Joint Analysis Results from the NOvA & T2K Experiments

CoSSURF 2024 – Rapid City

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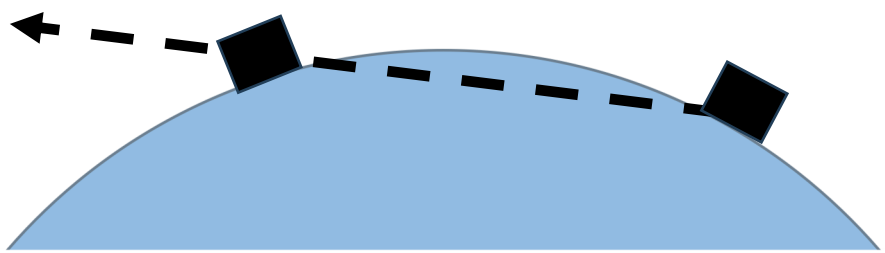
Long-Baseline Accelerator Neutrino Experiments

General Theme

Produce a beam of muon neutrinos and antineutrinos

- Alternate between beam modes



Shoot the beam through the Earth

Measure Disappearance and Appearance Modes of Oscillation

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

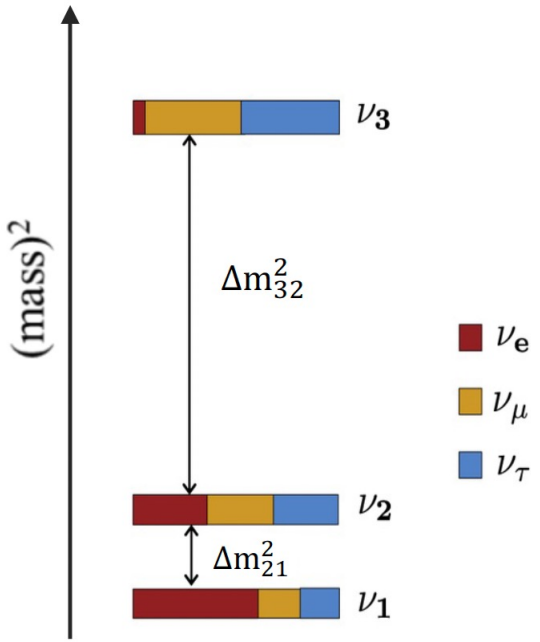
Near and Far Detectors

- Near Detector(s)
  - Measure beam before standard oscillation
- Far Detector(s)
  - Measure the oscillated beam

Long-Baseline Accelerator Neutrino Experiments

Physics Sensitivity

Oscillations governed by Δm^2_{32} (Δm^2_{31})



Long-Baseline Accelerator Neutrino Experiments

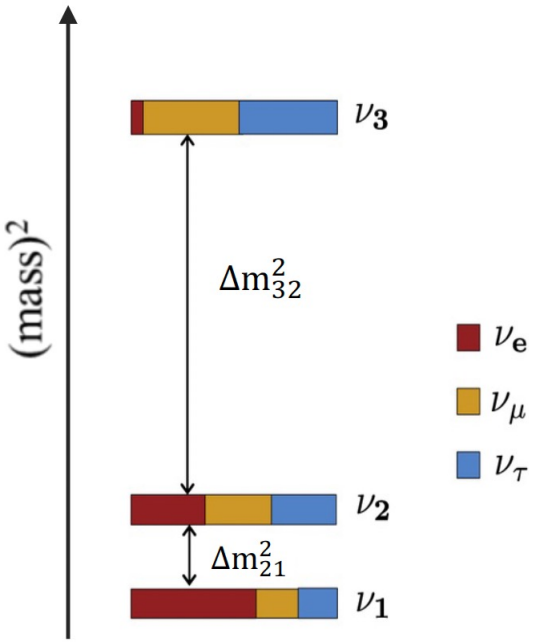
Physics Sensitivity

Oscillations governed by Δm^2_{32} (Δm^2_{31})

Disappearance Mode Sensitivity

$|\Delta m^2_{31}|$ Mass-Squared Splitting

$\sin^2(2\theta_{23})$: Maximal Mixing



Long-Baseline Accelerator Neutrino Experiments

Physics Sensitivity

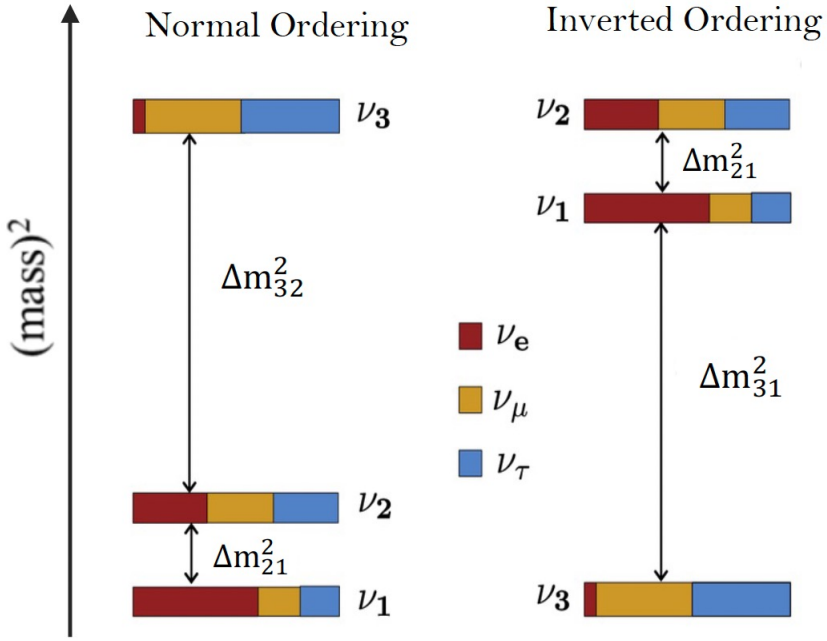
Oscillations governed by Δm^2_{32} (Δm^2_{31})

Disappearance Mode Sensitivity

$\lvert\Delta m^2_{31}\rvert$	Mass-Squared Splitting
$\sin^2(2\theta_{23})$:	Maximal Mixing

Appearance Mode Sensitivity

Sign of Δm^2_{31}	Mass Ordering
$\theta_{23} > 45^o$ or $\theta_{23} < 45^o$	Octant of θ_{23}
δ_{CP}	CP-Violation ($\delta_{CP} \neq n\pi$)



Long-Baseline Accelerator Neutrino Experiments

Physics Sensitivity: Matter-Antimatter Differences

CP-Violation

δ_{CP} has opposite impact on appearance probability for neutrinos and antineutrinos

