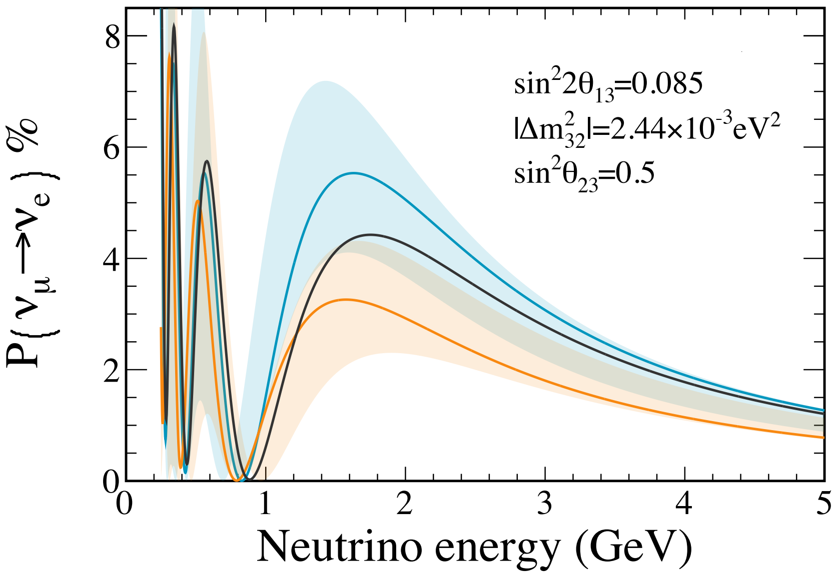
# Baselines

- Larger matter effect for higher neutrino energy → higher sensitivity to mass ordering.
  - Therefore, associated asymmetry is higher for the longer baseline.

**T2K: L = 295km**



**NOvA: L= 810 km**



| | T2K | NOvA |
|---|---|---|
| L (baseline) | 295 km | 810 km |
| Energy (beam peak) | 0.6 GeV | 2 GeV |
| Matter effect* | ~ ±9% | ~ ±19% |
| CP effect* | ~ ±30% | ~ ±25% |

*calculated at beam peak energy

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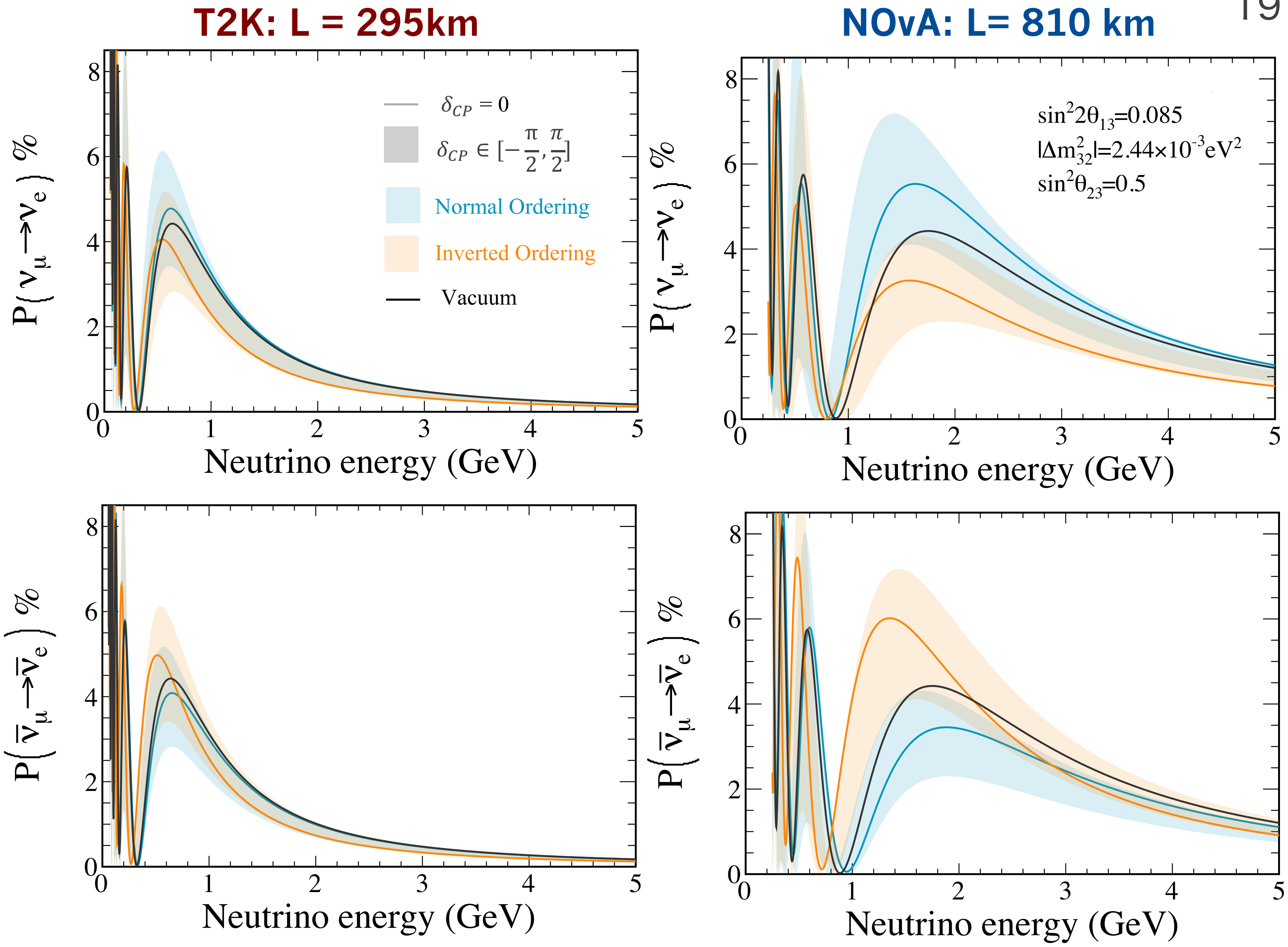
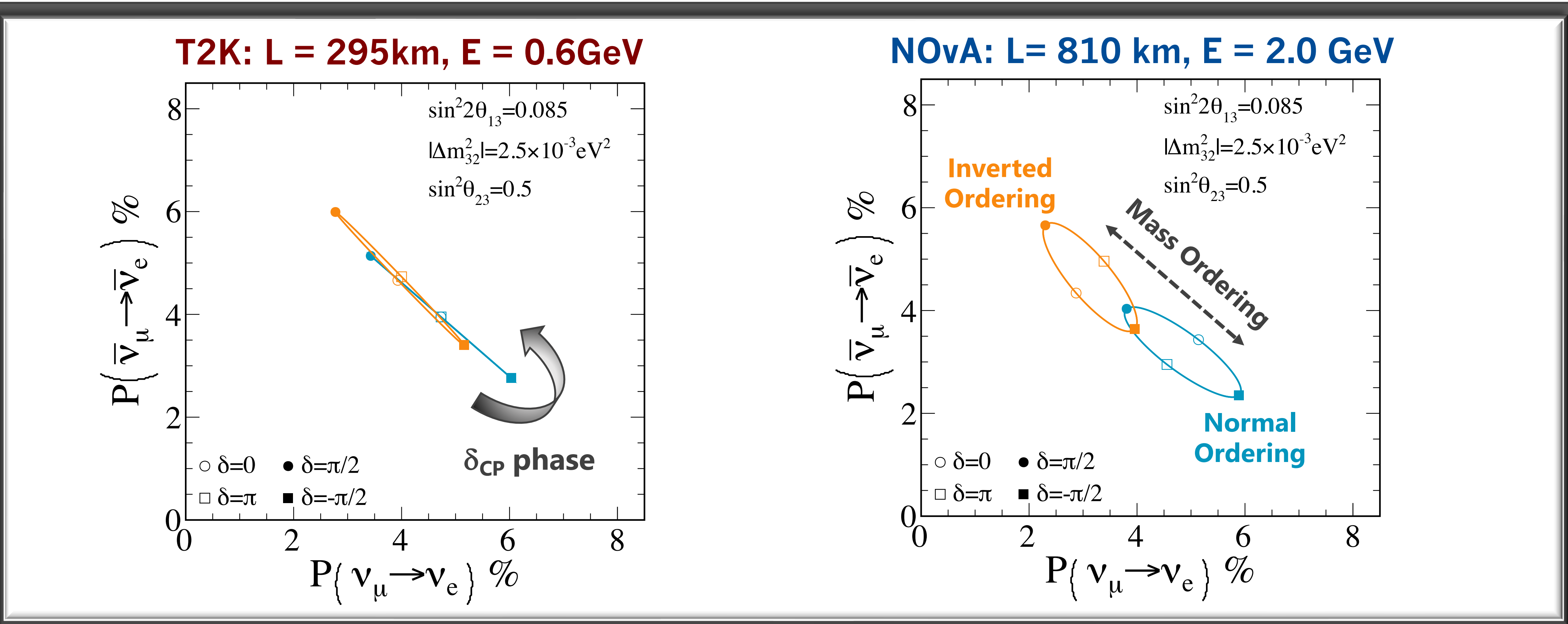
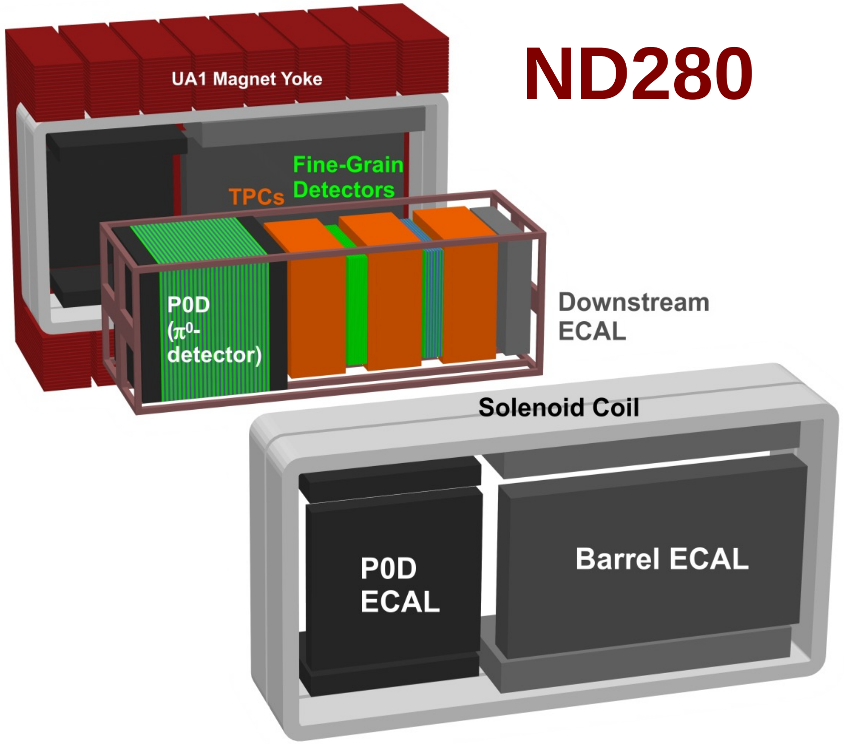


# Resolving degeneracies

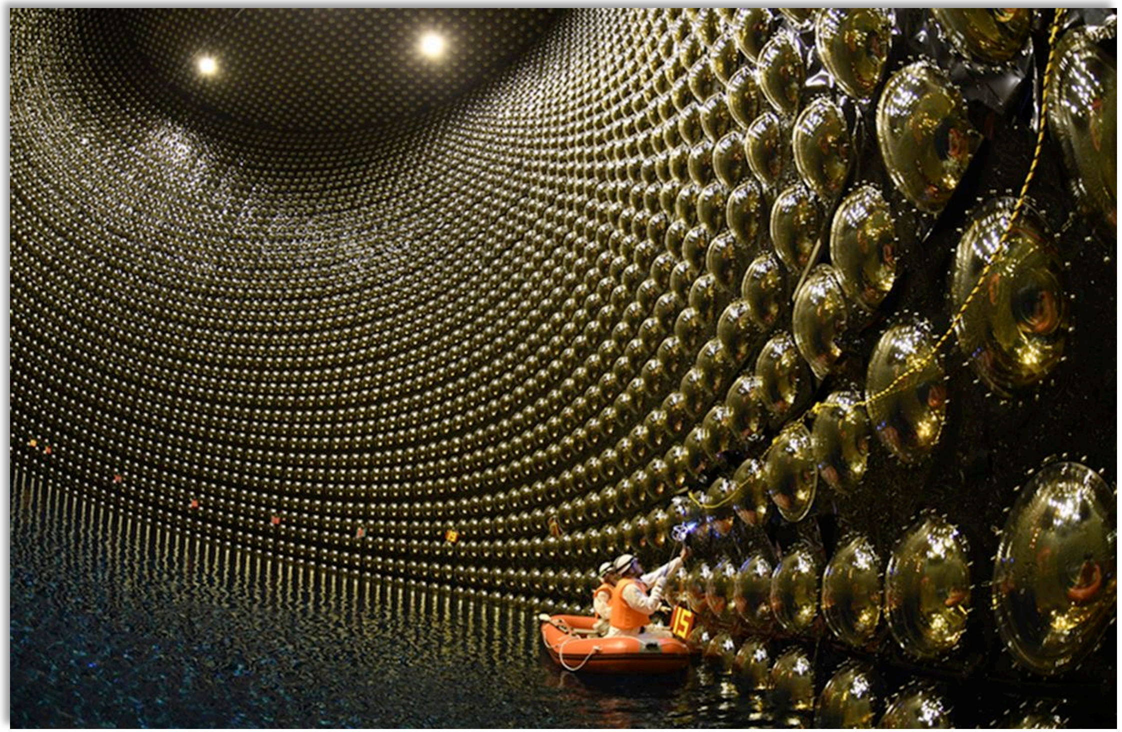
- **T2K** measurements isolate impact of **CP violation** while **NOvA** has significant **sensitivity to mass ordering.**
- **Joint analysis probes both spaces lifting degeneracies of individual experiments.**



# T2K Detectors



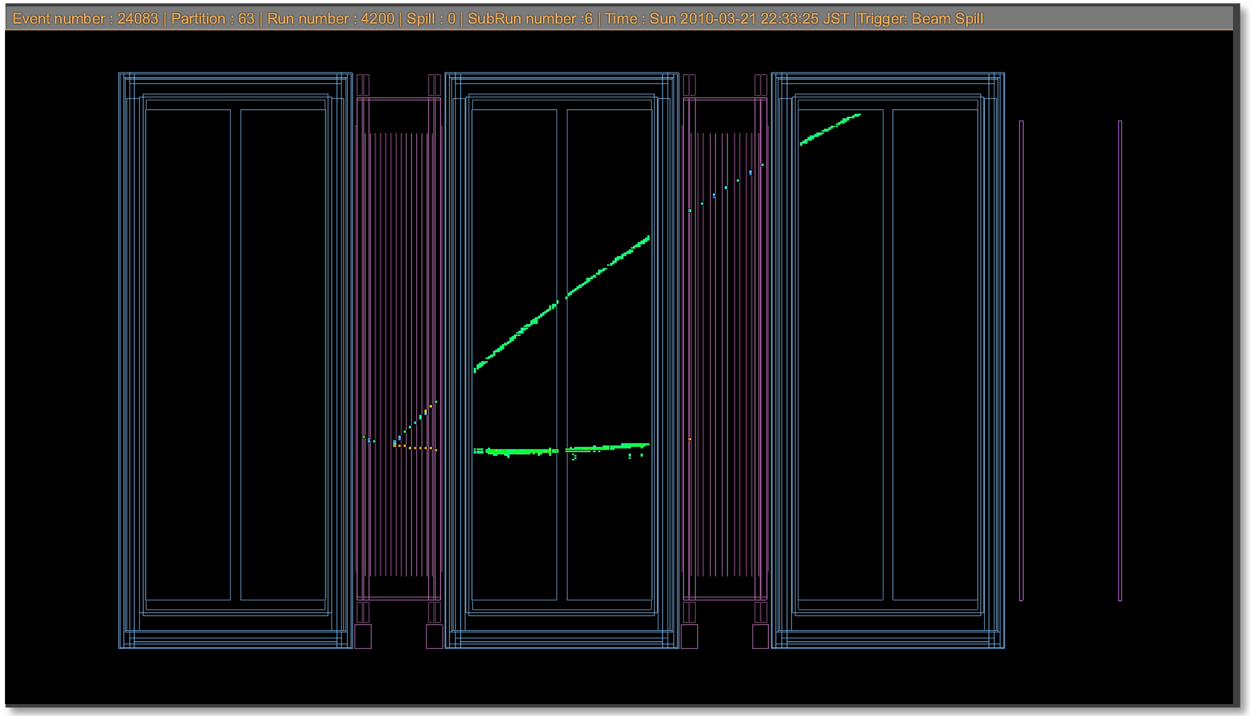
**T2K's FD: Super Kamiokande (SK)**

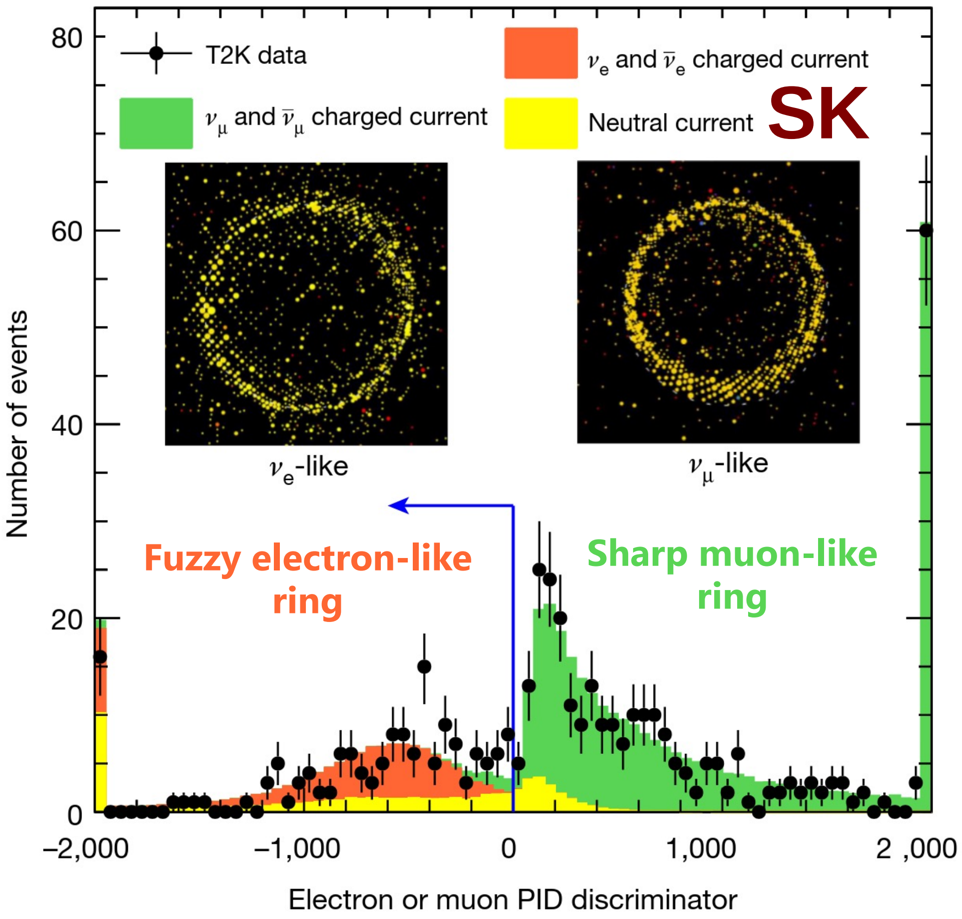


- T2K employs different detector technologies for Near and Far detectors.
  - ND comprises a set of magnetized detectors employing particle tracking with plastic scintillator as the target material.
  - FD is the 50 kt Water Cherenkov Super Kamiokande detector.