Enhancement or Reduction

Mass Ordering

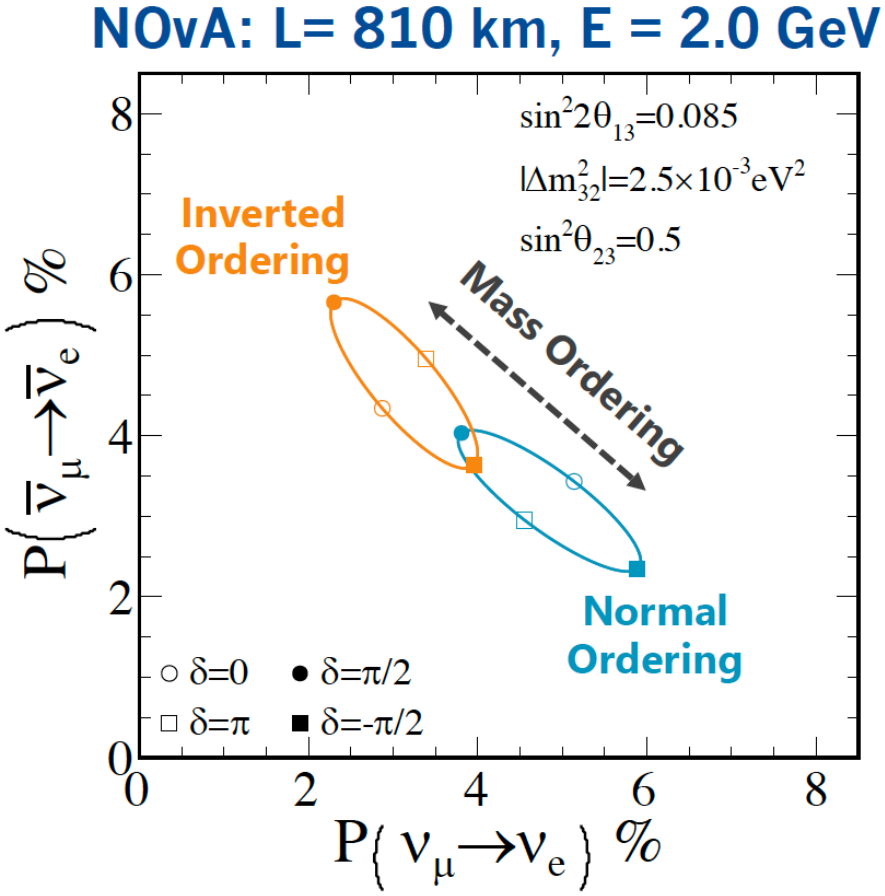
Matter Effect has impact on on appearance probability

Enhancement or **Reduction** depends on **Ordering**

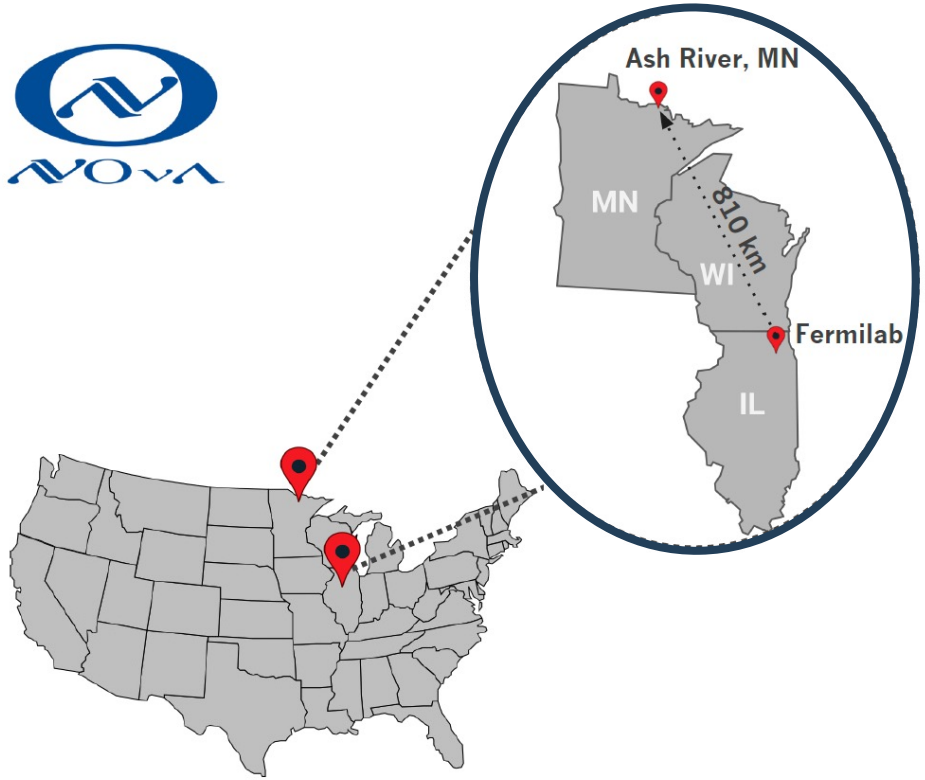
Source of degeneracy

Matter Effect has opposite impact on appearance probability for neutrinos and antineutrinos

Enhance or Reduction



NOvA + T2K – Complementary Baselines



T2K Beamline

E ≈ 0.6 GeV (off-axis narrow band beam)

L = 295 km

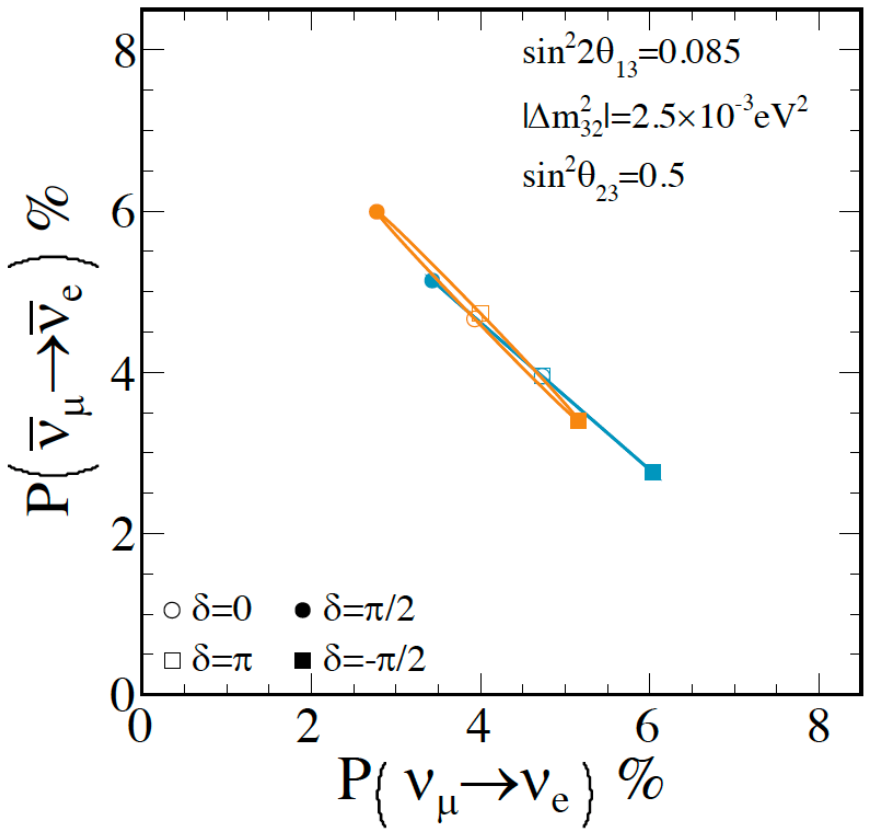
NOvA Beamline

E ≈ 1.9 GeV (off-axis narrow band beam)