# T2K Detectors

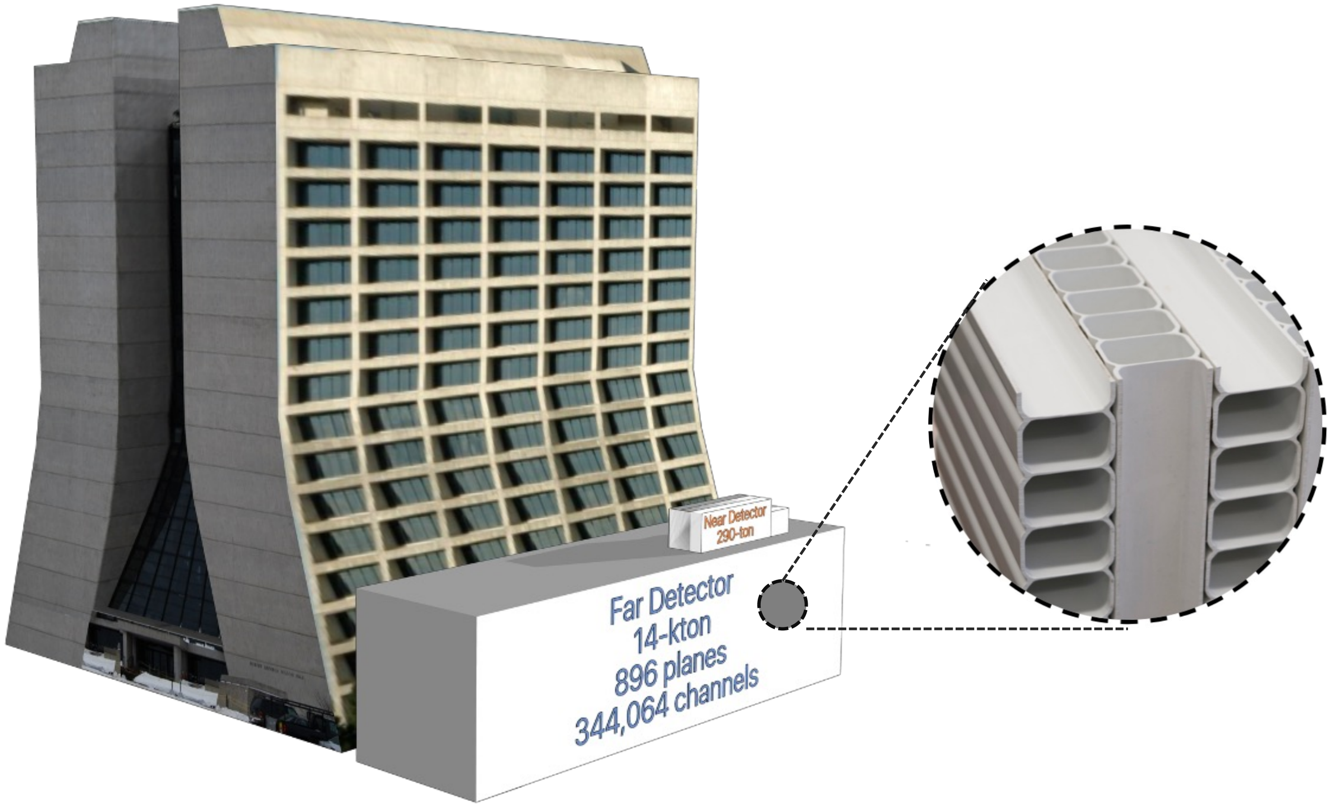
**ND280**





- Energy of the incoming neutrino is reconstructed from the lepton kinematics.
  - ND: Selection based on reconstructed muon track and number of pions - CC1$\mu$0$\pi$, CC1$\mu$1$\pi$, CC1$\mu$N$\pi$
  - FD: Particles are identified by their Cherenkov rings and selections use exclusive topologies.

# NOvA Detectors

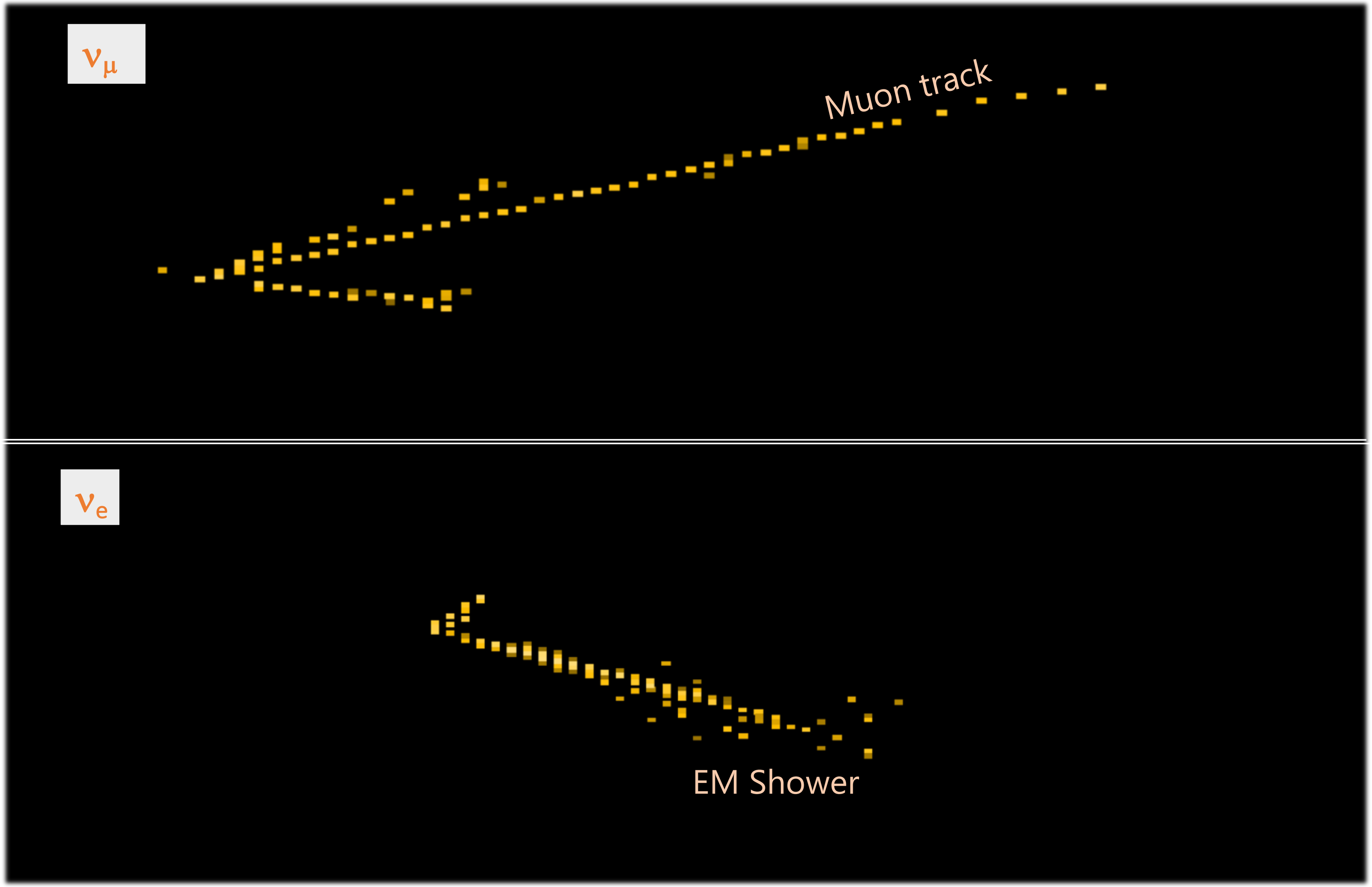


**NOvA FD**

- NOvA’s ND and FD are **functionally identical segmented liquid scintillator detectors.**
  - ND: ~290 t and ~100 m underground
  - FD: ~14 kt and on the surface

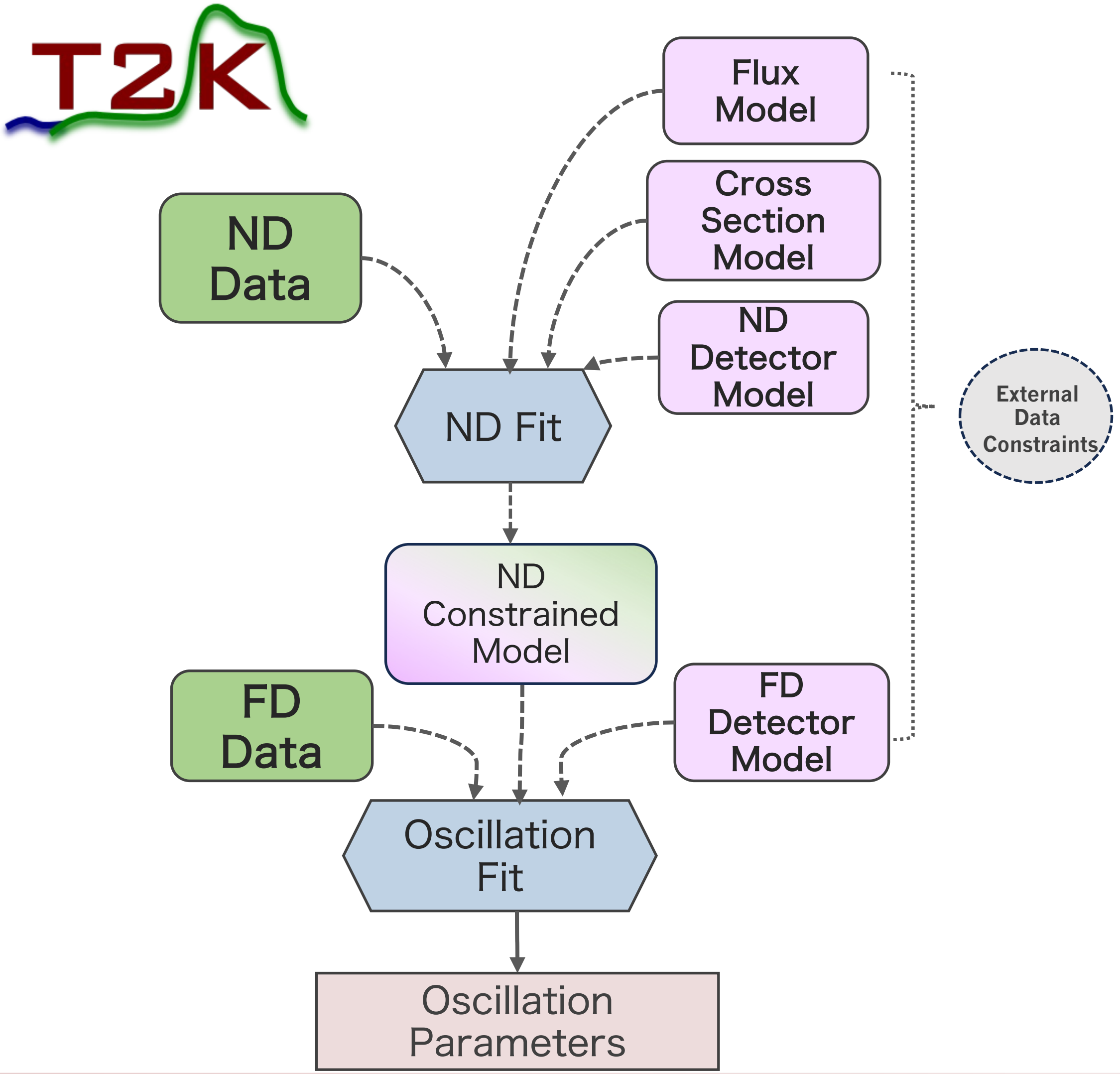
# NOvA Detectors

- For both ND and FD, neutrino energy is estimated from a **combination of lepton and hadronic components**:
  - Muon energy is reconstructed via track length.
  - Calorimetric energy estimation is done separately for EM and hadronic clusters.
- NOvA event selection uses inclusive CC interactions for both $\nu_\mu$ and $\nu_e$ channels.



# Analysis Strategy

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



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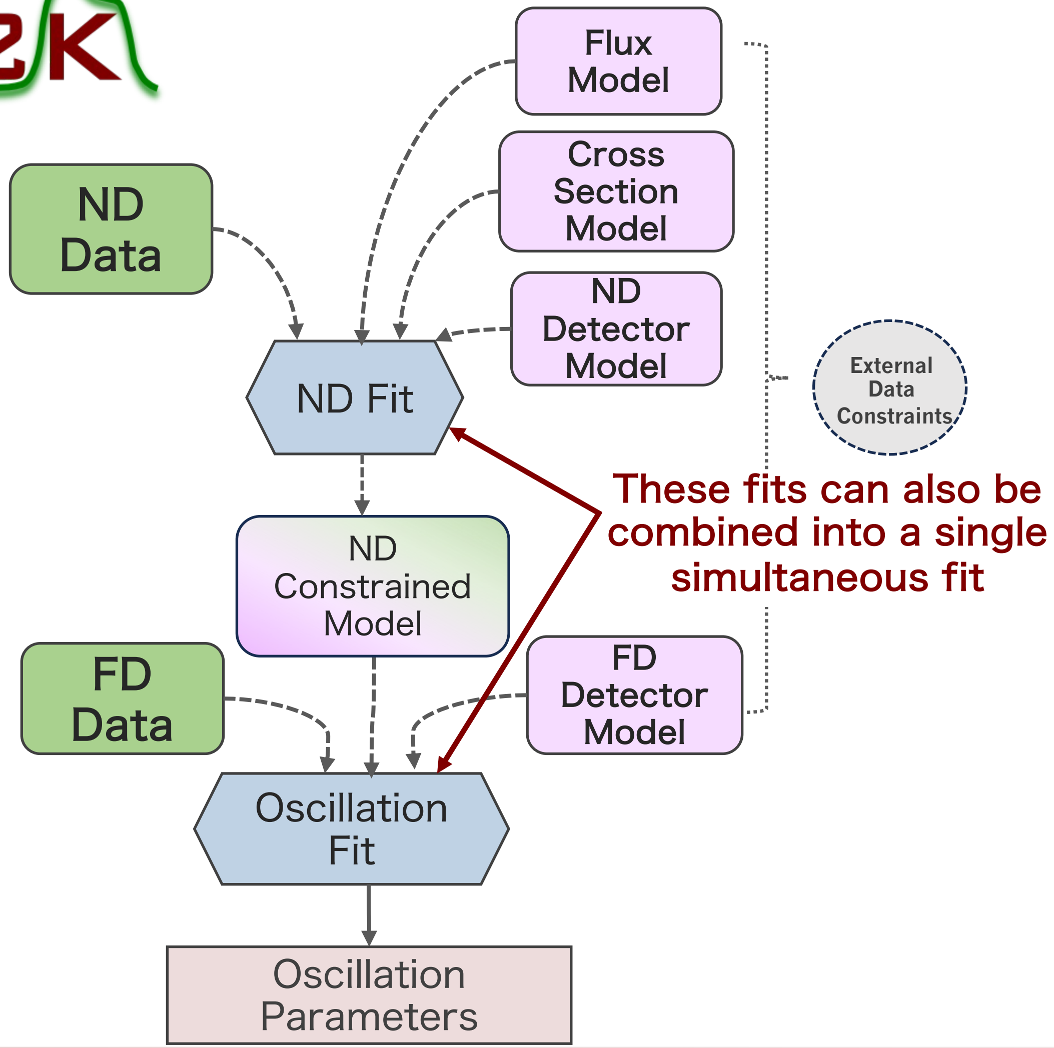