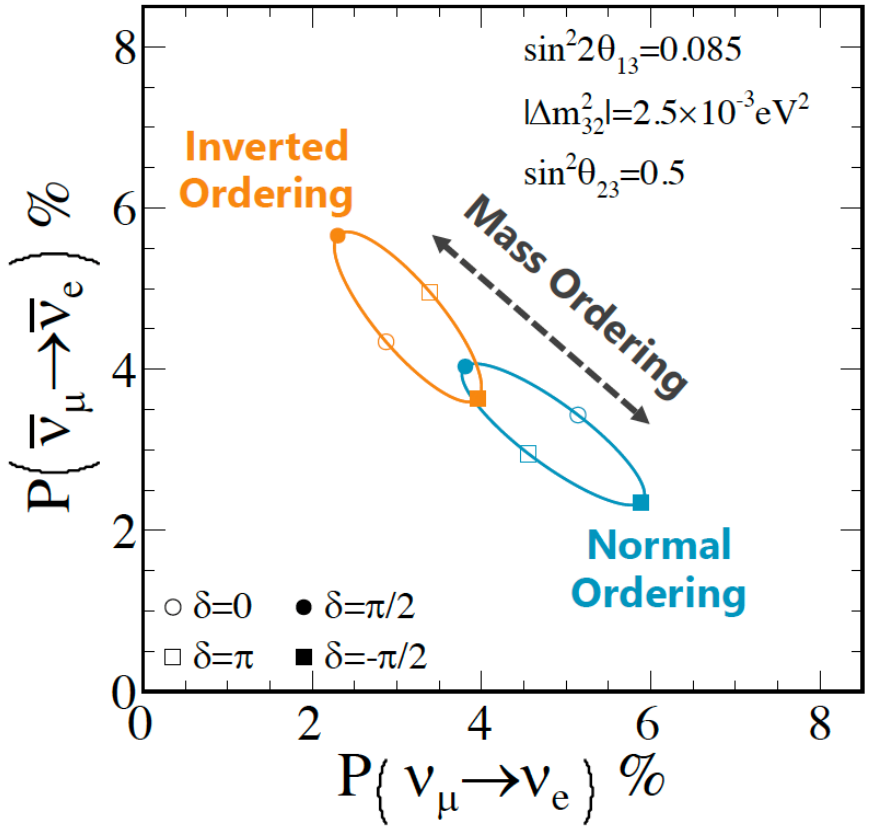
L = 810 km

NOvA + T2K – Complementary Parameter Spaces

T2K: L = 295km, E = 0.6GeV



NOvA: L= 810 km, E = 2.0 GeV



Impact on Appearance Probability
at peak energy

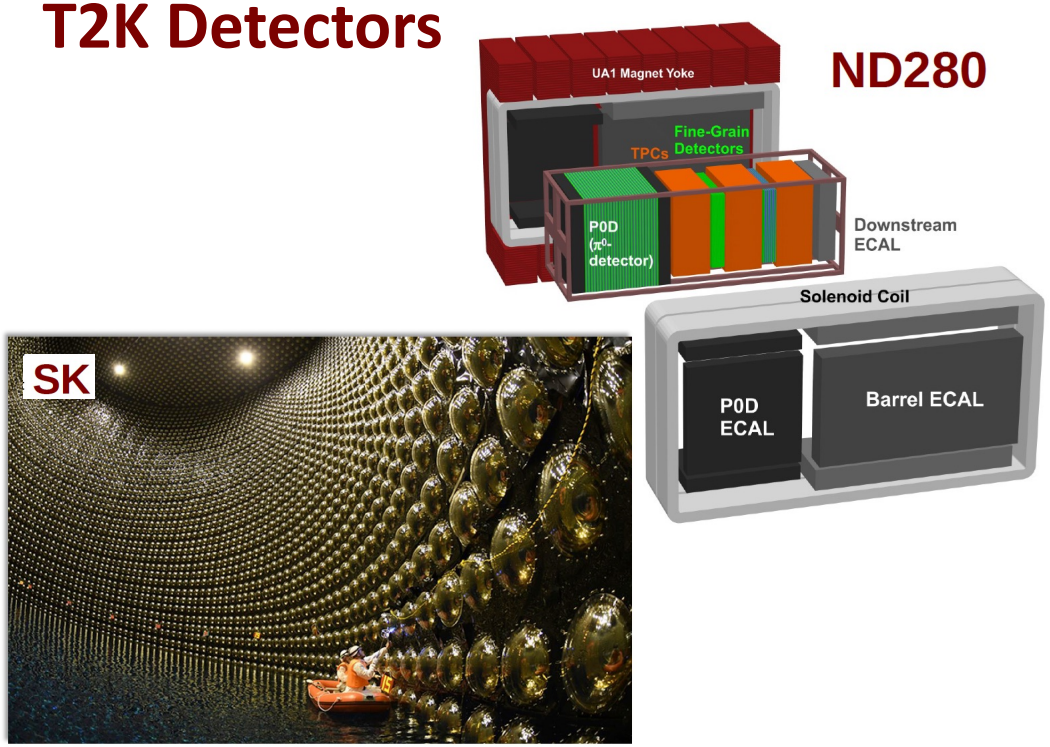
CP Violation	±30%
Matter Effect	±9%

Impact on Appearance Probability
at peak energy

CP Violation	±25%
Matter Effect	±19%

NOvA + T2K – Complementary Detectors

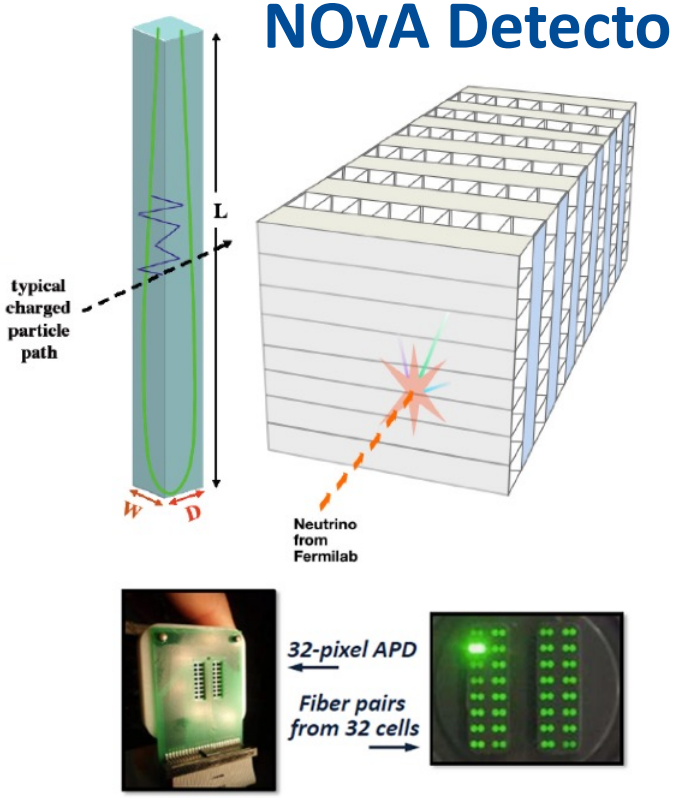
T2K Detectors



Near Detector: Magnetized Particle Tracking w/ Plastic Scintillator

Far Detector: Water Cherenkov

NOvA Detectors



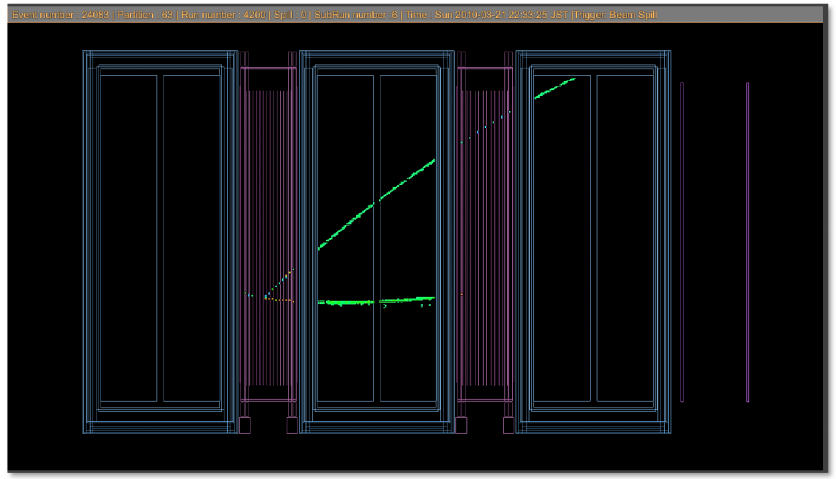
Far and Near Detectors

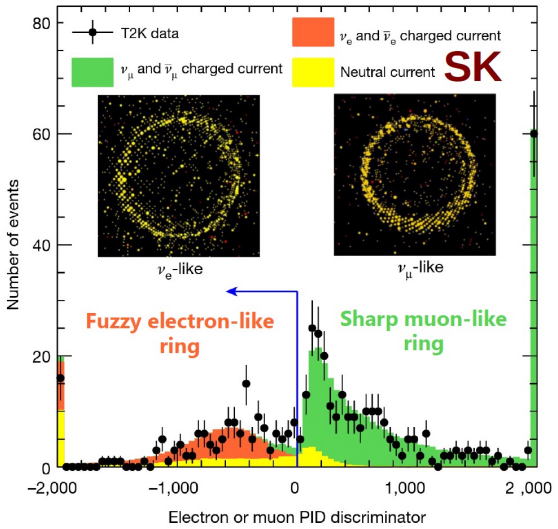
Functionally Identical
Liquid Scintillator
Tracking Calorimeters

NOvA + T2K – Event Topologies

T2K Detectors

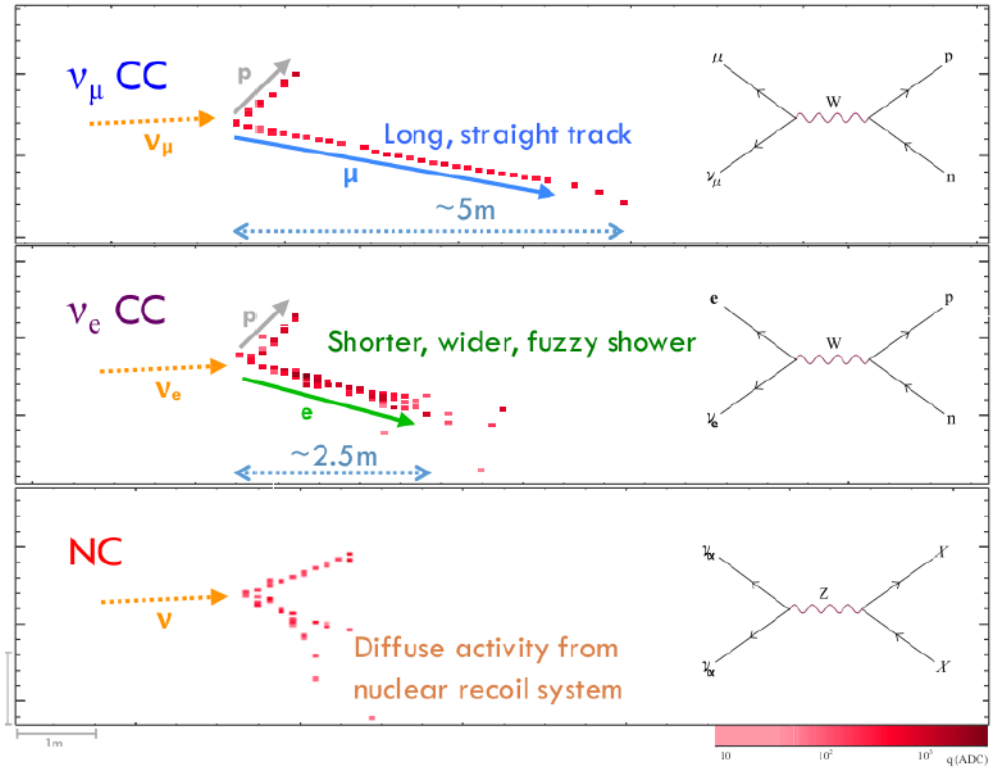
ND280





Focus of Lepton Kinematics
Exclusive 1 lepton + n π channels

NOvA Detectors



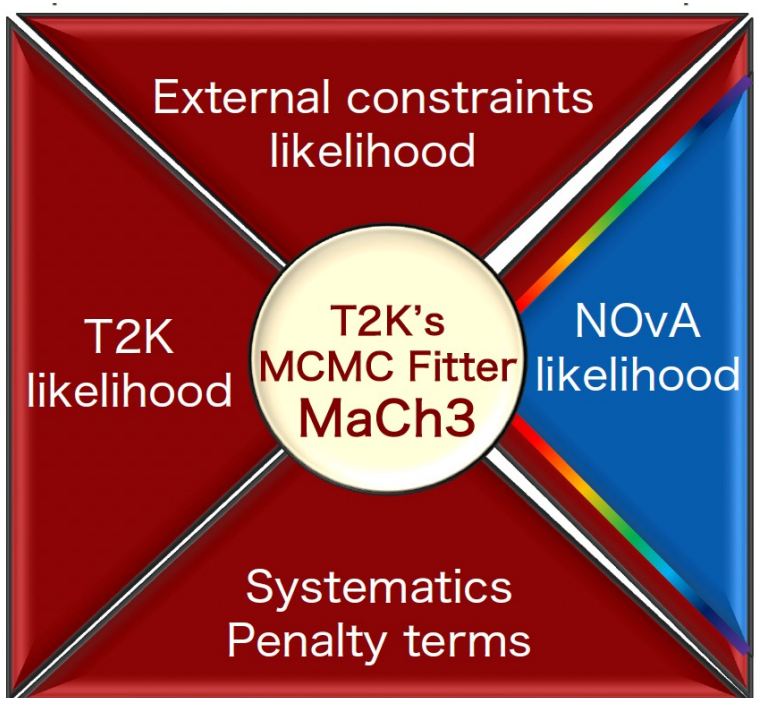
Lepton and Hadronic Energy Reconstruction
Inclusive Channel

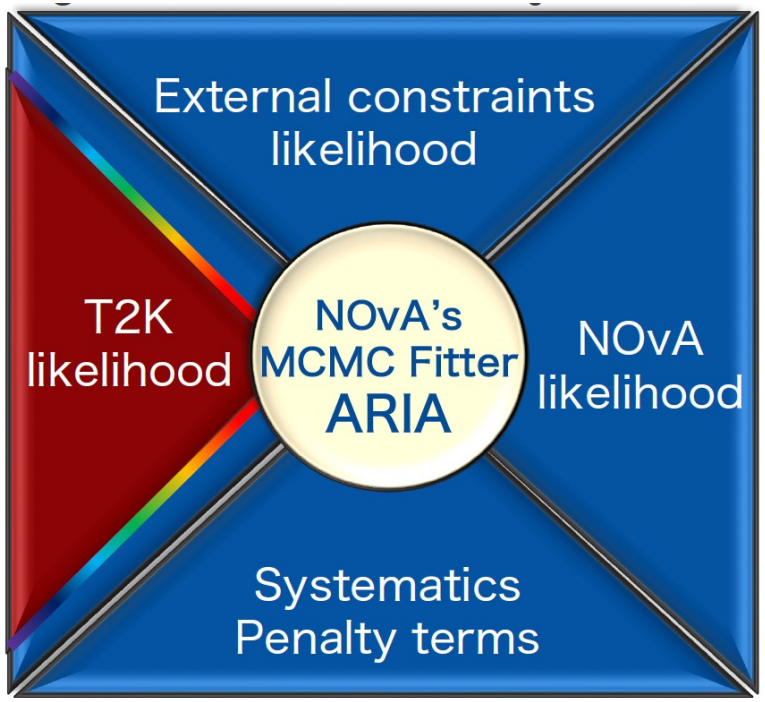
Joint Fit – Machinery

Bayesian Analysis

Use Penalty terms for systematics pulls

Use external constraints on θ_{13}, θ_{12}, Δm^2_{21}





Use Poisson likelihood from each experiment

Joint Fit -Correlations

Both experiments are statistics limited and systematic correlation is currently not significant to results