ND Data

Flux Model

Cross Section Model

ND Detector Model

External Data Constraints

ND Fit

ND Constrained Model

FD Data

FD Detector Model

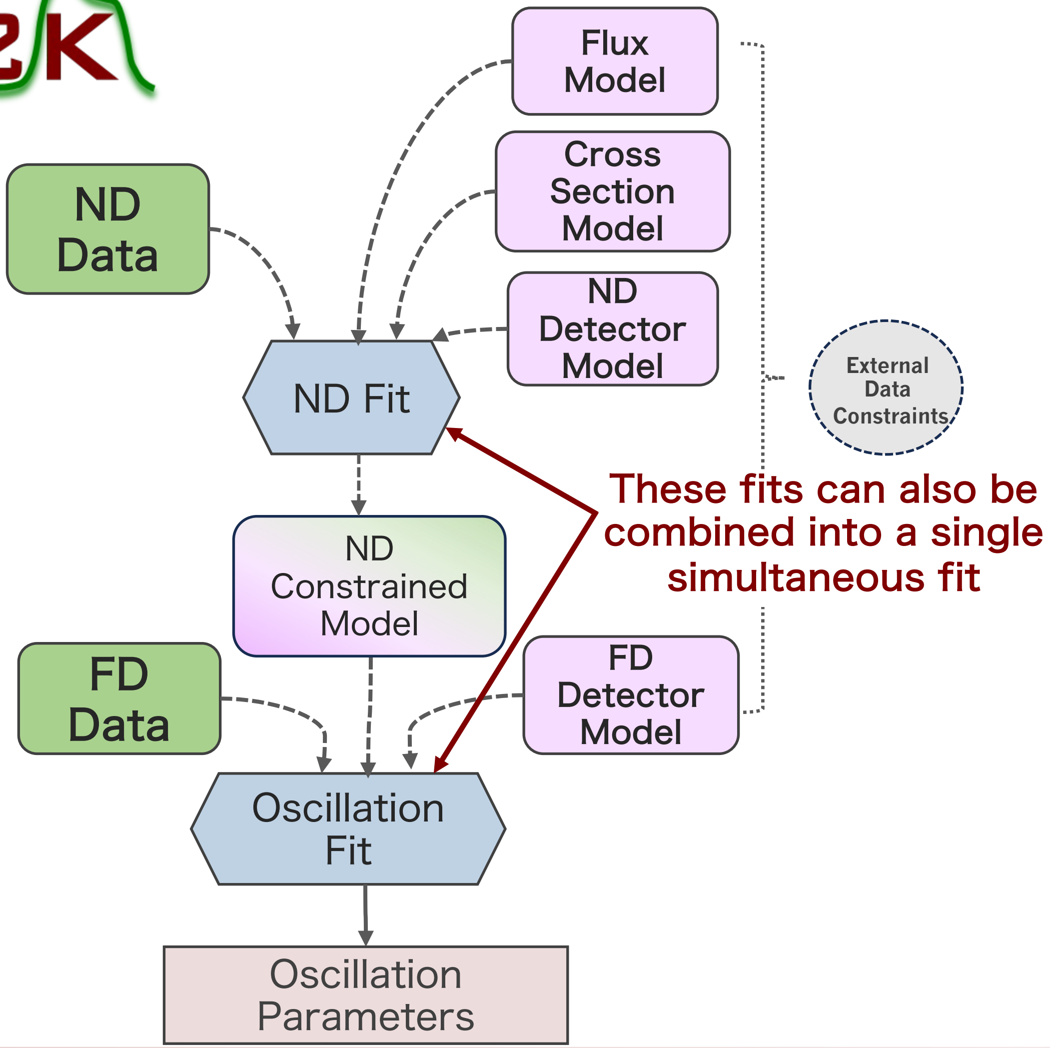
Oscillation Fit

Oscillation Parameters

These fits can also be combined into a single simultaneous fit

# Analysis Strategy

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



Flux Model

Cross Section Model

ND Detector Model

ND Data

ND Fit

External Data Constraints

These fits can also be combined into a single simultaneous fit

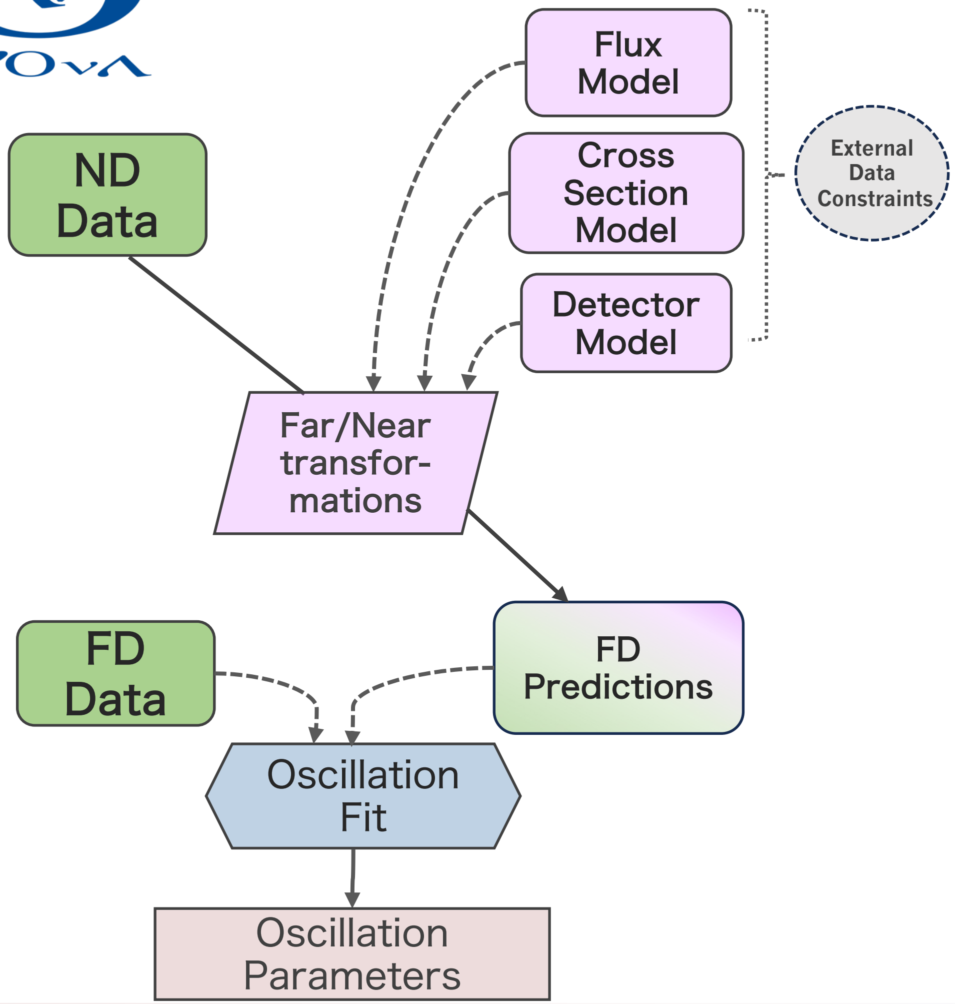
ND Constrained Model

FD Data

FD Detector Model

Oscillation Fit

Oscillation Parameters



Flux Model

ND Data

Cross Section Model

External Data Constraints

Detector Model

Far/Near transfor-mations

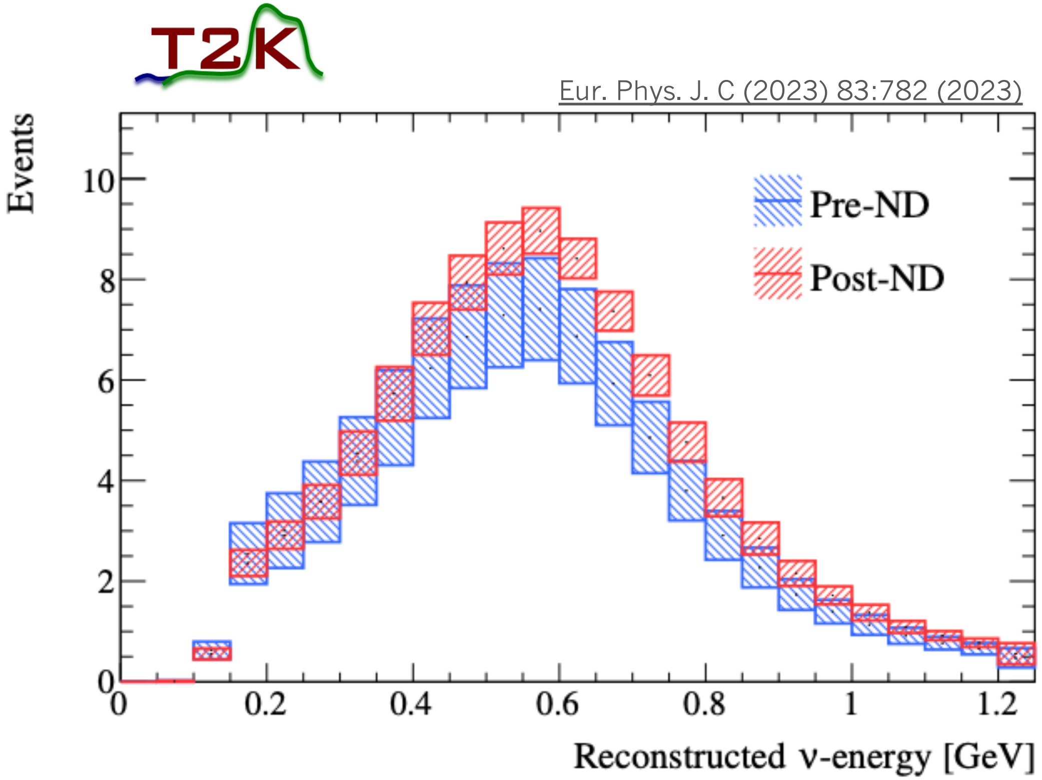
FD Data

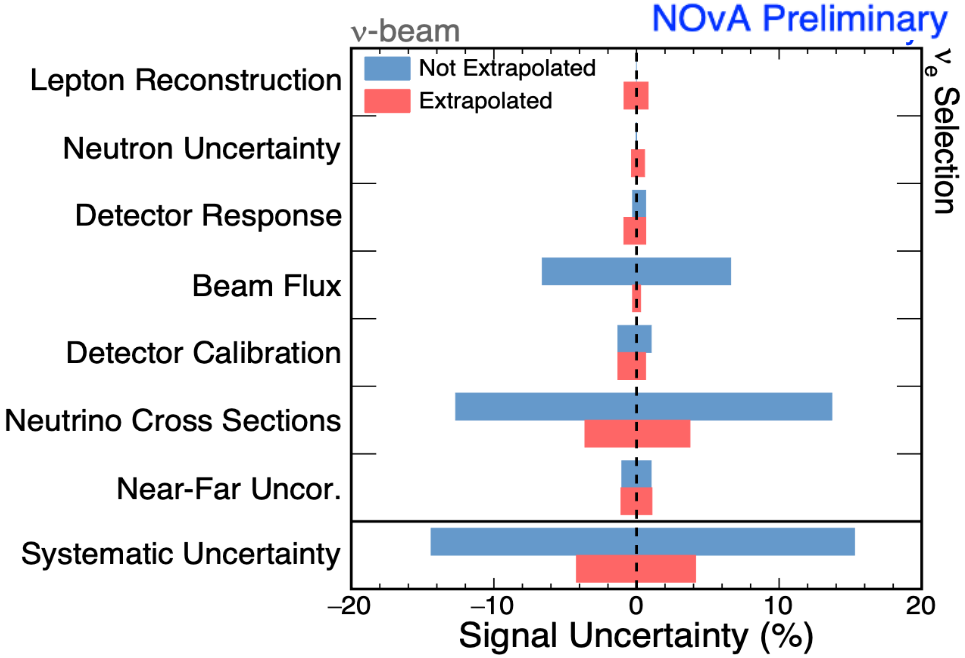
FD Predictions

Oscillation Fit

Oscillation Parameters

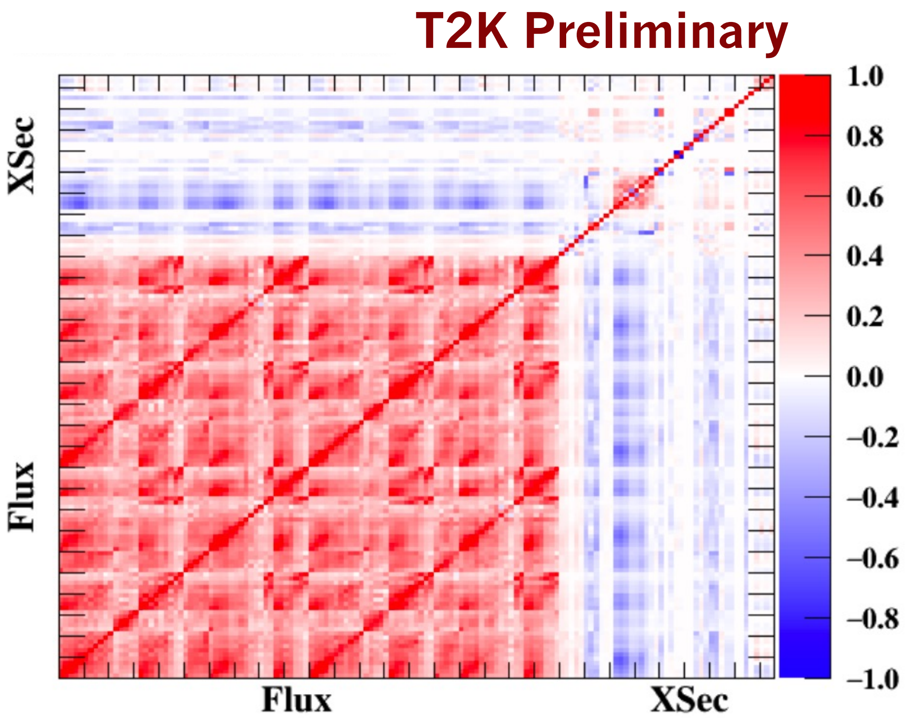
# Impact on systematics



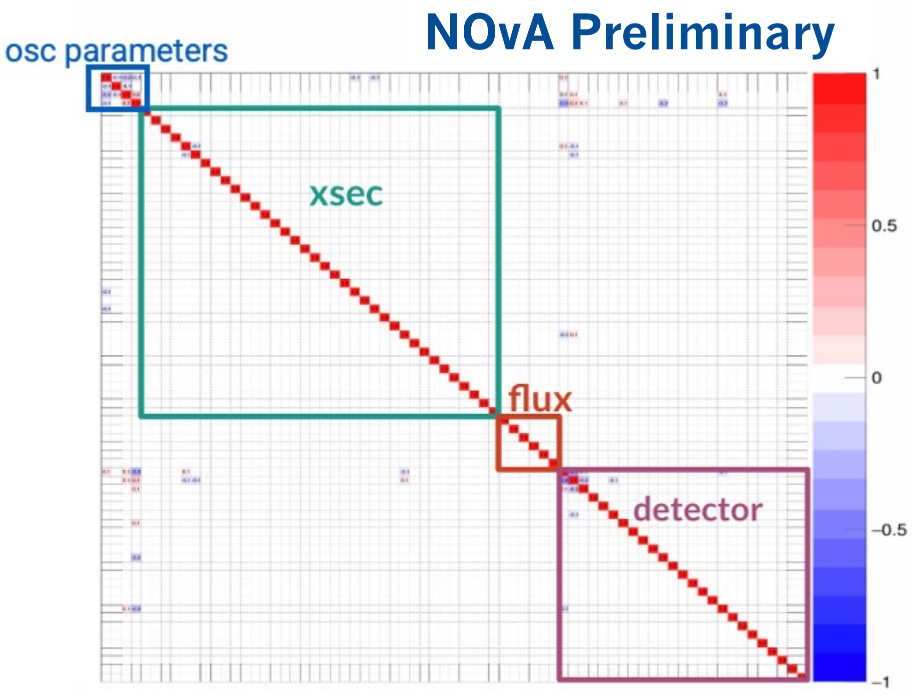


- **T2K**: Uncertainty on FD 1e-like ring $\nu_e$ event rate goes from ~13% to ~5% after applying constraints from ND data fit
- **NOvA**: Systematic uncertainties in the FD $\nu_e$ prediction from ~15% to ~4%

# Impact on systematics



**post-fit correlation matrix**



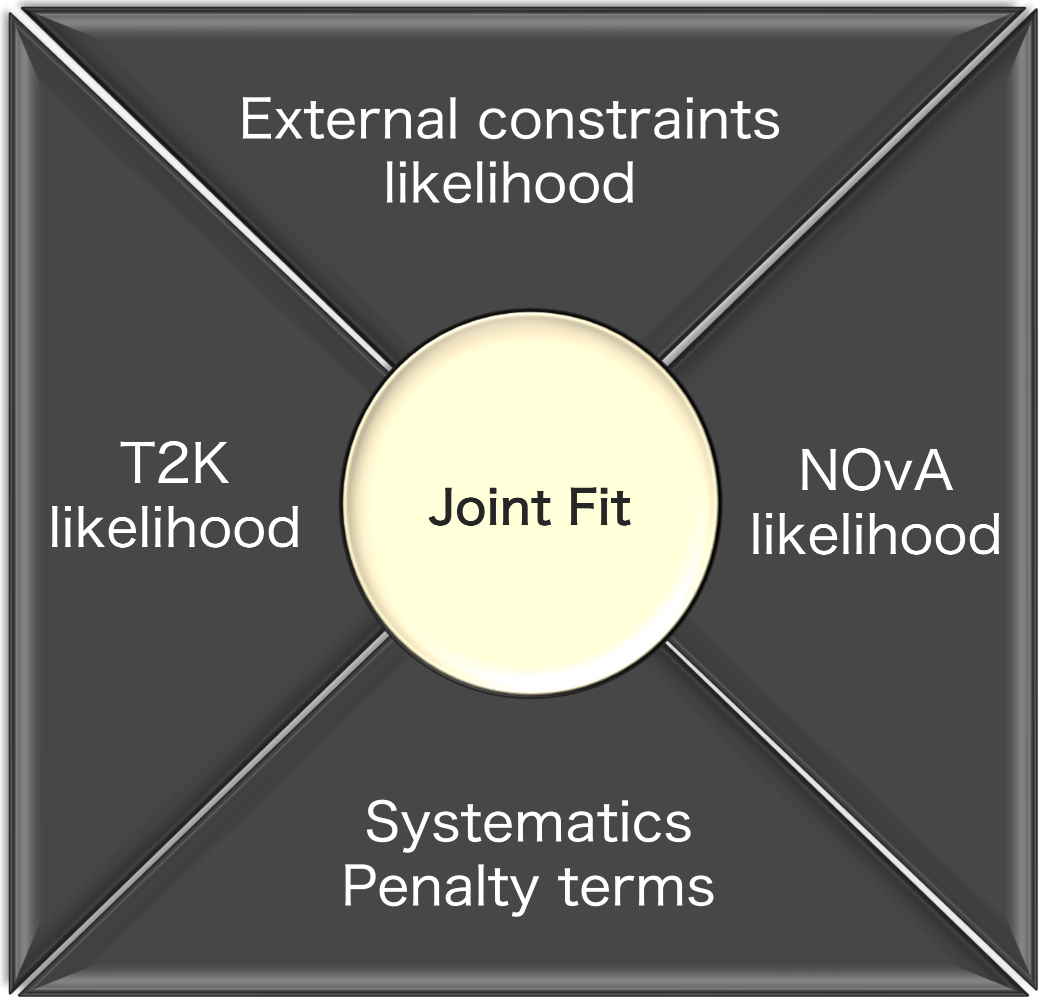
**post-fit correlation matrix**

- **T2K:** Leverages high-statistics ND data to **constrain model parameters and uncertainties** prior to oscillations, leading to significant anti-correlations between flux and cross-section.
- **NOvA:** Model and systematic parameters enter as a **ratio of how they impact near vs far detector**. This cancelation constraints the variations allowed by systematics, minimizing their correlations with oscillations and nuisance parameters.

# Constructing the NOvA-T2K joint analysis

# Constructing the joint-analysis

- The joint-fit is constructed using:
    - Poisson likelihood from each experiment
    - Penalty terms from the systematics pull
    - External constraints on $\theta_{13}$, $\theta_{12}$, $\Delta m^2_{21}$ from solar and reactor neutrino experiments
- The other experiment's likelihoods are integrated via a containerized environment.
    - Both experiments can run each other's analysis through these containers.
    - Full access to Monte-Carlo and data.



External constraints likelihood

T2K likelihood

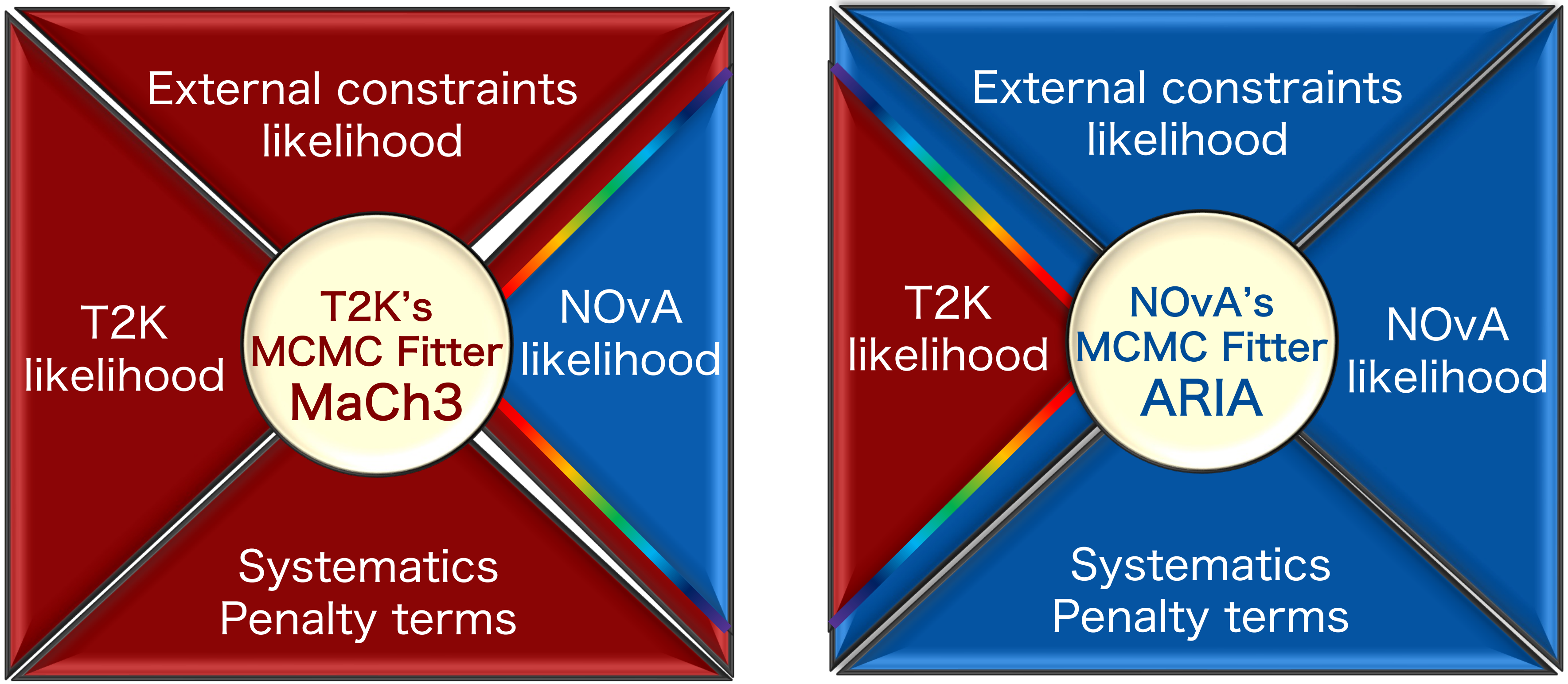
Joint Fit

NOvA likelihood

Systematics Penalty terms

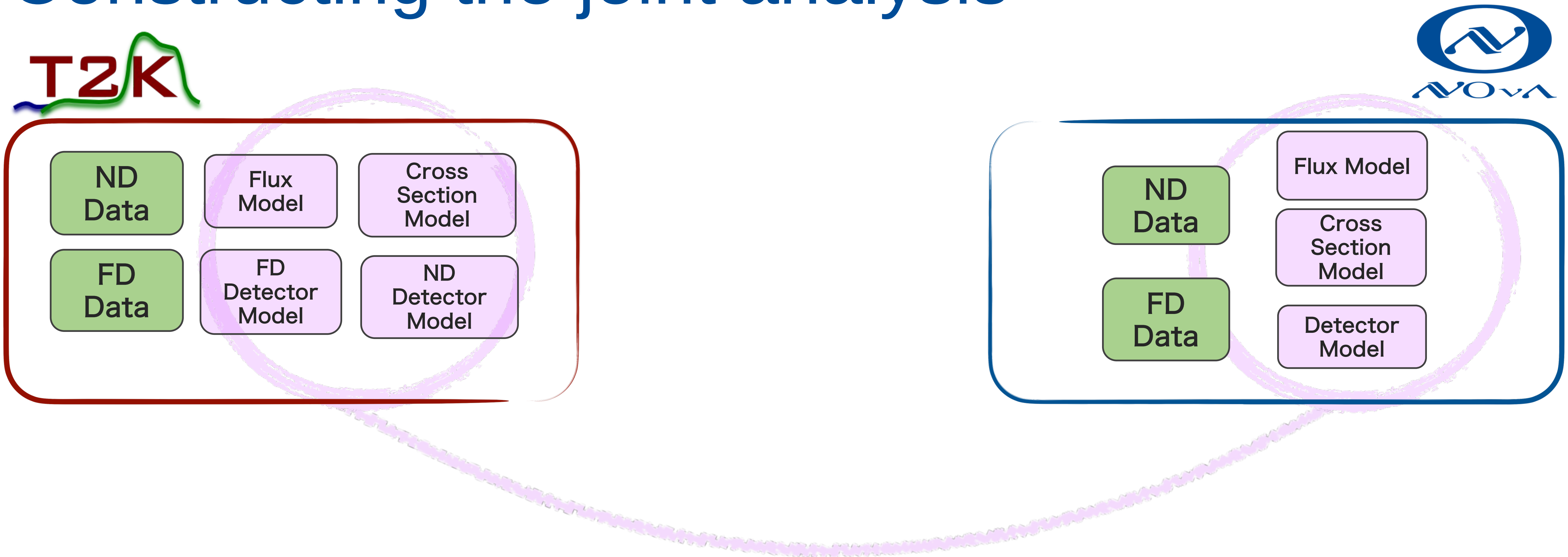
# Constructing the joint-analysis

- Both T2K and NOvA have used their Bayesian Markov Chain Monte Carlo (MCMC) fitters.
- Both produce same output format:
  - Posterior densities and credible intervals for parameters-of-interest.
  - Bayes factor for discrete model preferences (ordering and octant).
- Independent implementation of the framework provided rigorous validation of the joint fit.