- Flux Modeling
  - Different beam energies and external data sources (not significant source of correlation)
- Detector Modeling
  - Different detector designs
    - Selection Criteria and Energy Reconstruction
- Neutrino-Nucleus Interaction Modeling correlations
  - Different beam energies with different primary interaction modes
  - Stats-limited correlations not as significant on results
  - Different generators (NEUT vs GENIE)
    - Less straightforward to implement correlation
    - Uncertainty on ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$ cross section ratio implemented

Joint Fit -Results

Use Published Data Results from 2020

T2K: *Eur. Phys. J. C (2023) 83:782 (2023)*

NOvA: *Phys. Rev D 106, 032004 (2022)* *(Frequentist)*

and *arXiv:2311.07835* *(Bayesian)*

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

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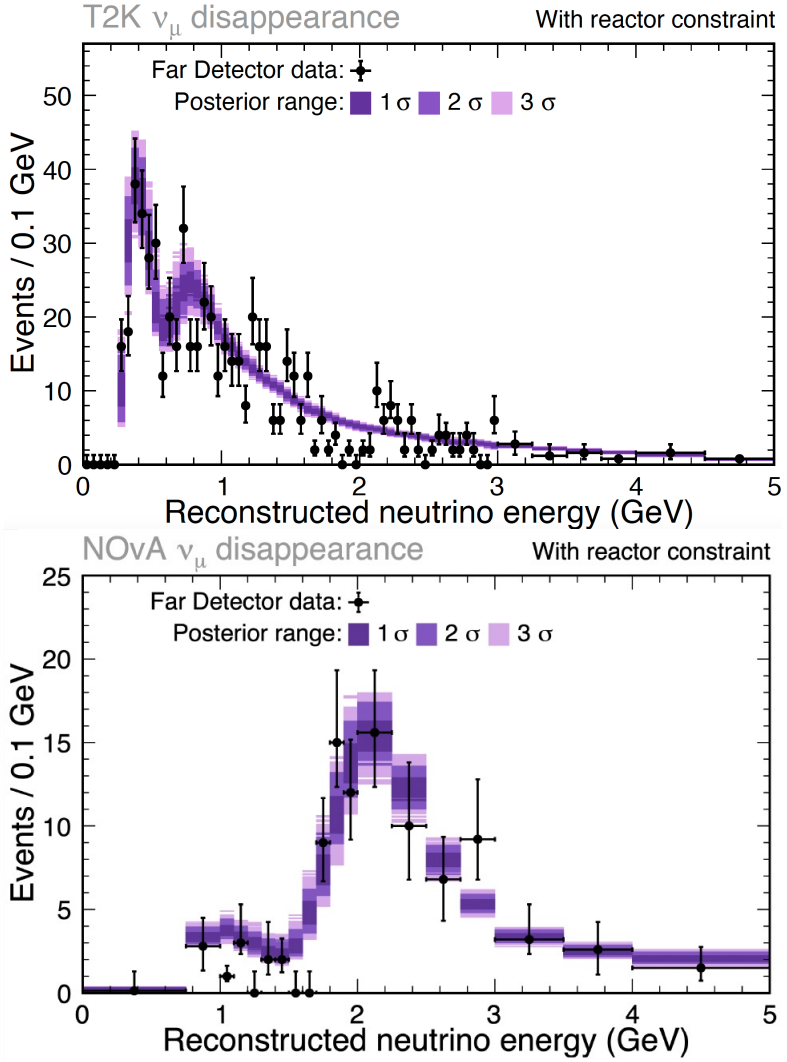
Both experiments data consistent with joint fit result



NOvA-T2K Preliminary

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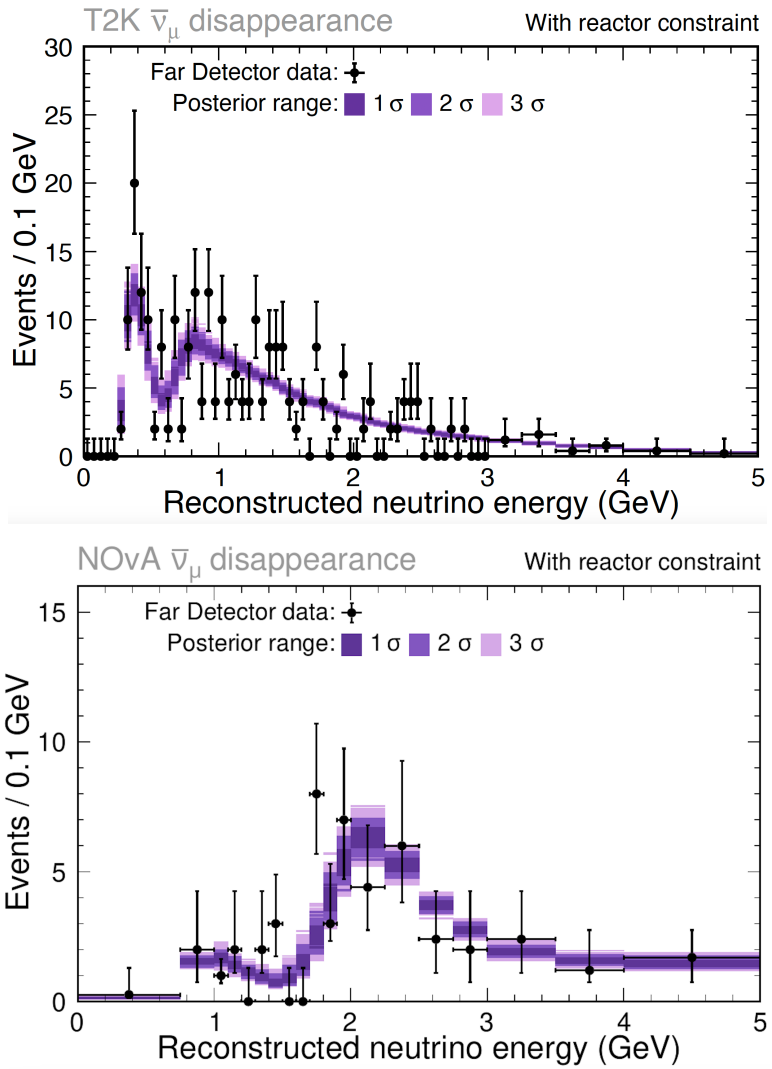