Red represents T2K codebase & blue shows NOvA codebase.

# Constructing the joint analysis



Challenge: When? What? How? to correlate common physics parameters between the two experiments.

# Models & Systematics

Flux Model

Detector Model

Cross Section Model

- Challenge: When? What? How? to correlate common physics parameters between the two experiments.

- Strategy:
  - ☐ Is the overall impact negligible on the result?
  - ☐ Do we expect any correlations between the experiments?
  - ☐ Is the impact of the correlations negligible on the result?

# Models & Systematics

**Flux Model**

- Different energies
- Different tuning to external data
  - thin target vs thick target data
- Enters the analysis differently

❑ No significant correlations between the experiments

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☐ No significant correlations between the experiments

---

**Detector Model**

- Different detector design and targets
- Different selections
    - inclusive vs exclusive outgoing pions
- Different energy reconstruction
    - calorimetric vs lepton kinematics

☐ Explored possible correlations between leptonic energy scales; pion and neutron secondary interactions

# Models & Systematics

**Flux Model**

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**Cross Section Model**

- As the underlying physics is fundamentally the same, we expect correlations
- Different neutrino interaction models
  - optimized for different energy ranges
- Systematics are designed for individual models and analysis strategies

☐ Investigate the impact of models and correlations on the joint analysis

# Cross-section: Impact of correlations

- **Challenge:** No direct mapping between the cross-section systematics parameters
  - Exception: **Uncertainties in $\nu_e/\nu_\mu$** and $\bar{\nu}_e/\bar{\nu}_\mu$ cross-section have identical origin* and similar treatment
    - **Fully correlated in the joint fit.**

*Phys. Rev. D **86**, 053003

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        - **Fully correlated in the joint fit.**

- **Strategy:** Explore a range of artificially crafted scenarios to bracket the impact of possible correlations.

---

*Phys. Rev. D **86**, 053003

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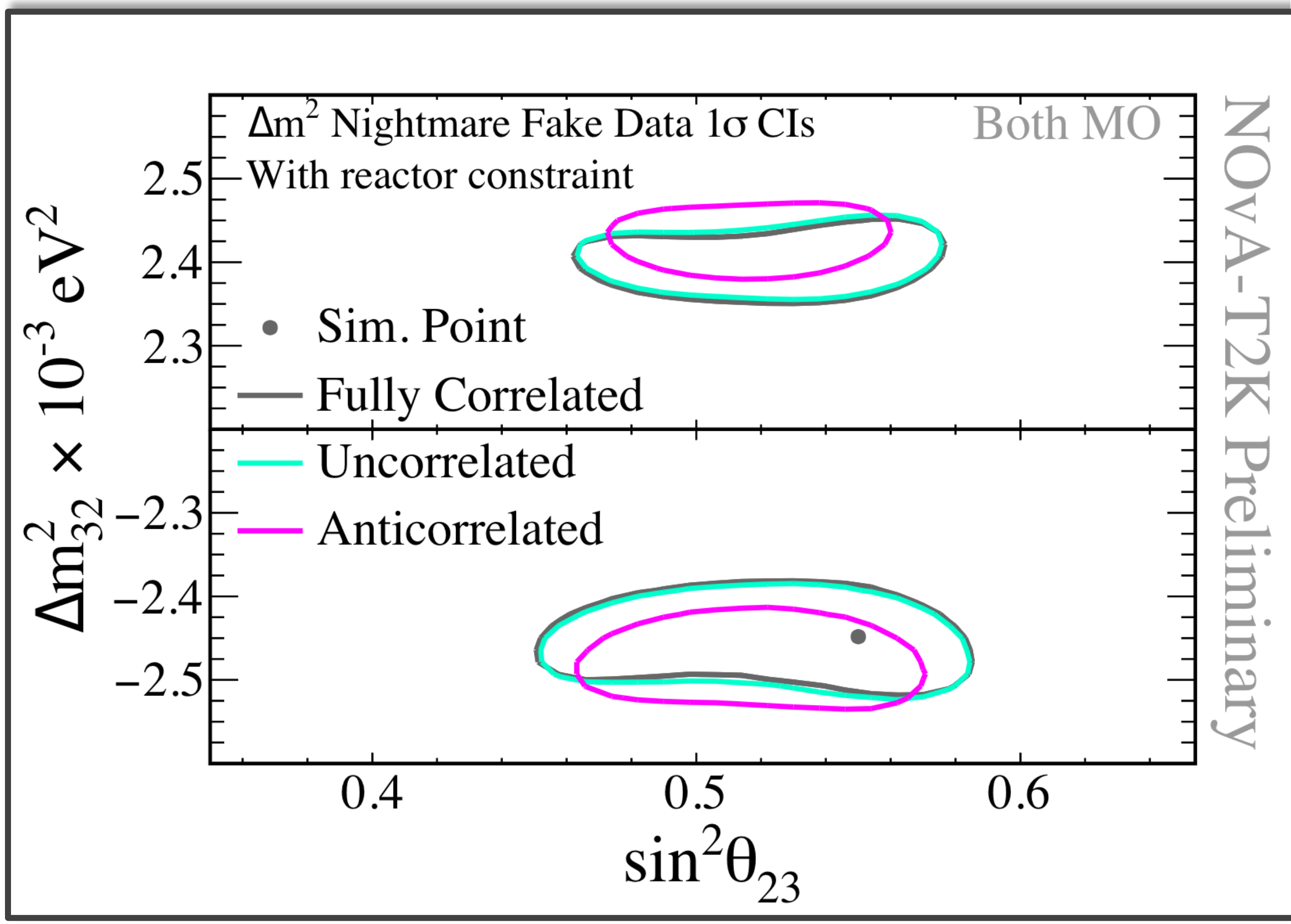
  - Exception: **Uncertainties in $\nu_e/\nu_\mu$** and **$\bar{\nu}_e/\bar{\nu}_\mu$** cross-section have identical origin* and similar treatment
    - **Fully correlated in the joint fit.**
- **Strategy:** Explore a range of artificially crafted scenarios to bracket the impact of possible correlations
  - Example: Fabricated systematics equal in size to total statistical uncertainty, causing a correlated bias in the oscillation dip across both experiments.
  - **Uncorrelated and correctly correlated (full correlation) credible intervals agree with negligible differences**, while **incorrectly correlating systematics shows a bias**.



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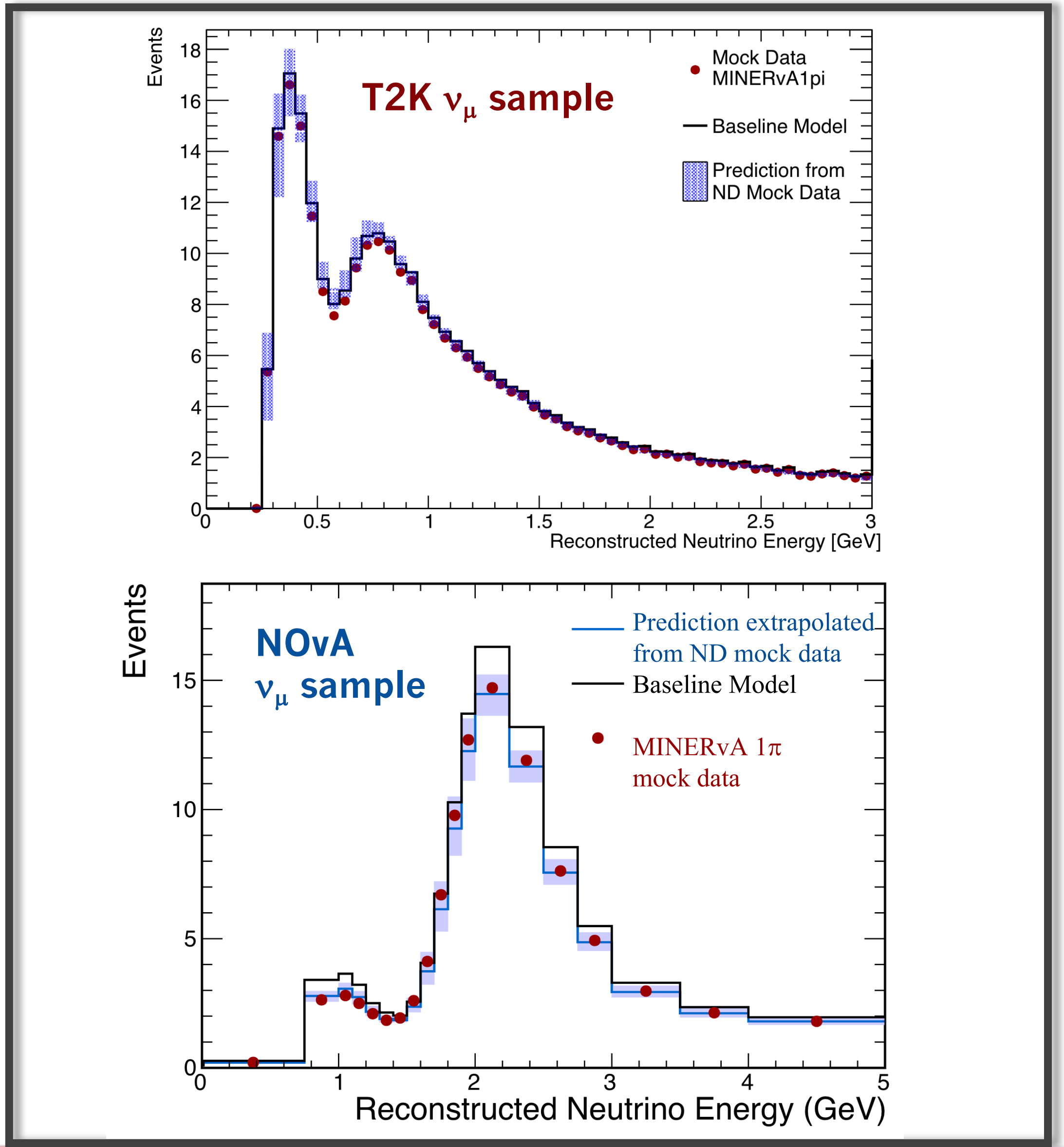
*Phys. Rev. D **86**, 053003

# Cross-section: Impact of alternate models

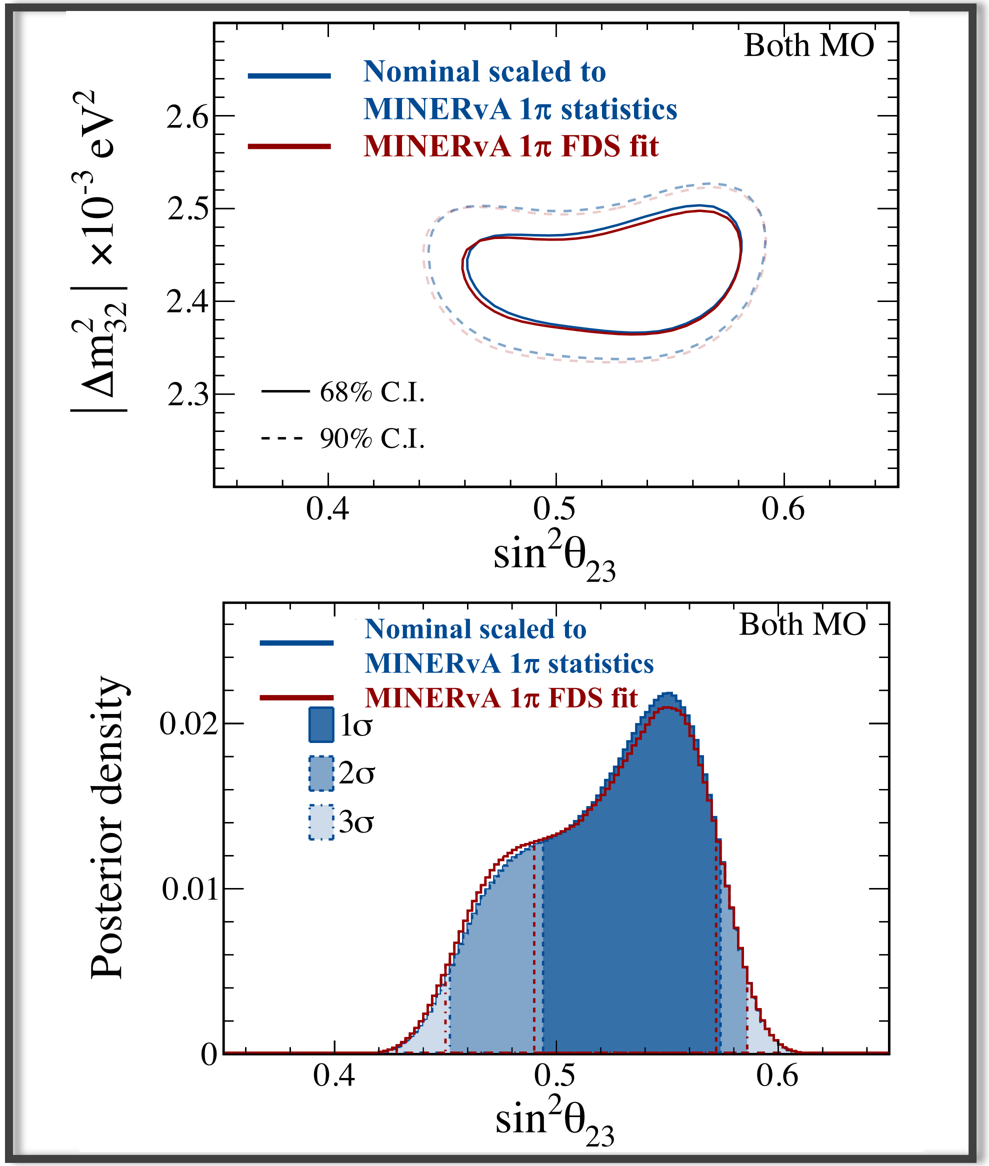
- Evaluate the robustness of the fit against various alternate models
- Generated simulated fake data using reweighting to alternate models for both the near and far detector, then analyze the credible intervals of the full joint-fit
- Pre-decided thresholds for bias:
  - Change in the width of the 1D intervals <10%
  - Change in central value < 50% of systematic uncertainty
- **Example: Suppression in single pion channel based on tune to the MINERvA data***



*Phys. Rev. D 100, 072005 (2019)

# Cross-section: Impact of alternate models

- **Example: Suppression in single pion channel based on the tune to the MINERvA data***
- Additional tests:
  - Cross-experiment models after the ND constraint
  - Impact of alternative nuclear response model: HF-CRPA**
  - Full list available in backup
- **No alternate model tests failed the preset threshold bias criteria.**



*Phys. Rev. D 100, 072005 (2019)

** Phys. Rev. D 106, 073001 (2022)

# Models & Systematics

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---

**Cross Section Model**

- As the underlying physics is fundamentally the same, we expect correlations
- Different neutrino interaction models
  - optimized for different energy ranges
- Systematics are designed for individual models and analysis strategies

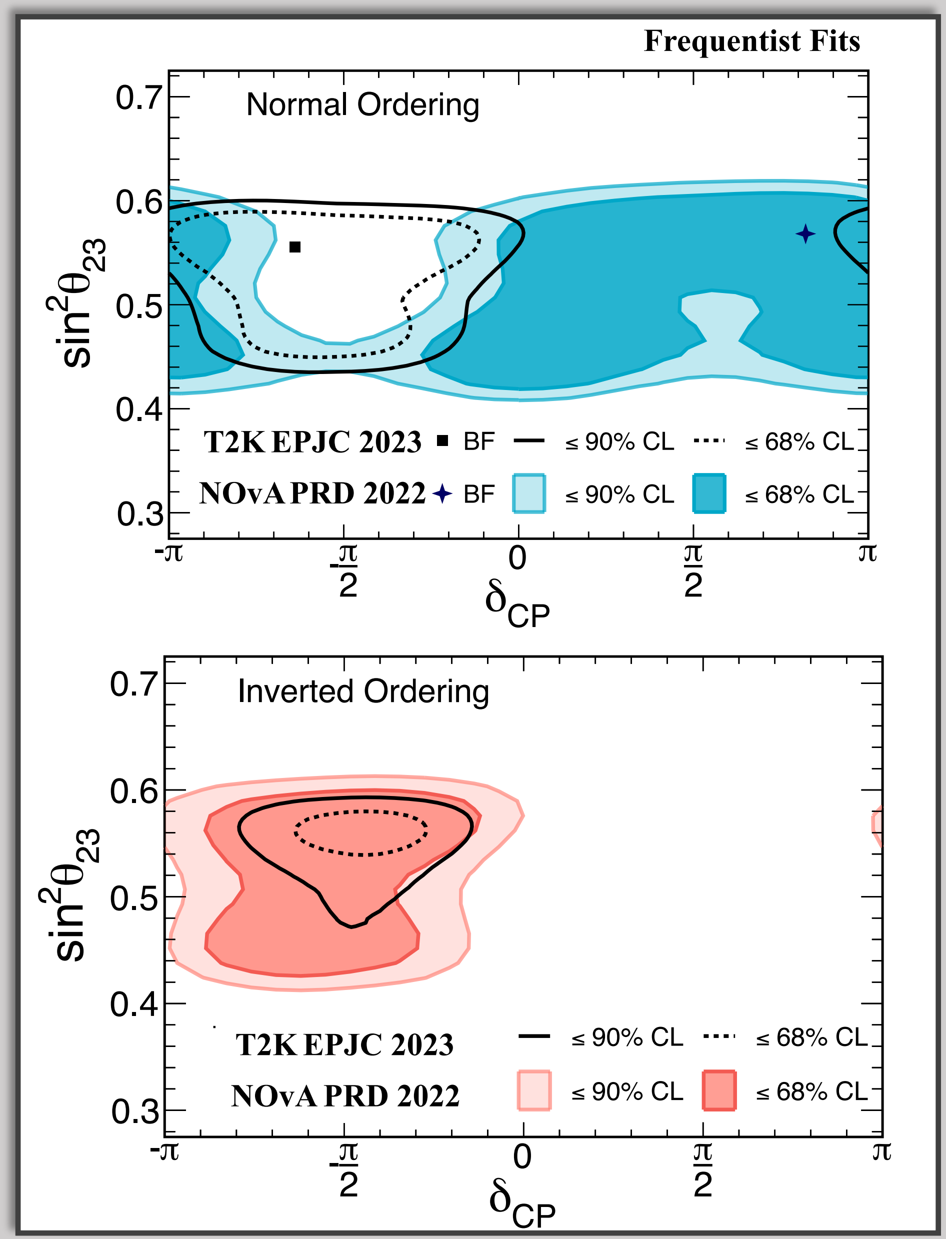
❑ Impact of correlations is negligible on the results at the current statistical significance.

❑ Merits continued investigations for higher data exposures.

# Why NOvA-T2K joint fit?

☑ The complementarity between the experiments provides the power to **break degeneracies.**

- Full implementation of:
  - ☑ **Energy reconstruction and detector response**
  - ☑ **Detailed likelihood** from each experiment
  - ☑ Consistent **statistical inference across the full dimensionality**
- In-depth review of:
  - ☑ **Models, systematic uncertainties and possible correlations**
  - ☑ **Different analysis approaches** driven by contrasting detector designs.



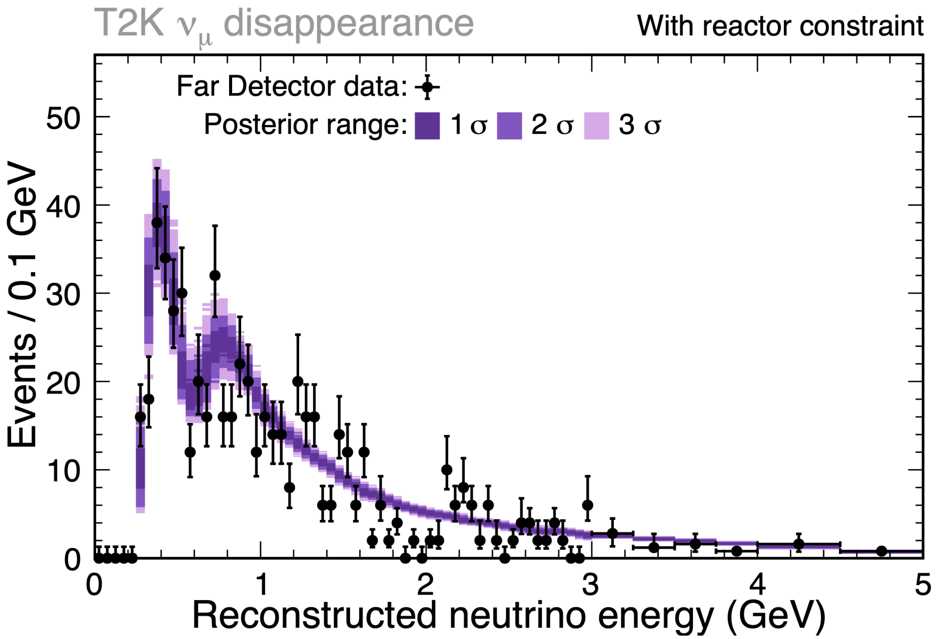
**Results from NOvA and T2K from 2020 datasets**

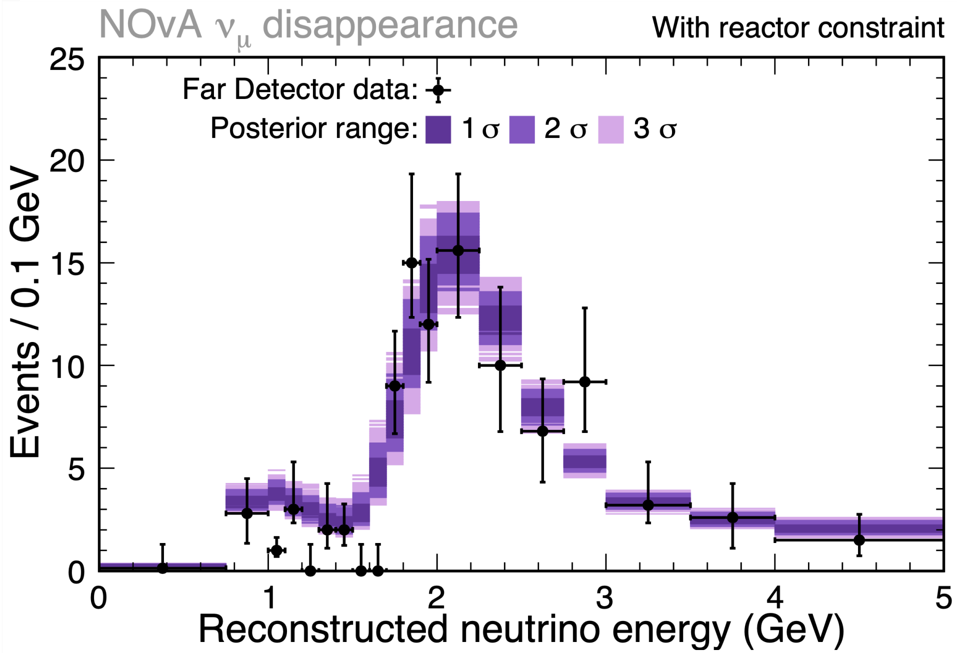
# Data Results

# FD Data Samples

- The joint-fit uses the data collected by each experiment up until 2020.
- Using both experiments data roughly doubles the total statistics at the far detectors.

| **Channel** | **NOvA** | **T2K** |
|---|---|---|
| $\nu_e$ | **82** | **94** ($\nu_e$)<br>**14** ($\nu_e 1\pi$) |
| $\bar{\nu}_e$ | **33** | **16** |
| $\nu_\mu$ | **211** | **318** |
| $\bar{\nu}_\mu$ | **105** | **137** |





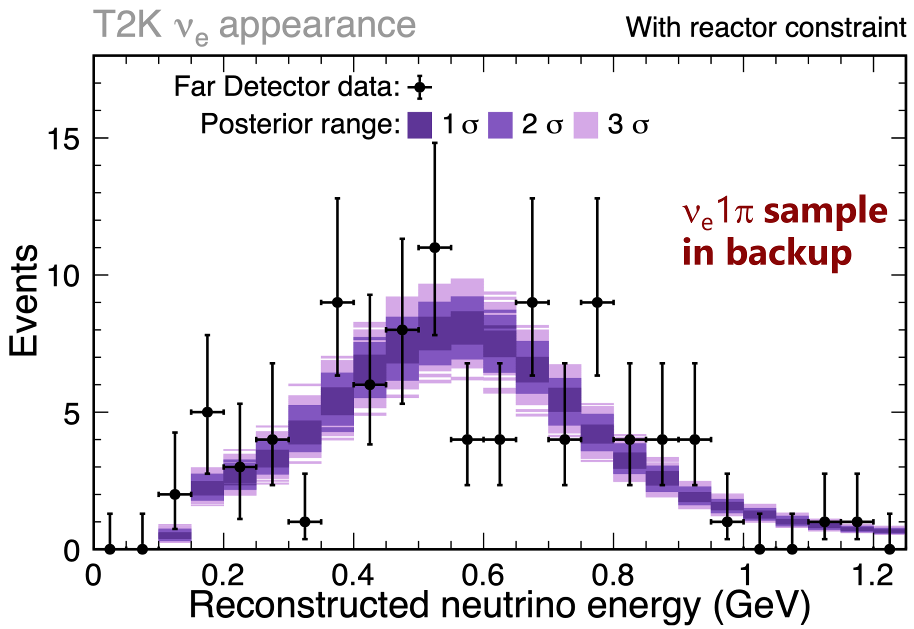
**$\bar{\nu}_\mu$ samples in backup**

# Compatibility of datasets

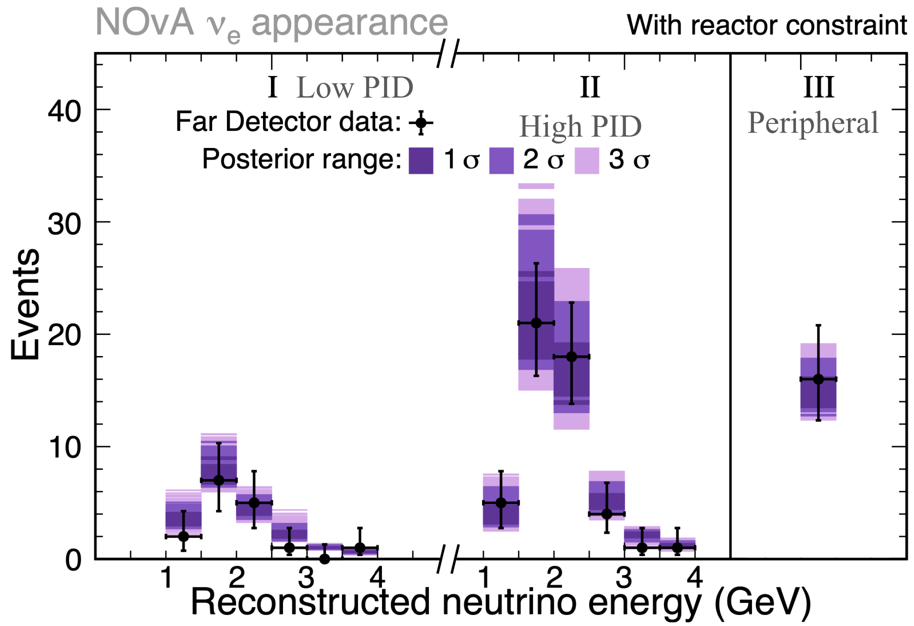
- Posterior predictive p-values (PPP)*
  - Compare likelihood best fit to data and fluctuated predictions
  - A good PPP is around 0.5
- The data from both experiments is described well by the joint fit.

| Channel | NOvA | T2K | Combined |
|---|---|---|---|
| $\nu_e$ | **0.90** | **0.19** ($\nu_e$)<br>**0.79** ($\nu_e 1\pi$) | **0.62** |
| $\bar{\nu}_e$ | **0.21** | **0.67** | **0.40** |
| $\nu_\mu$ | **0.68** | **0.48** | **0.62** |
| $\bar{\nu}_\mu$ | **0.38** | **0.87** | **0.72** |
| Total | **0.64** | **0.72** | **0.75** |

posterior predictive p-value



**$\nu_e 1\pi$ sample in backup**



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*Statistica Sinica, vol. 6, no. 4, 1996, pp. 733–60. JSTOR

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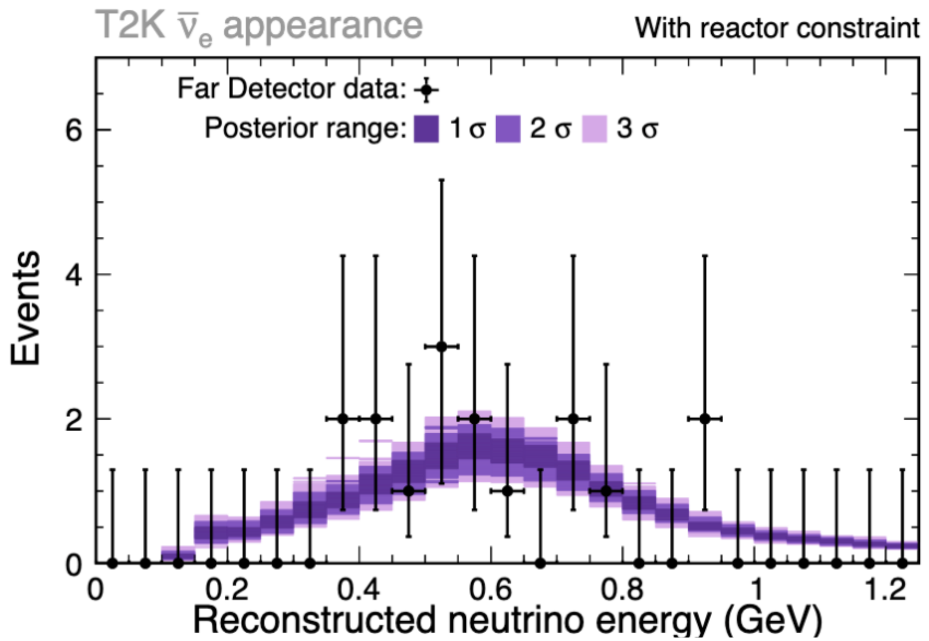
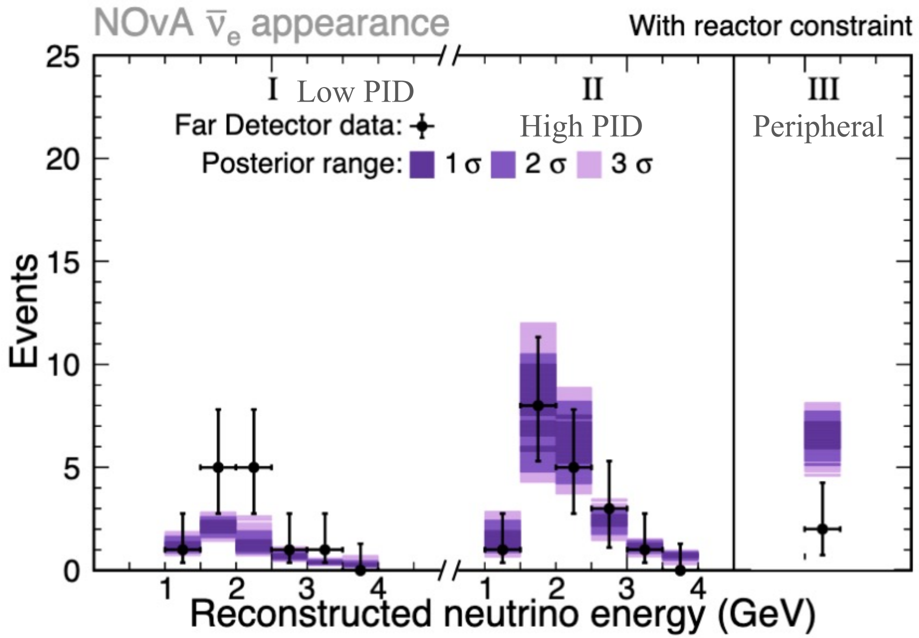
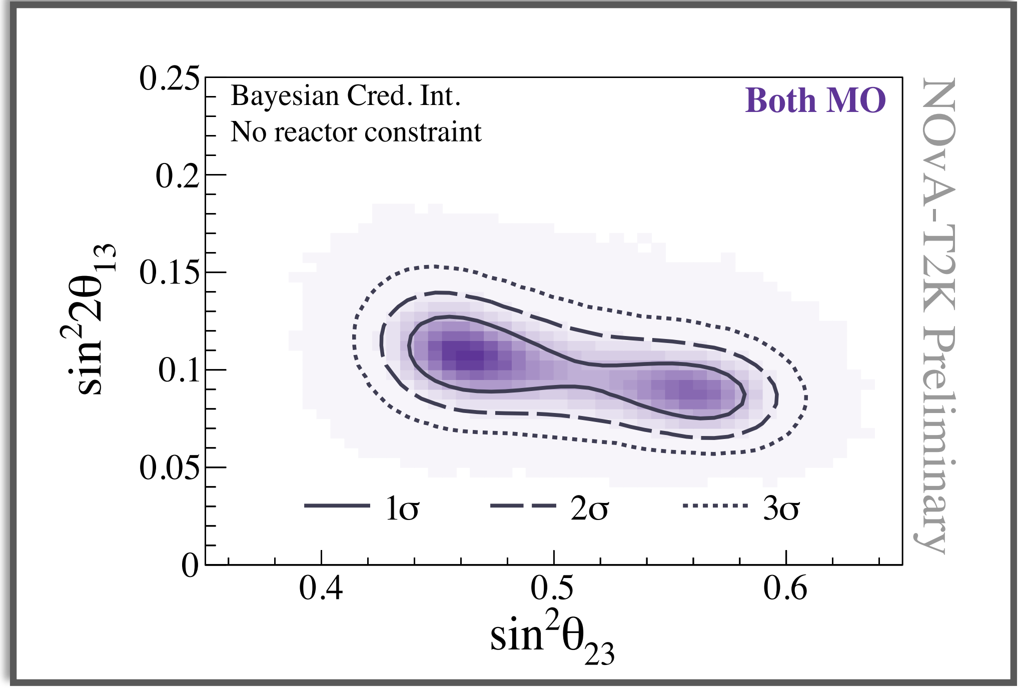




*Statistica Sinica, vol. 6, no. 4, 1996, pp. 733–60. JSTOR

# Mixing angles: $\theta_{23}$ & $\theta_{13}$

- Without any external constraint from reactor experiments, long-baseline measurements have a degeneracy in $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$ parameters.



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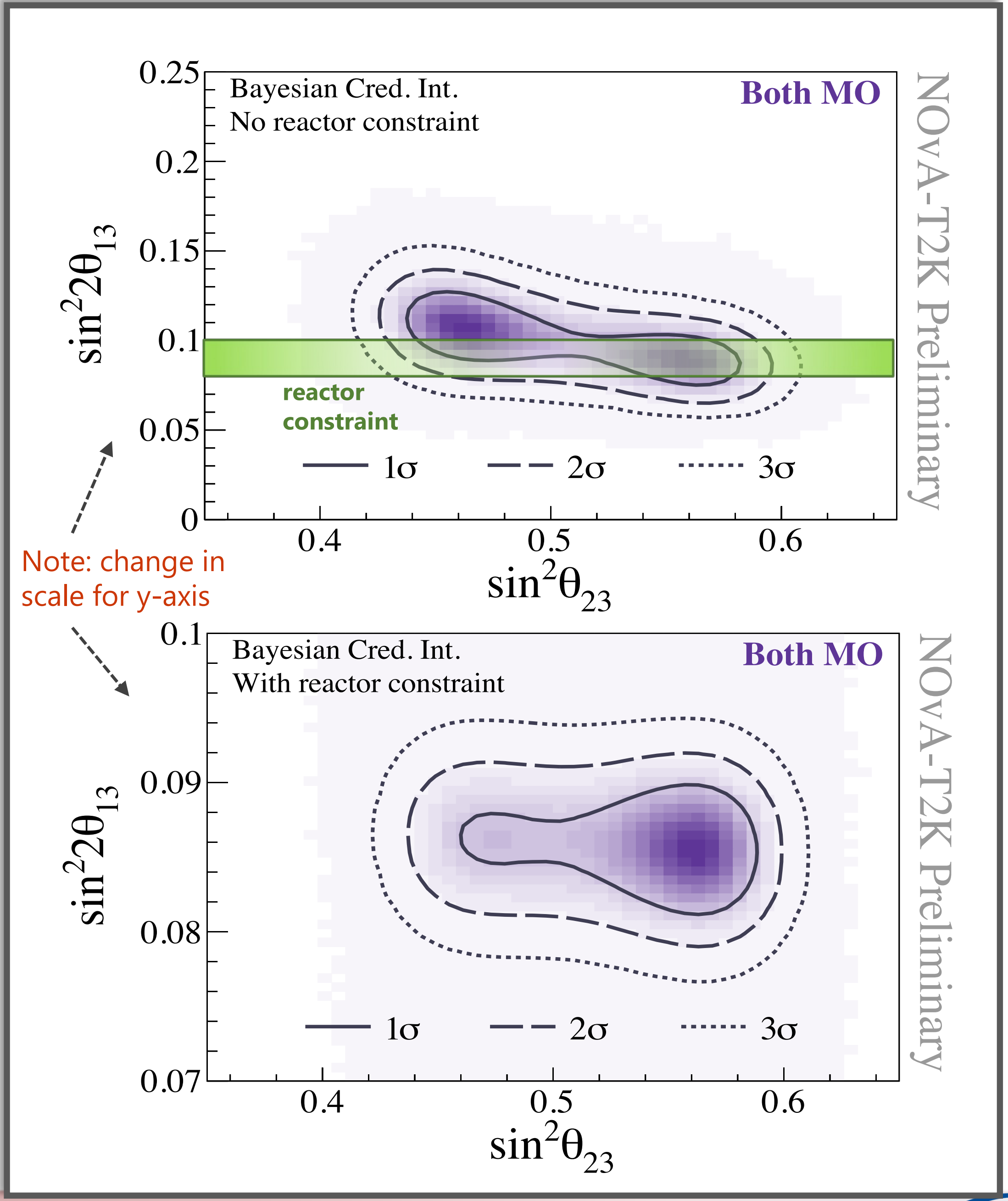
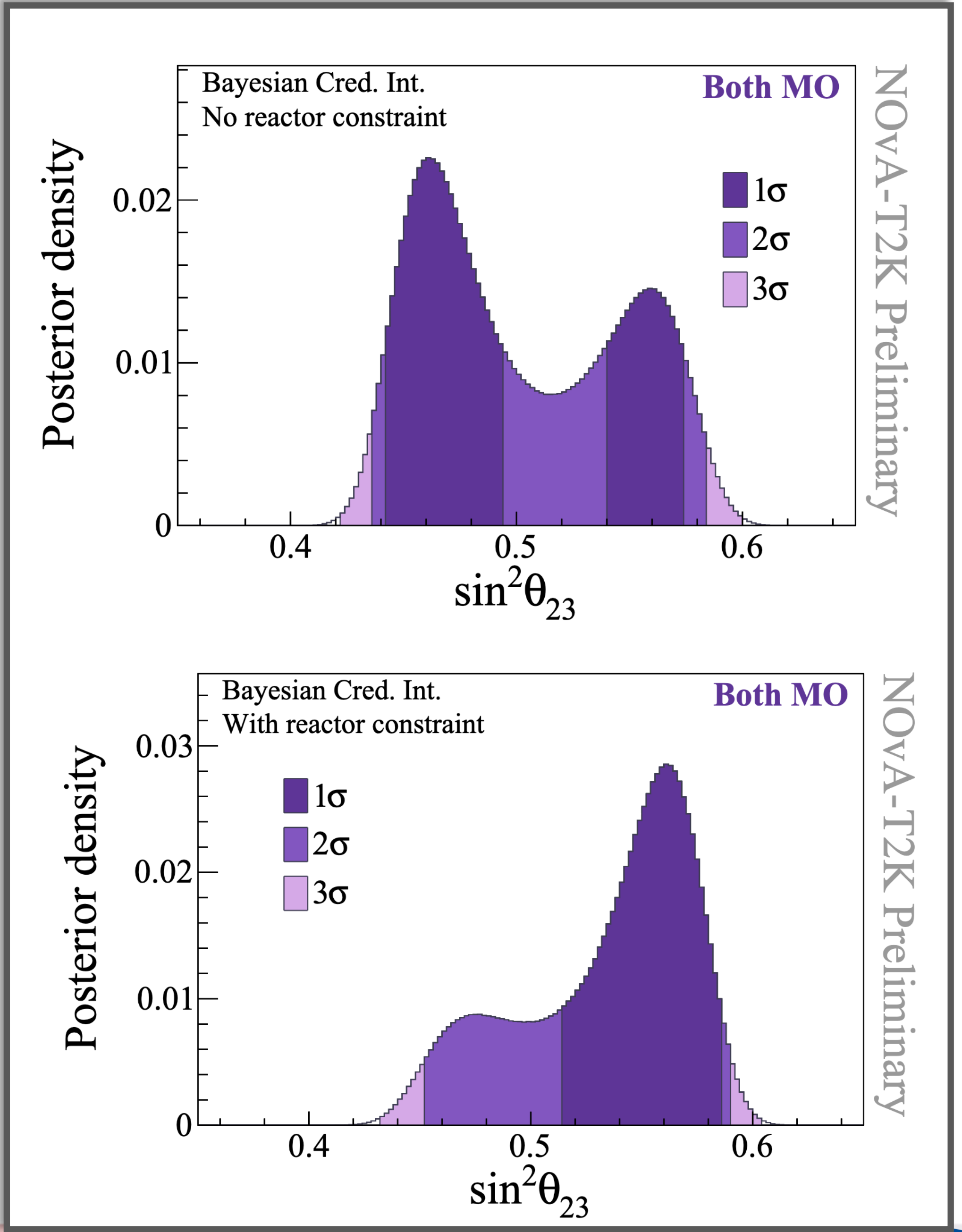
- Using the average constraint on $\sin^2 2\theta_{13} = 0.085 \pm 0.0027$ [PDG 2020], restricts us to a narrow posterior in $\theta_{13}$ and lifts this degeneracy.