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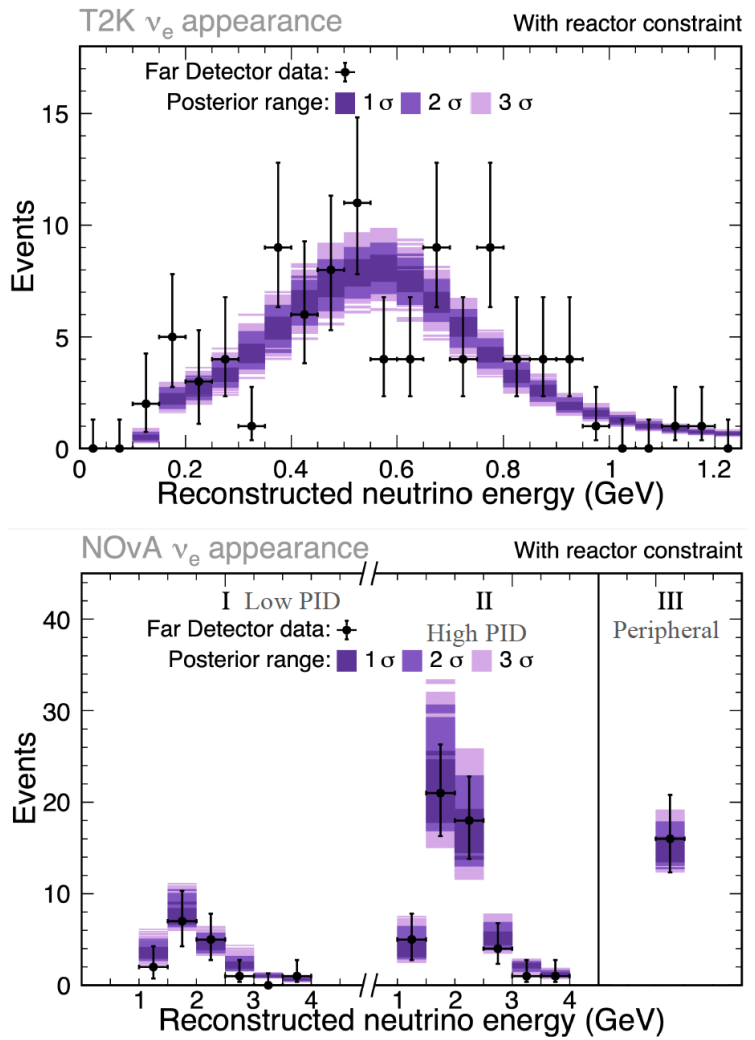

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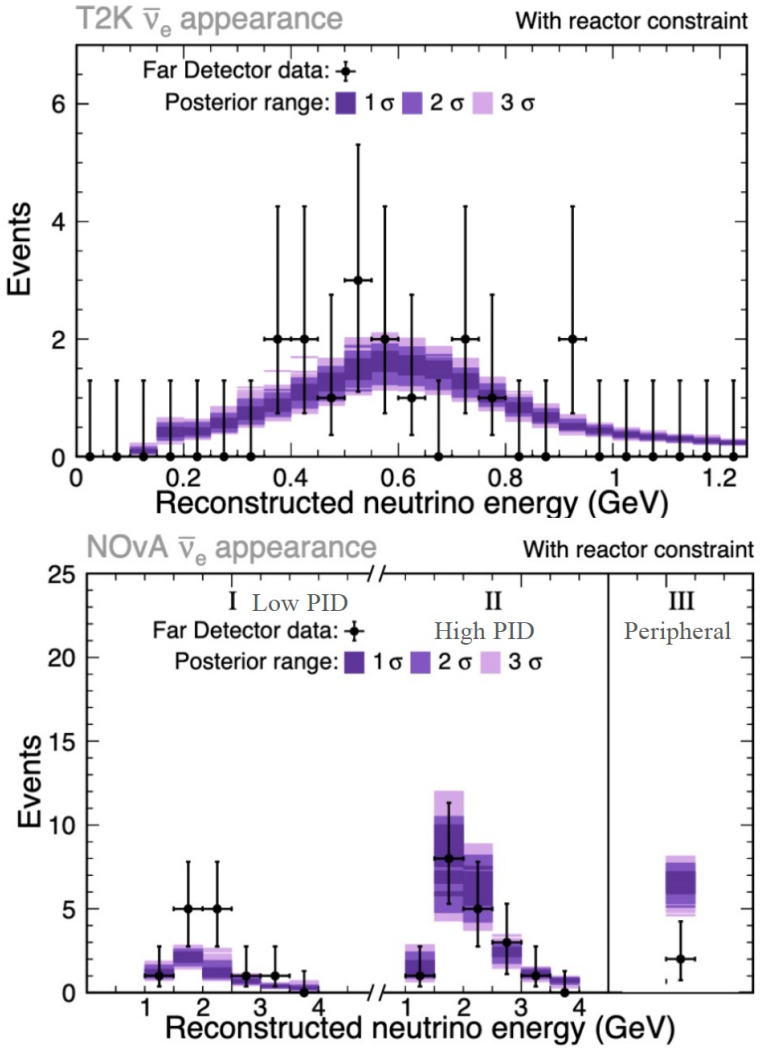

NOvA-T2K Preliminary

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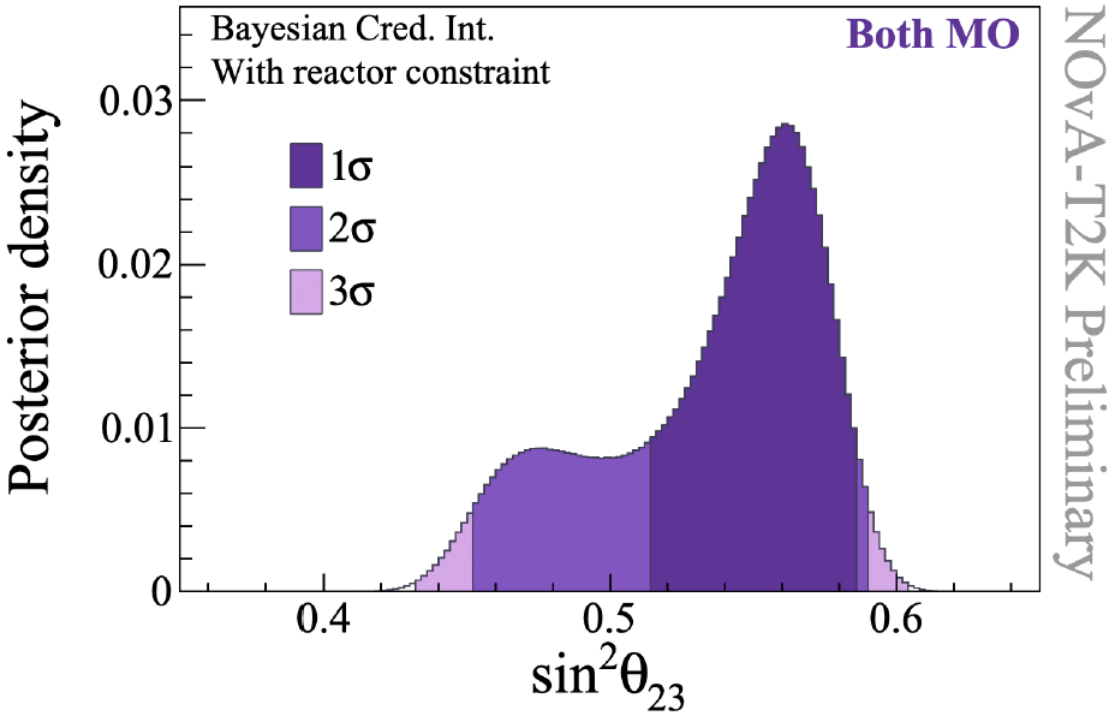
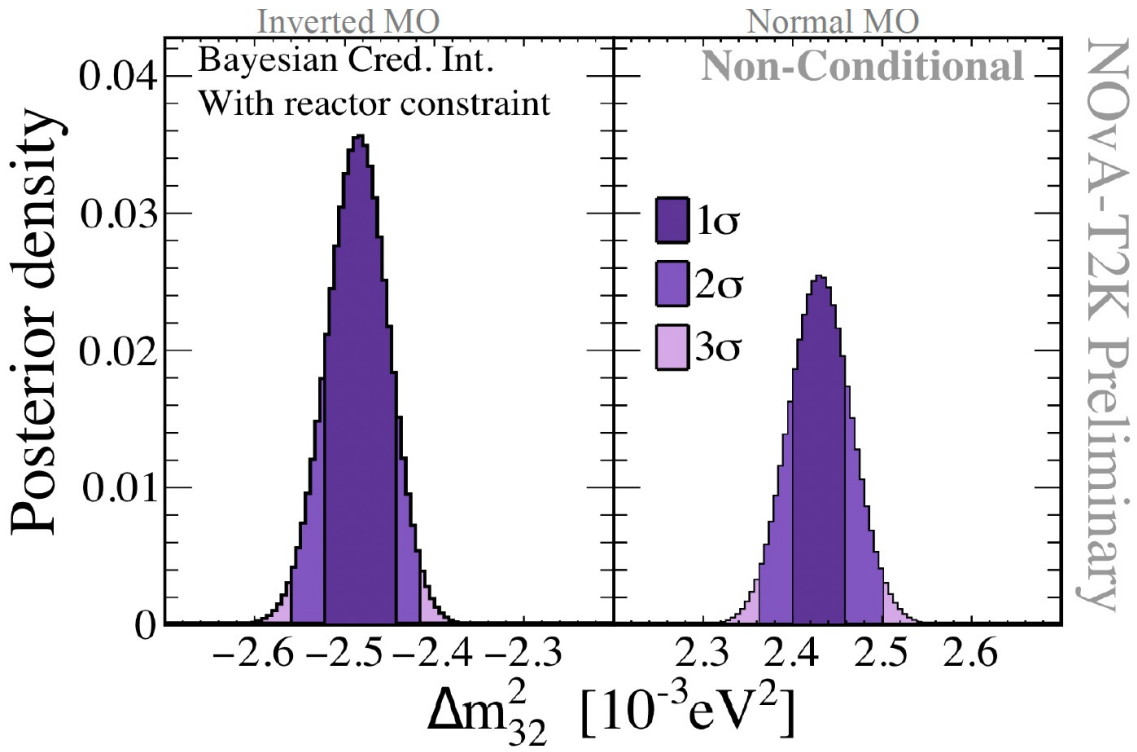