Note: change in scale for y-axis

# Mixing angles: $\theta_{23}$ & $\theta_{13}$

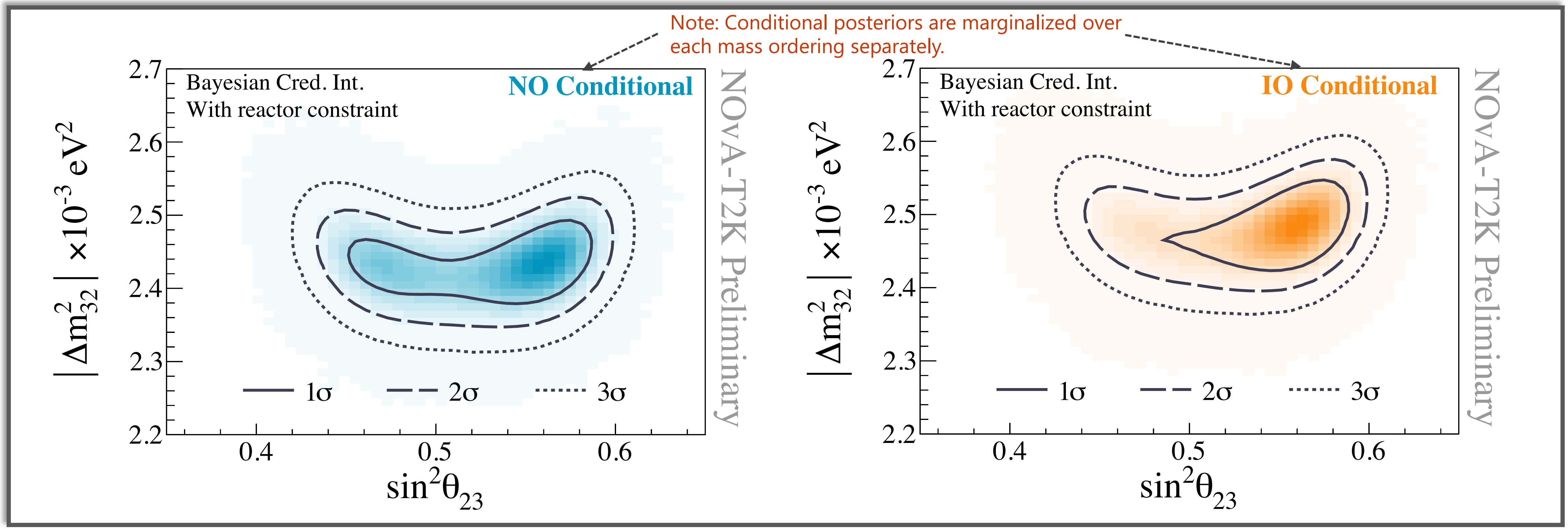
- Modest preference for lower octant from the joint-analysis.
- This preference shifts to a small preference for the upper octant when the reactor constraint on $\theta_{13}$ is applied.

| | NOvA - T2K w/o reactor | NOvA – T2K – w/ reactor |
|---|---|---|
| Bayes factor | **1.17**<br>Lower Octant/Upper Octant<br>~54% : ~46% posterior | **3.59**<br>Upper Octant/Lower Octant<br>~78% : 22% posterior |



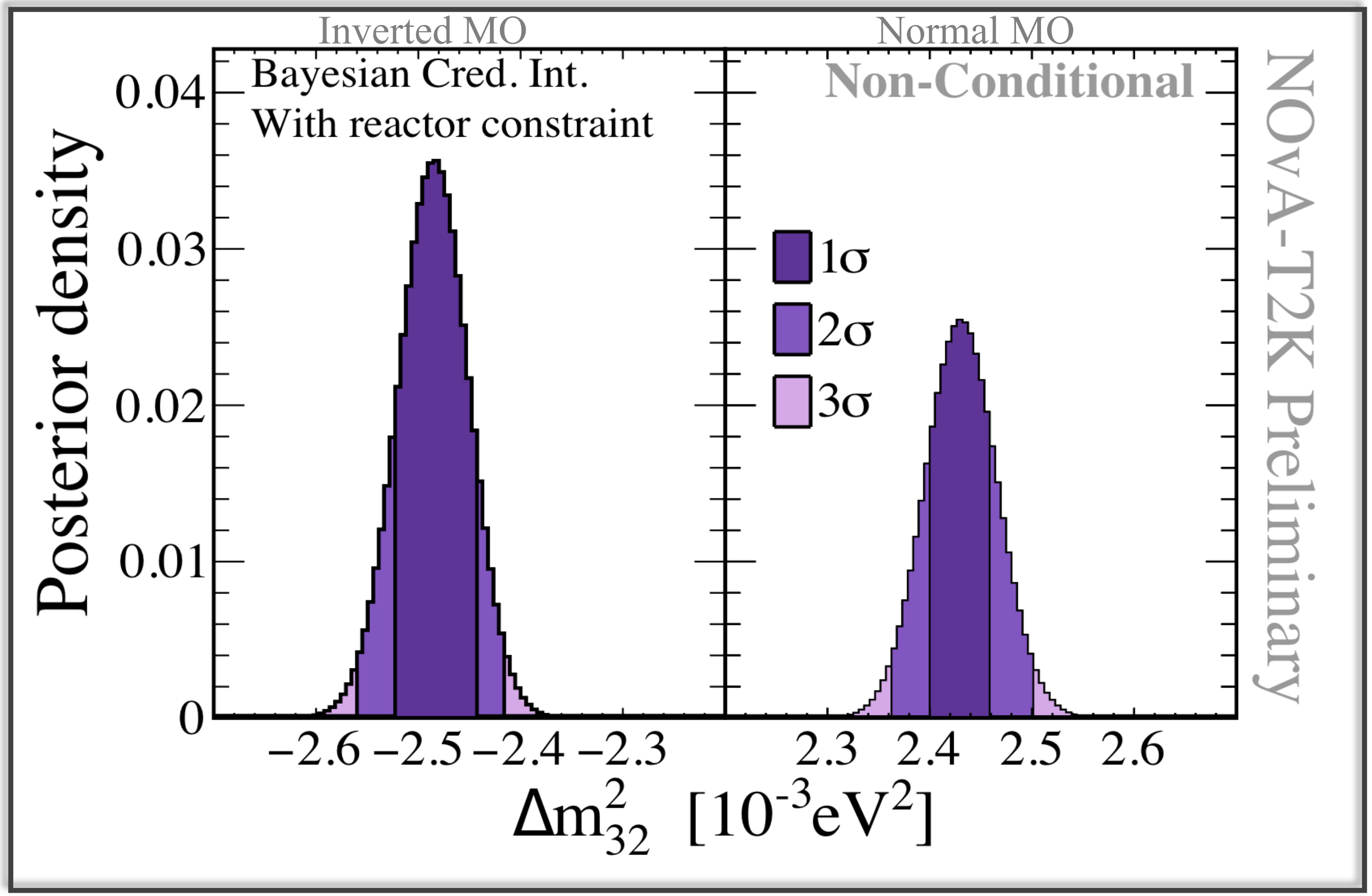
# $\Delta m^2_{32}$ and $\sin^2\theta_{23}$

- Marginalizing over each mass ordering, we note a small but distinct difference in the $\sin^2\theta_{23}$ and $\Delta m^2_{32}$ phase space.
- Measurements remain consistent with the maximal mixing hypothesis for $\theta_{23}$ mixing angle.



Note: Conditional posteriors are marginalized over each mass ordering separately.

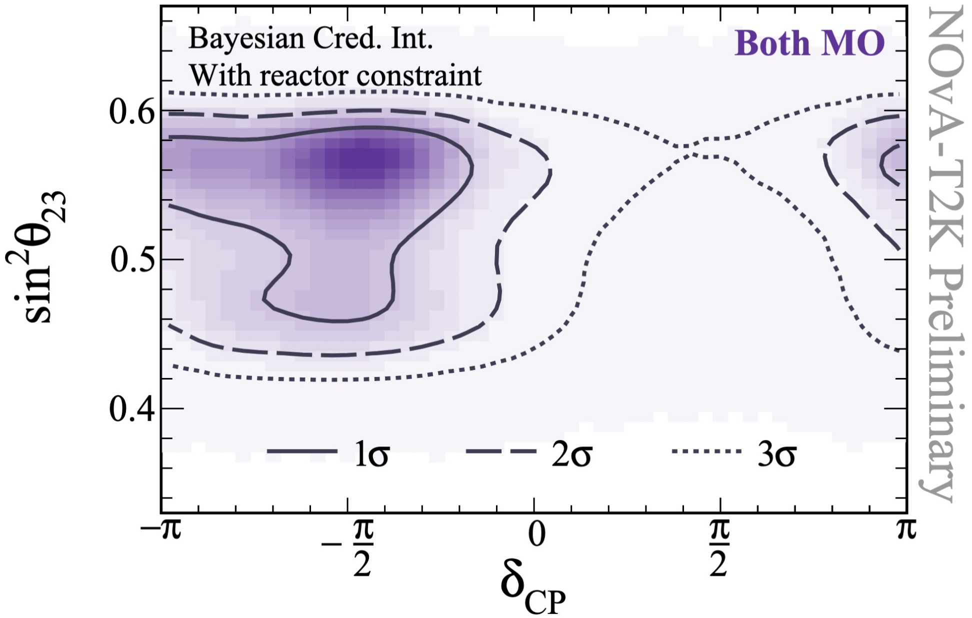
# Mass Ordering

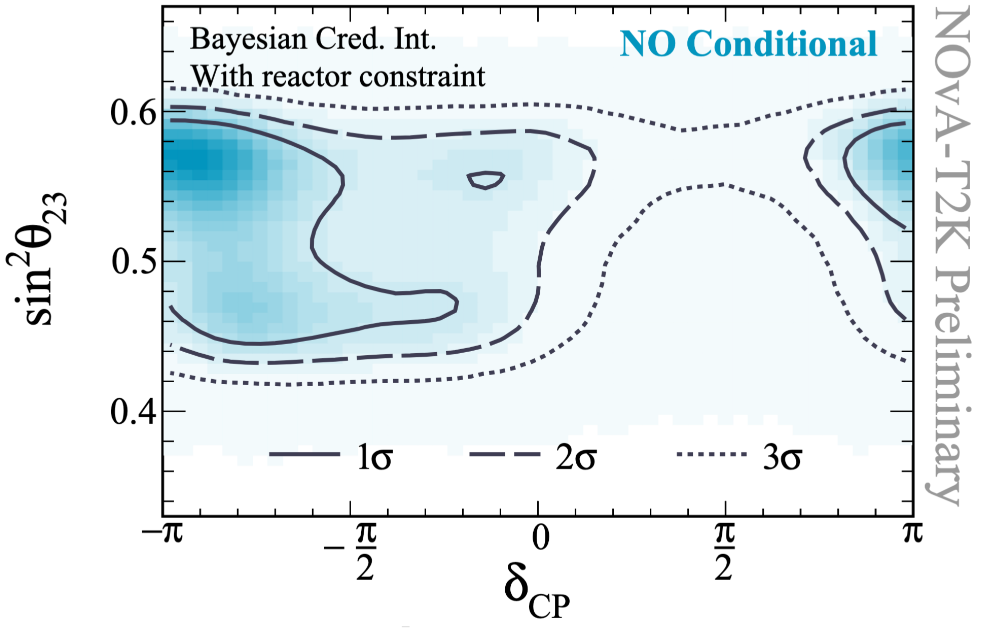


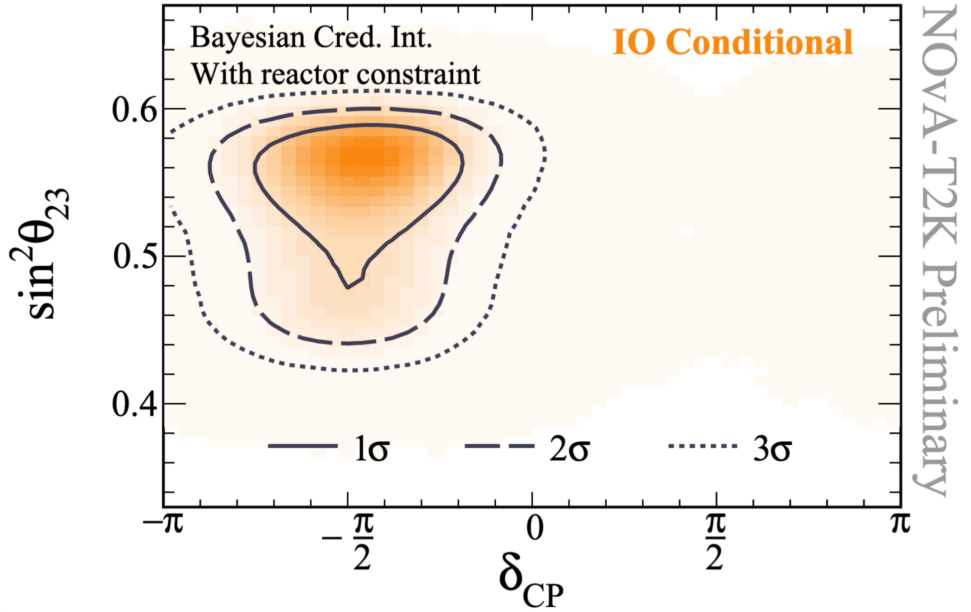
- Comparing the posterior density in each mass ordering, it is evident that the NOvA-T2K joint fit has a **modest preference for the Inverted Ordering.**

| | **NOvA – T2K – w/ reactor** |
|---|---|
| Bayes factor | **1.36**<br>**Inverted Ordering/Normal Ordering**<br>**~58% : ~42% posterior** |

# CP Phase - $\delta_{CP}$



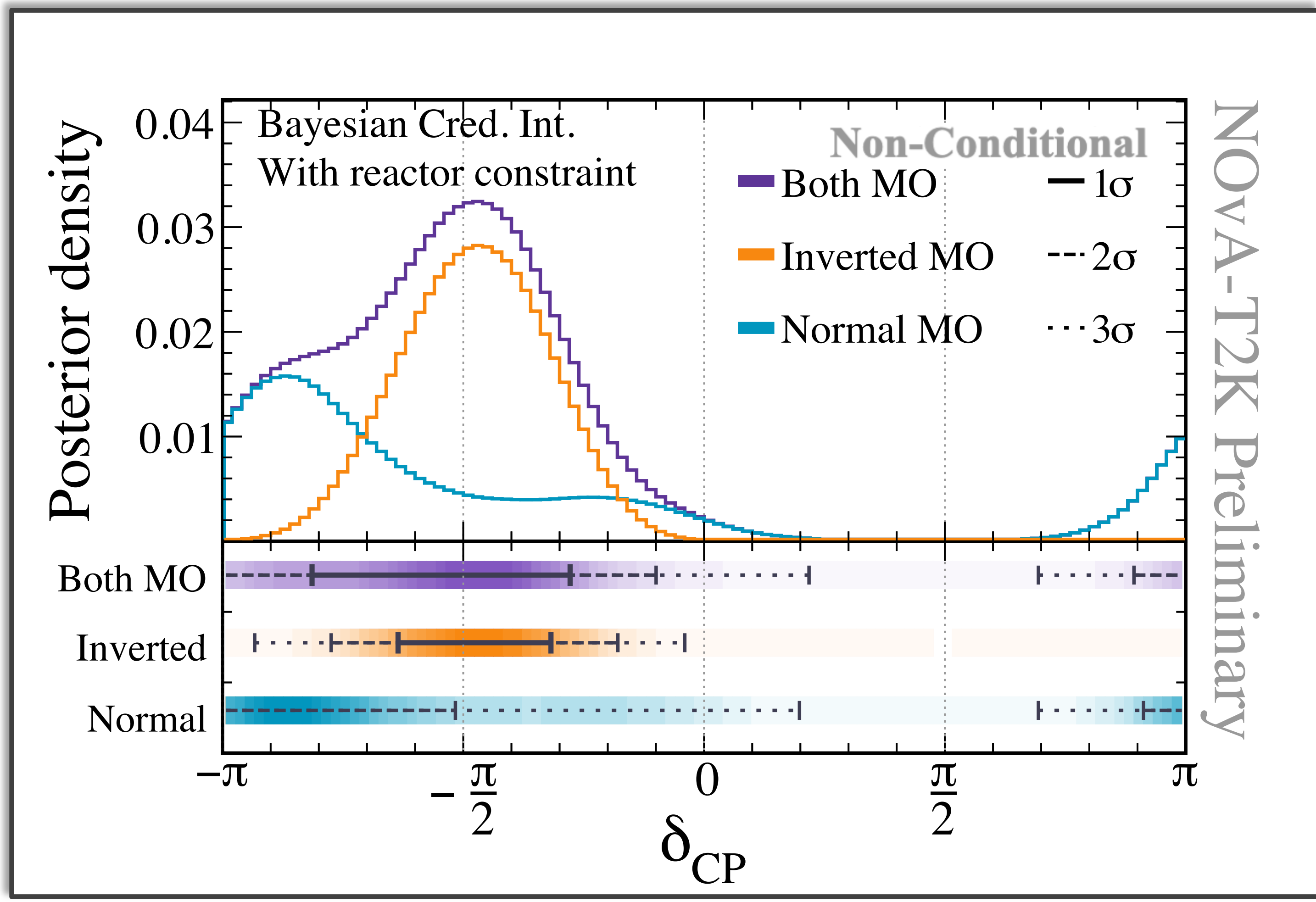




- **Normal MO:** wider range of allowed values with higher posterior density near CP conservation
- **Inverted MO:** enhanced preference for maximum CP violation and a large exclusion of $\delta_{CP}$ phase space.

# CP Violation

- For both mass orderings, $\delta_{CP} = \pi/2$ lies outside 3-sigma credible interval.
- Normal Ordering allows for a broad range of permissible $\delta_{CP}$
- For the Inverted Ordering, CP conserving values of $\delta_{CP}$ (0, $\pi$) lie outside the 3-sigma credible interval.



# CP Violation: Jarlskog

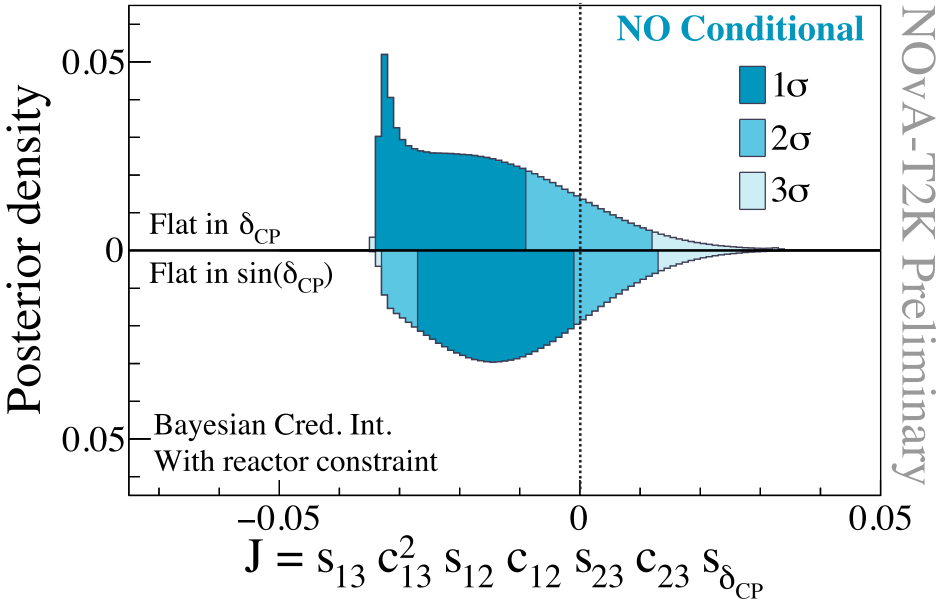
- Jarlskog-invariant is a parameterization independent way* to measure CP violation.

$$\boxed{J = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}}$$

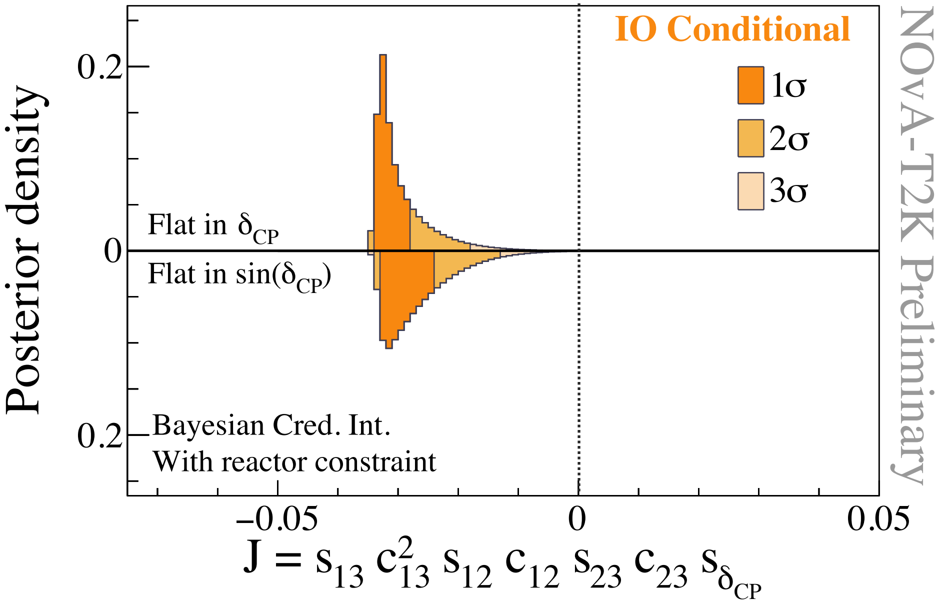
J=0: CP-Conservation J ≠ 0: CP-Violation

- For Normal Ordering, a considerably wider range of probable values for J
- J = 0 lies outside the 3σ interval for the Inverted Ordering
  - for priors that are both uniform in $\delta_{CP}$ and uniform in sin $\delta_{CP}$

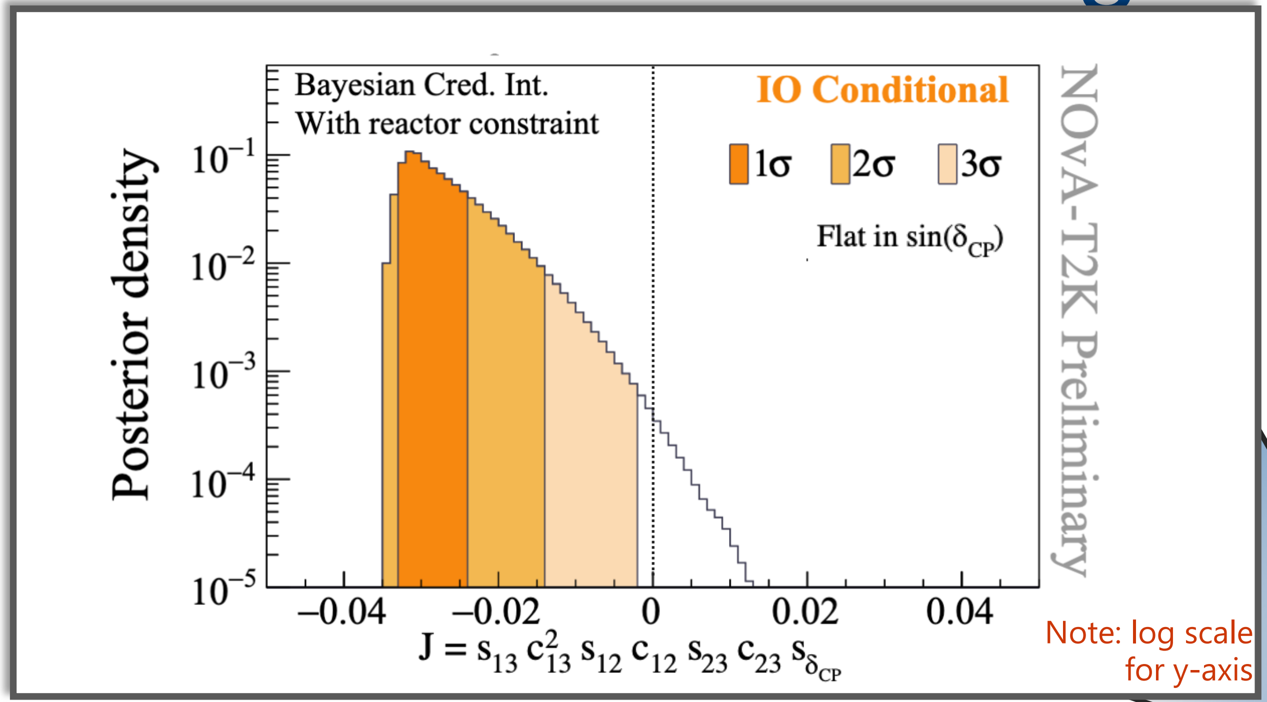
*Phys. Rev. D 100, 053004 (2019)



$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$
$s_{\delta_{CP}} = \sin\delta_{CP}$

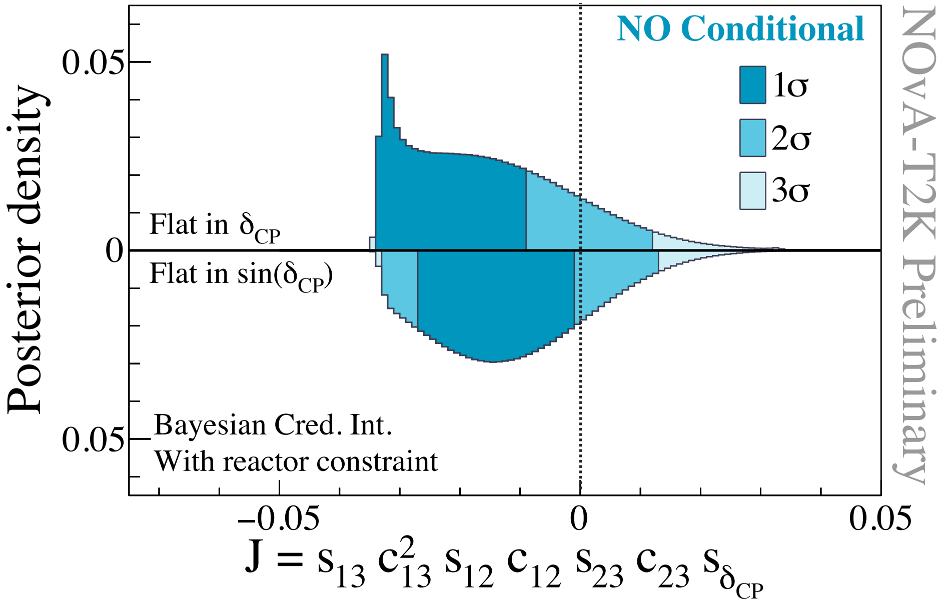


# CP Violation: Jarlskog



Note: log scale for y-axis

- J = 0 lies outside the 3σ interval for the Inverted Ordering
  - for priors that are both uniform in $\delta_{CP}$ and uniform in sin $\delta_{CP}$



$c_{ij} = \cos\theta_{ij}$
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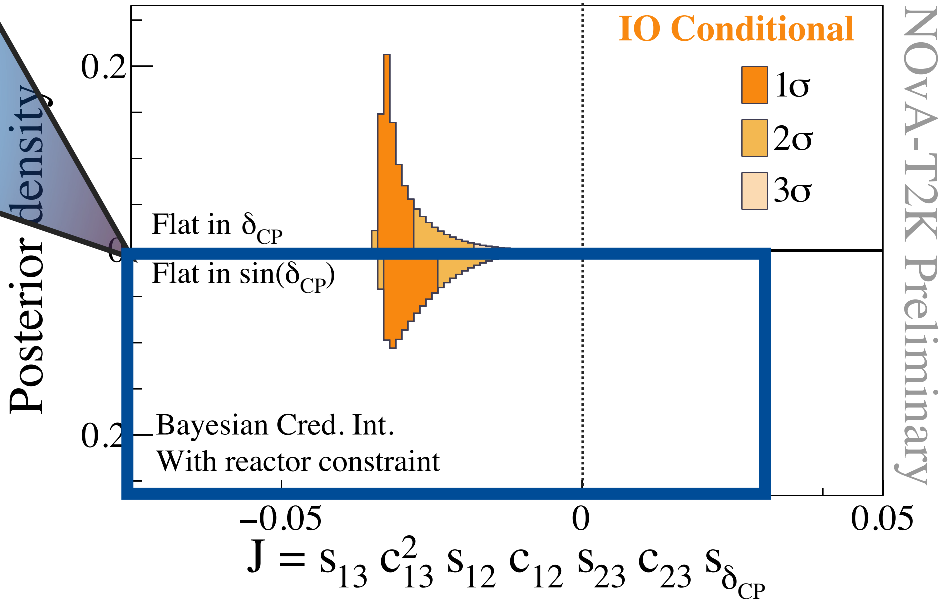
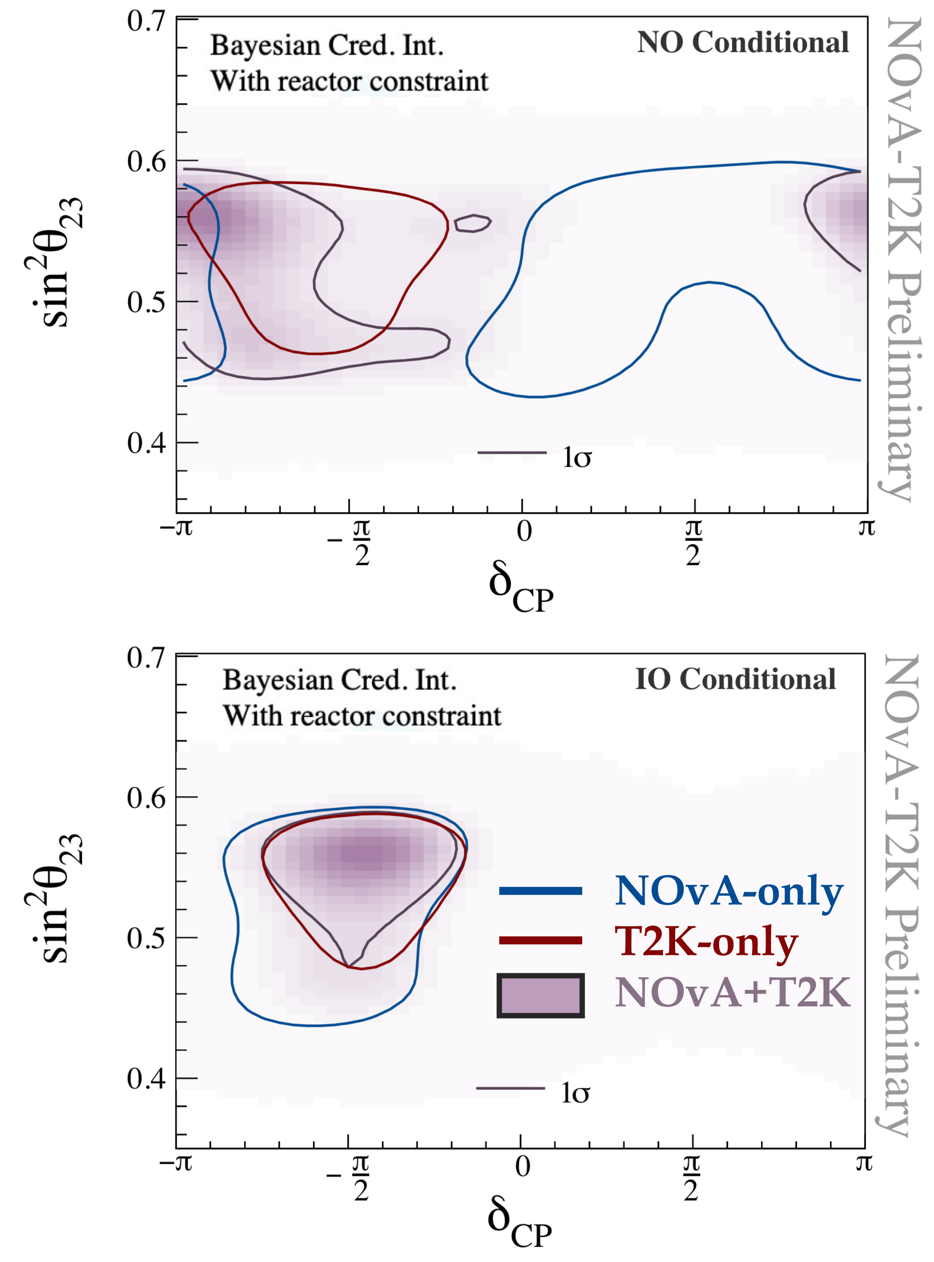


*Phys. Rev. D 100, 053004 (2019)

# Comparisons

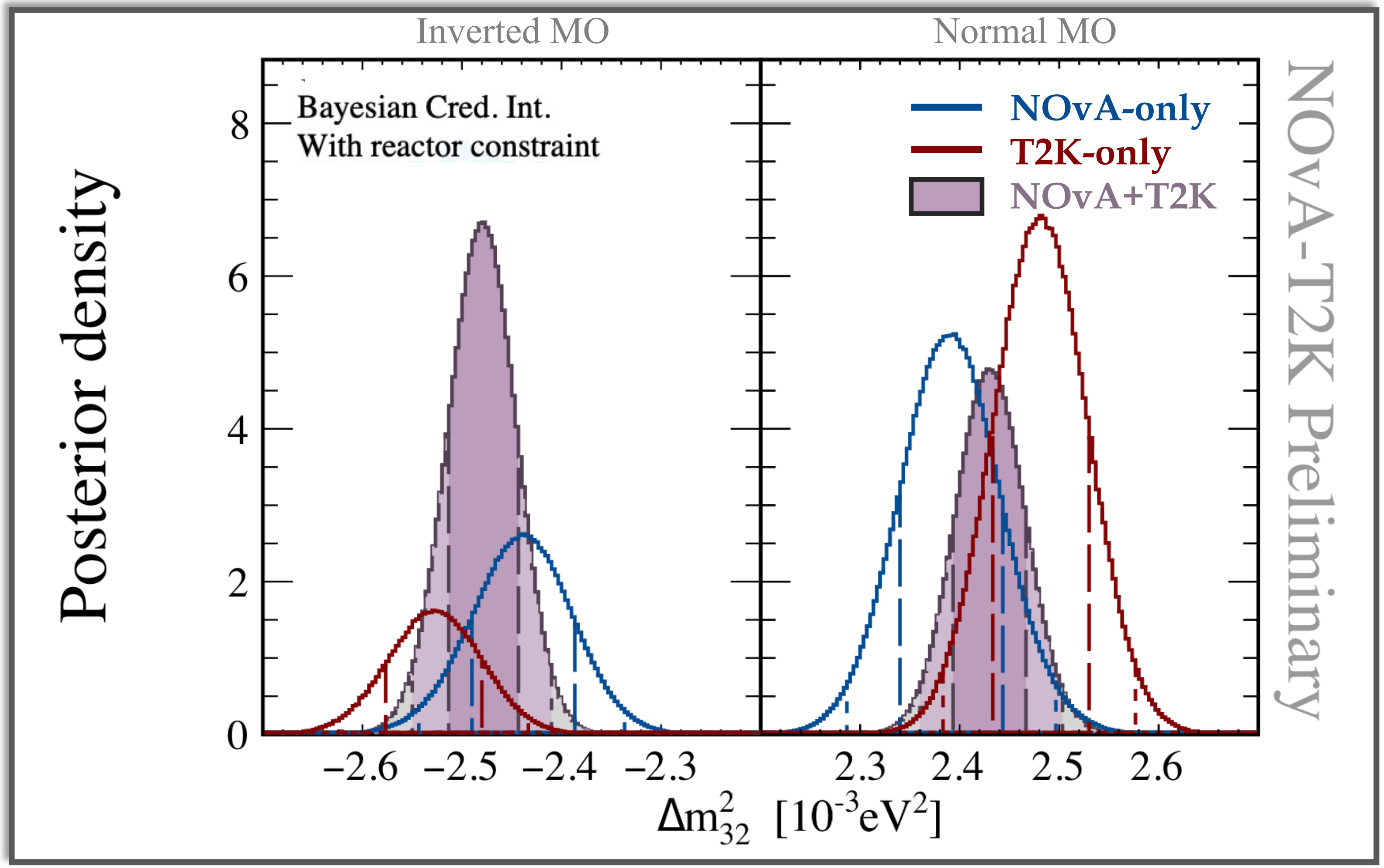
# Comparison with NOvA-only & T2K-only fits

- The joint-fit **splits the difference in the Normal Ordering** where the individual experiments preferred differing phase-spaces and provides **tighter constraint in the Inverted Ordering** where there was good agreement between NOvA-only and T2K-only fits.