Results Consistent with Maximal Mixing

Slight Preference for Upper Octant

Posterior 78% to 22%

Upper vs Lower

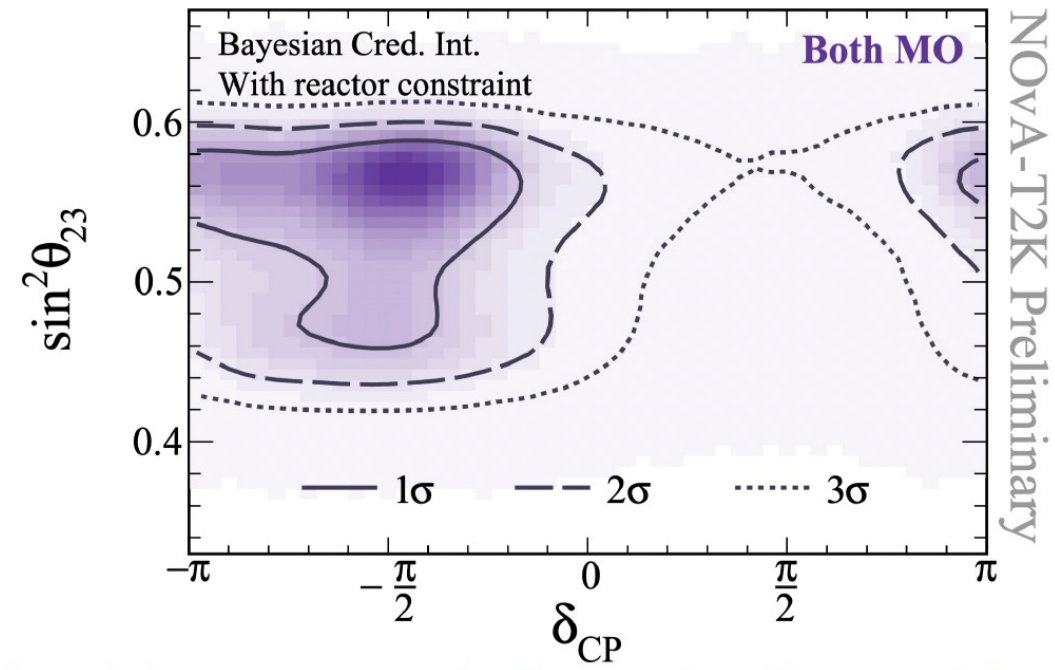


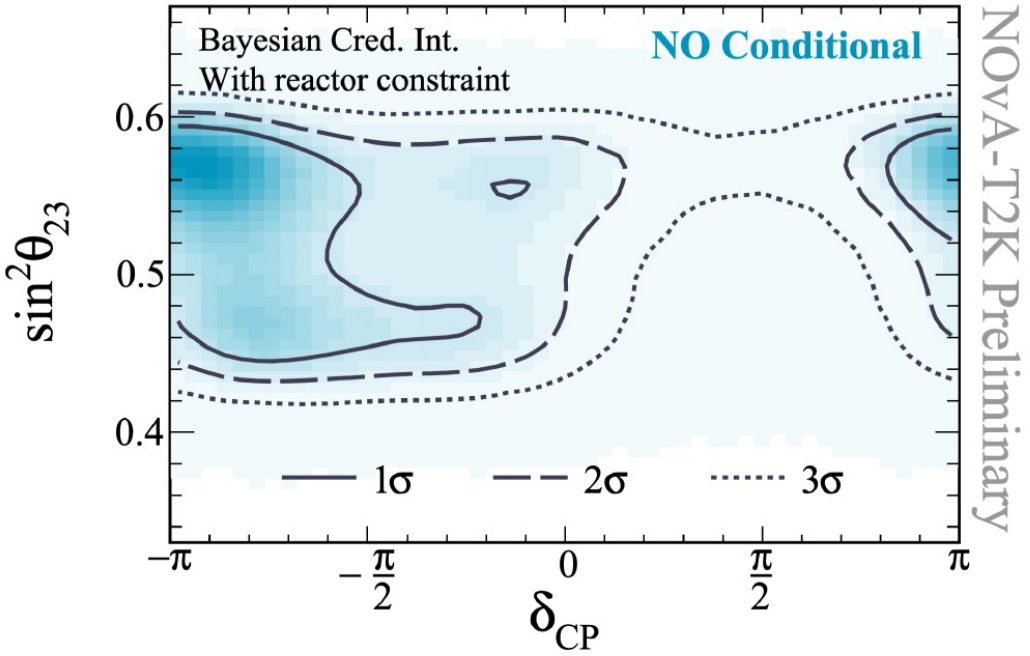
No significant preference for Mass Ordering