# Comparison with NOvA-only & T2K-only fits

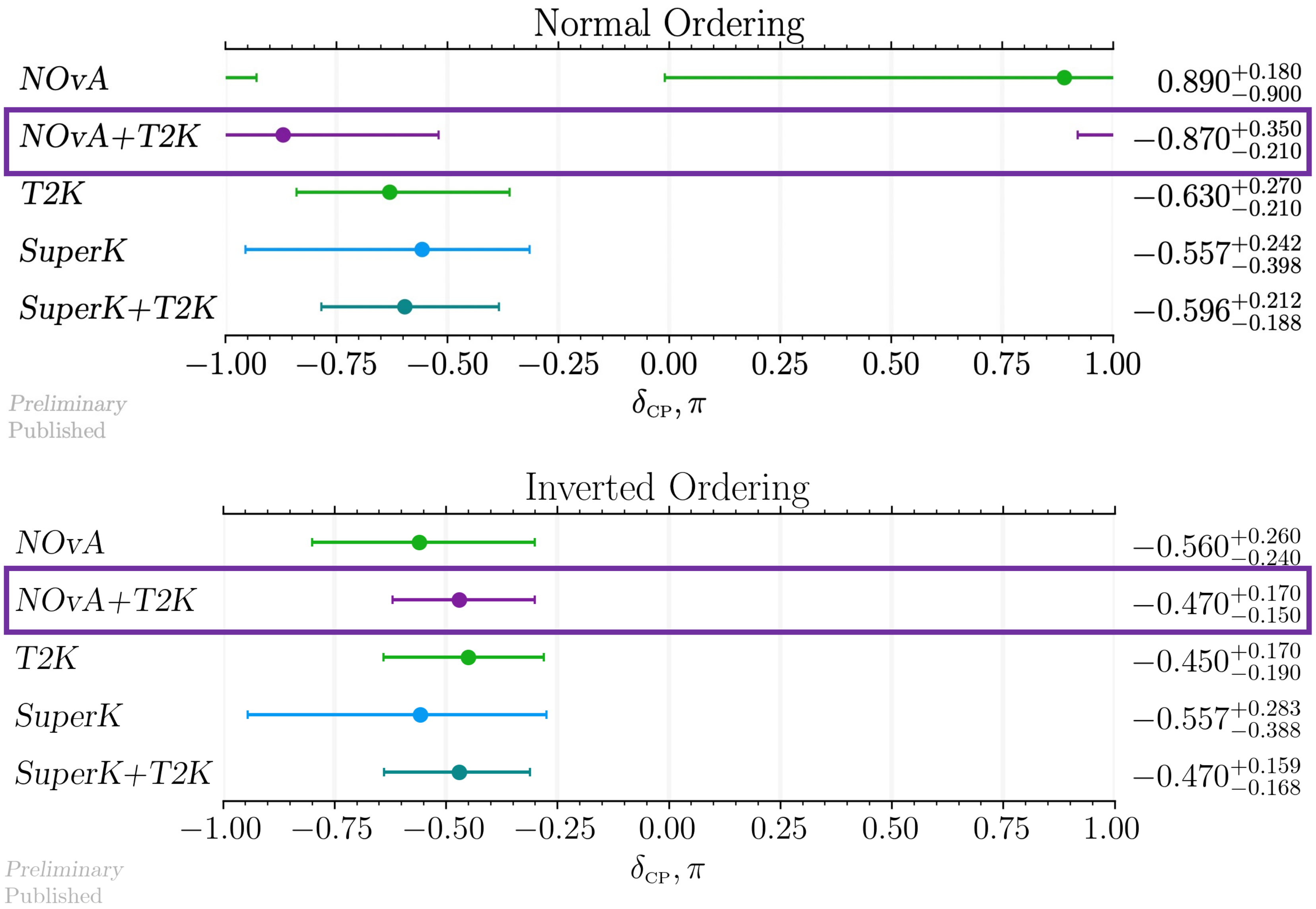
- The 1D posterior in $\Delta m^2_{32}$ highlights the switch in the mass ordering preference when NOvA and T2K are combined.
- The joint-fit enhances the precision of $\Delta m^2_{32}$ over individual experiments.



| | NOvA only | T2K only | NOvA+T2K |
|---|---|---|---|
| Bayes factor | 2.07<br>Normal/Inverted<br>~67% : ~33% posterior | 4.24<br>Normal/Inverted<br>~81% : ~19% posterior | 1.36<br>Inverted/Normal<br>~58% : ~42% posterior |

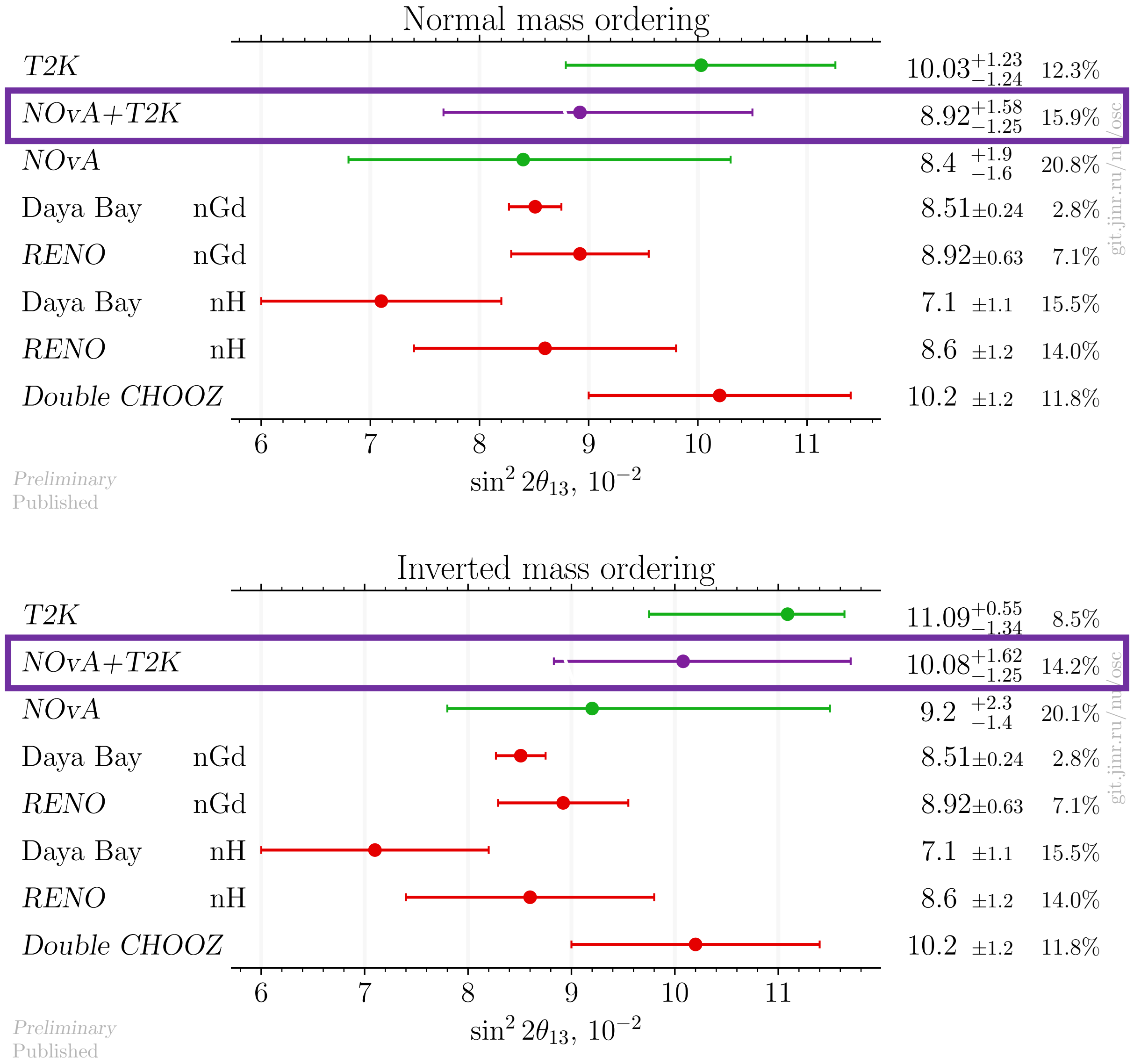
# Global Comparisons - $\delta_{CP}$

- The $\delta_{CP}$ measurements are consistent across all experiments and their combinations.
- The uncertainty on $\delta_{CP}$ remains large.



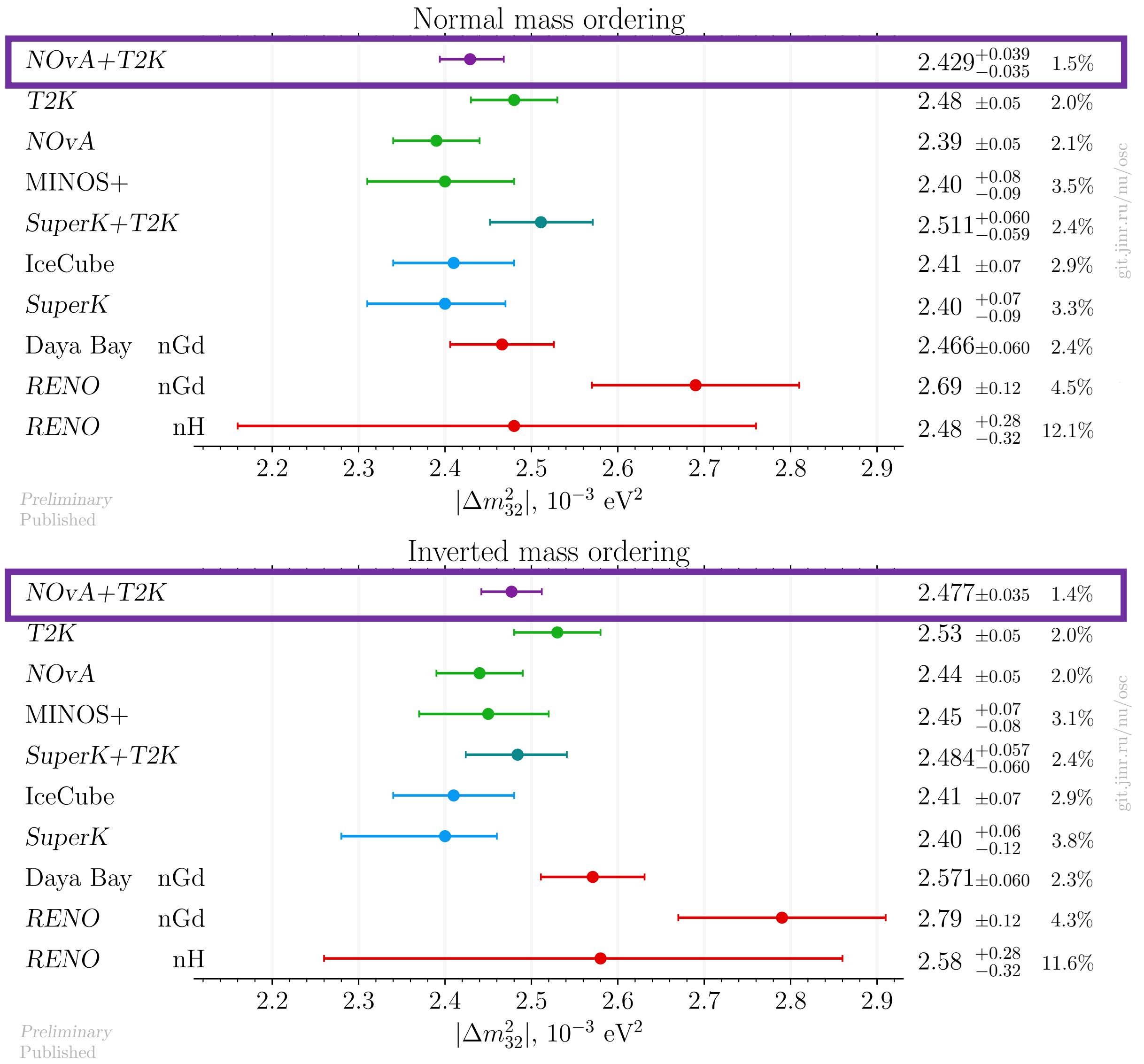
# Global Comparisons – $\theta_{13}$

- Daya Bay leads the precision on the measurement of $\theta_{13}$ with 2.8% uncertainty.
- Overall, the long-baseline measurements are consistent with reactor experiments, with larger consistency in the normal ordering than the inverted ordering.



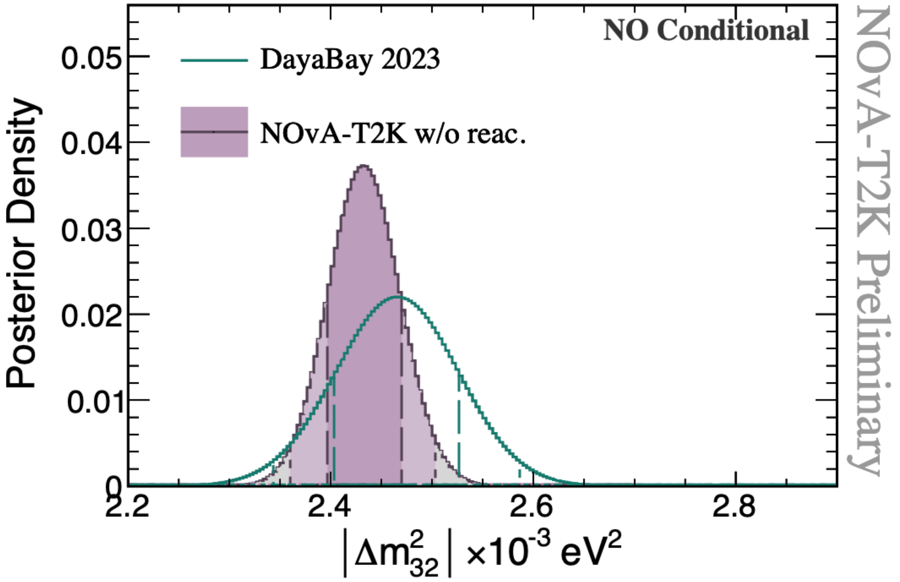
# Global Comparisons - $\Delta m^2_{32}$

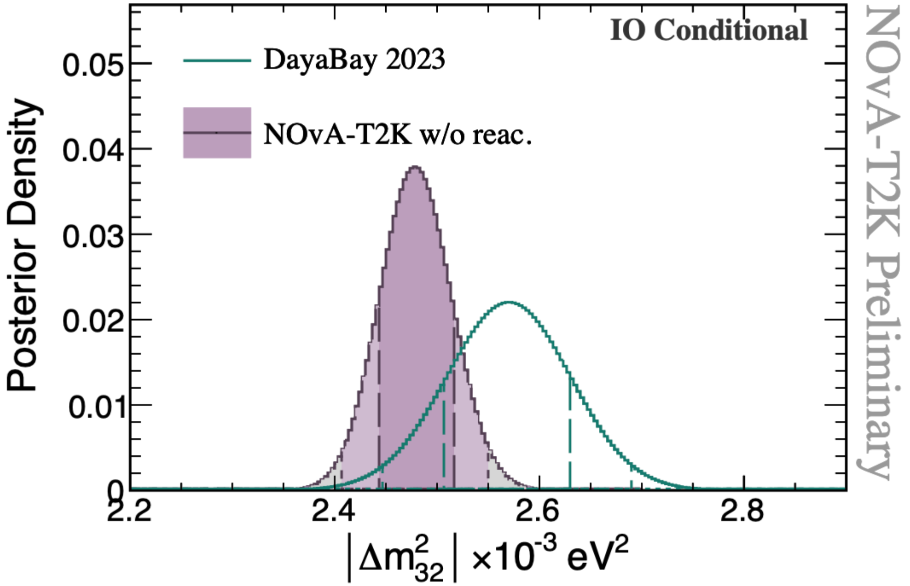
- This analysis has the **smallest uncertainty on $|\Delta m^2_{32}|$** as compared to other previous measurements.



# NOvA+T2K+Daya Bay

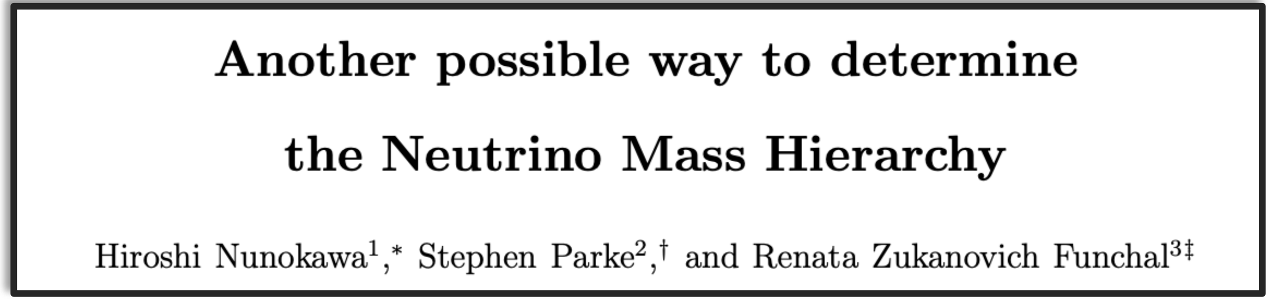
- Enhanced precision in $\Delta m^2_{32}$ presents a “new” lever on measuring neutrino mass-ordering*.
- In the true mass ordering, reactor and long-baseline measurements of $\Delta m^2_{32}$ would be consistent but in the incorrect mass ordering would be wrong by different amounts.





Also see: Stephen Parke W&C, 2023

*Phys. Rev. D 72: 013009, 2005

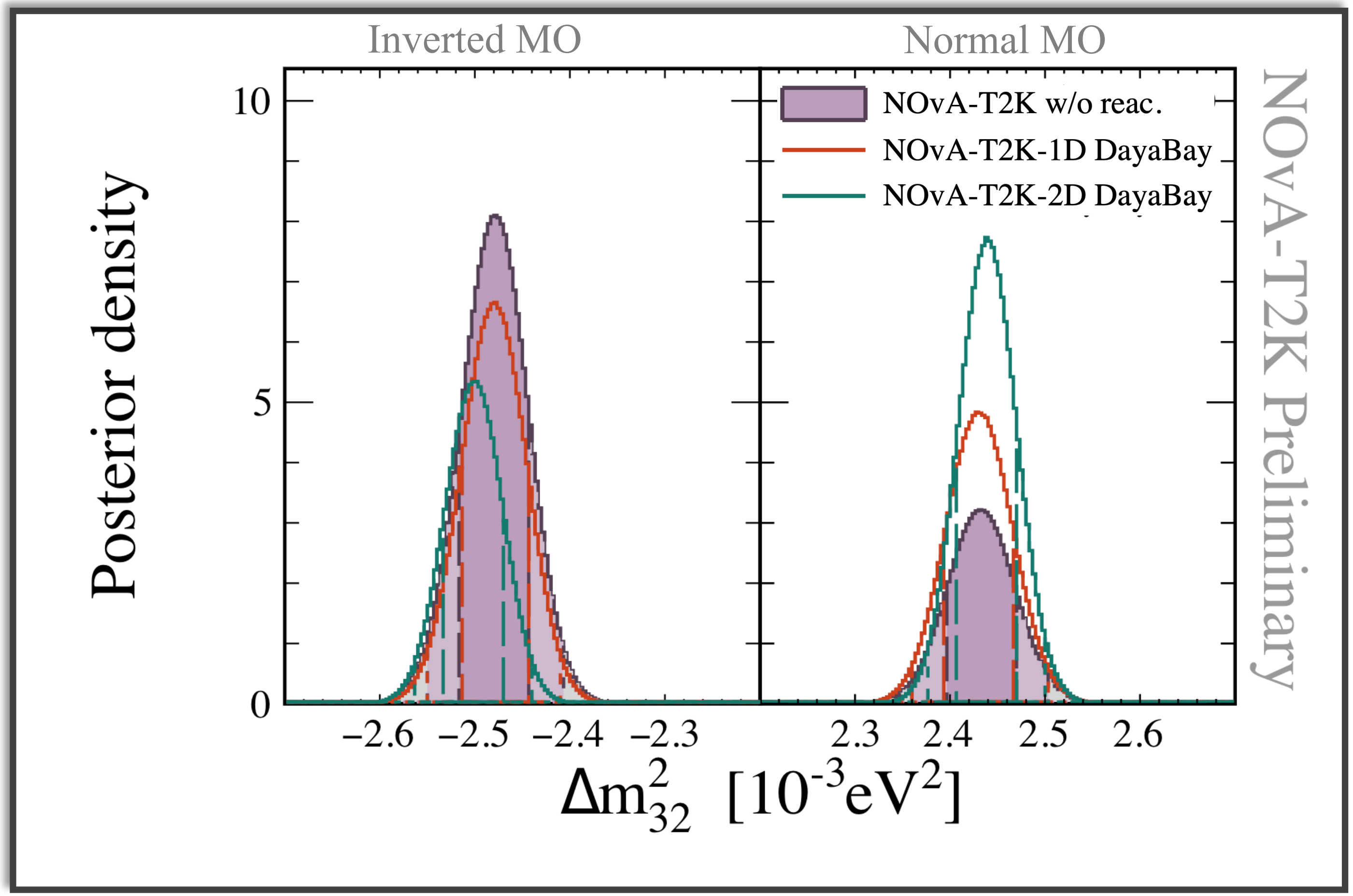


**Another possible way to determine the Neutrino Mass Hierarchy**

Hiroshi Nunokawa[1],* Stephen Parke[2],† and Renata Zukanovich Funchal[3]‡

# NOvA+T2K+DayaBay

- Including the $\Delta m^2_{32}$ constraint from the Daya Bay*, reverse the mass ordering preference back to the Normal Ordering.
- Overall, this analysis does not show a significant preference for either mass ordering.



*Phys. Rev. Lett. **130**, 161802, 2023

| | NOvA - T2K w/o reactor | NOvA – T2K – 1D Daya Bay | NOvA - T2K - 2D Daya Bay |
|---|---|---|---|
| Bayes factor | 2.47<br>Inverted/Normal<br>~71% : ~29% posterior | 1.34<br>Inverted/Normal<br>~57% : ~43% posterior | 1.44<br>Normal/Inverted<br>~59% : ~41% posterior |

# Summary & Outlook

# Summary

- The joint analysis of NOvA and T2K demonstrates **simultaneous compatibility** with both datasets.
- The constraint on $\theta_{13}$ from reactor experiments resolves the degeneracy in the measurement of $\theta_{23}$ and $\theta_{13}$, shifting the octant preference from lower to upper.
- The joint analysis shows:
    - Very **strong constraint on $|\Delta m^2_{32}|$.**
    - Mass Ordering preference remains inconclusive.
        - **Small preference for the Inverted Ordering** in the joint fit whereas individual experiments prefer Normal Ordering.
        - Reverts to a weak preference for Normal ordering on adding simultaneous constraint on $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{13}$ from Daya Bay.
    - **$\delta_{CP} = \pi/2$ lies outside 3-sigma credible interval** for both mass ordering.
    - Normal ordering permits a wide range of permissible $\delta_{CP}$ ,while **CP conserving values for the Inverted Ordering fall outside the 3-sigma range.**
        - Similar conclusions for Jarlskog.

# Outlook

- Both experiments continue to collect high quality data and improve their analyses -
  - Data collected by both experiments is **expected to double** before the end of their operational lifetimes.
  - Updated interaction models, detector response, and new data samples to better constraint systematic uncertainties are being incorporated for both experiments.
- This has been a productive process -
  - Active collaboration and knowledge sharing between the experiments.
  - Mutual exchange of information has resulted in a deeper understanding of the analyses conducted by both groups.
- We are actively exploring the scope and timeline for the next steps to take this work forward!