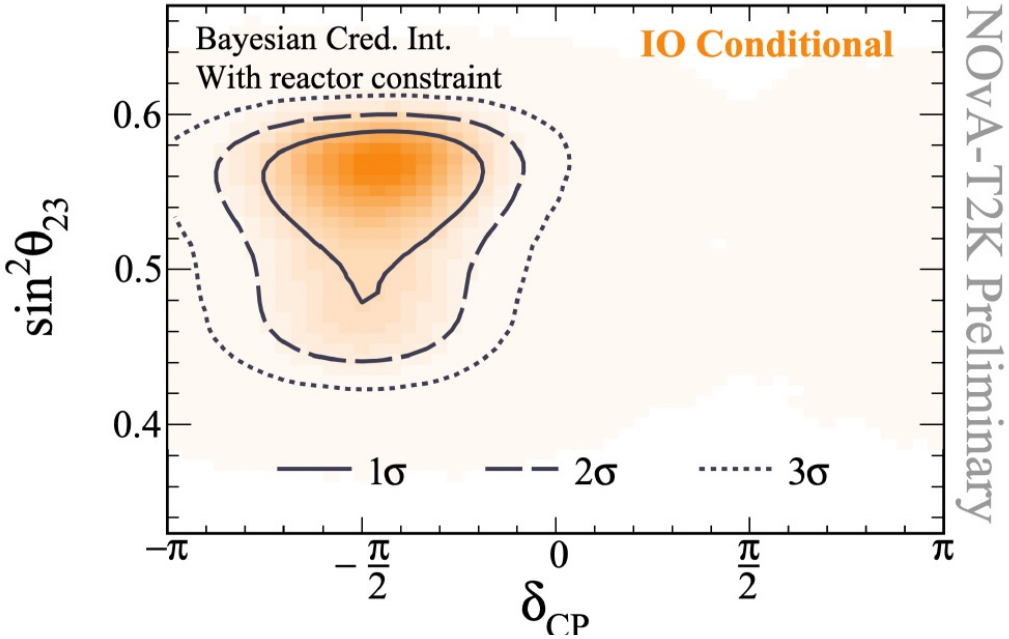
Posterior 58% to 42%

Inverted vs Normal

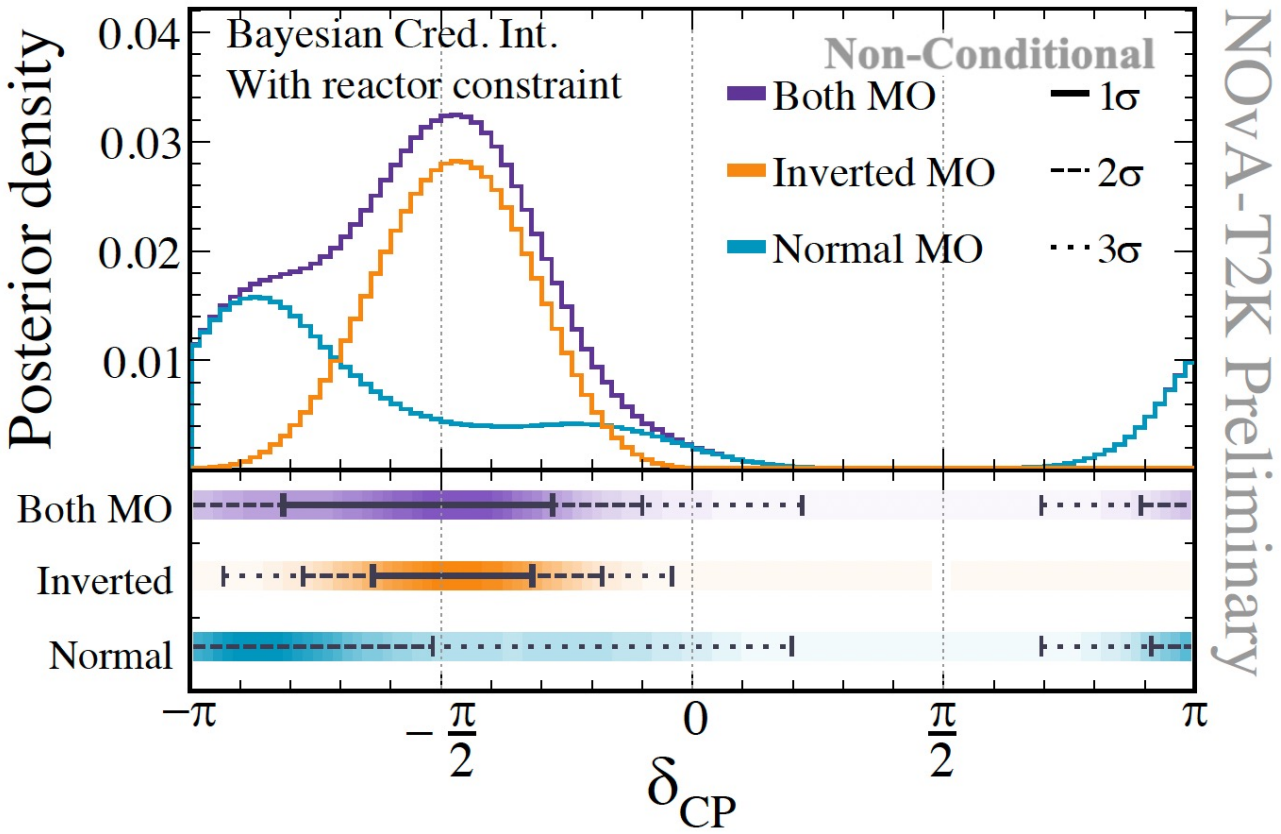
Joint Fit -Results







Joint Fit -Results



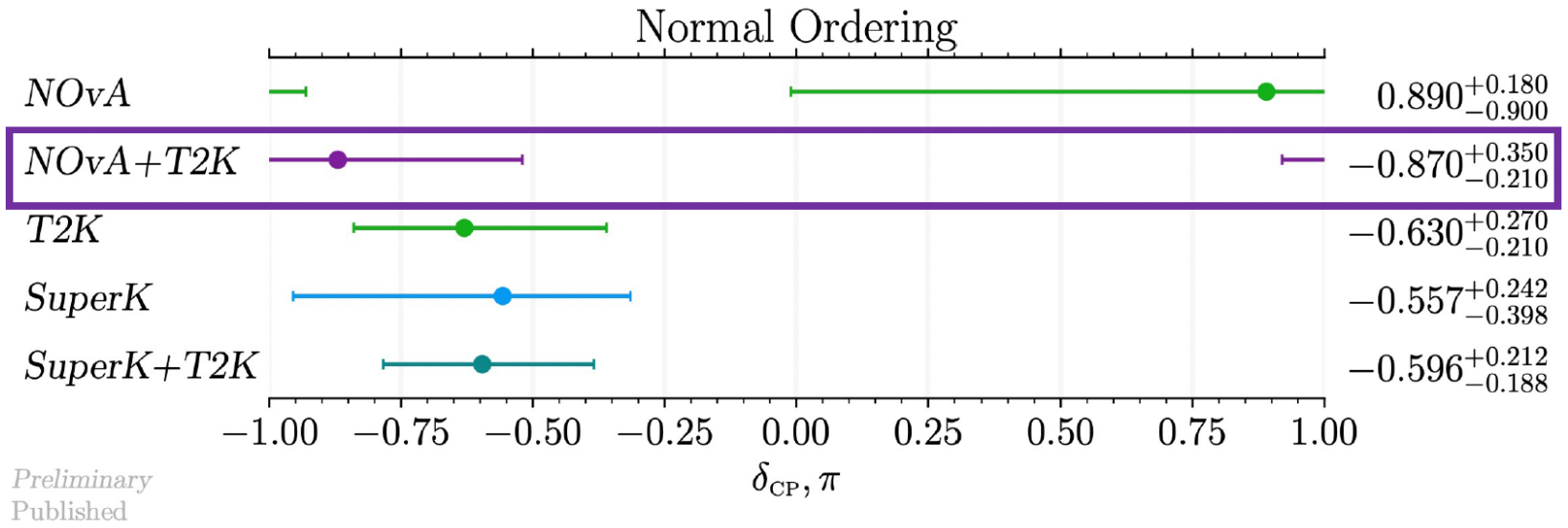
$\delta_{CP} = \frac{\pi}{2}$ ruled out at 3σ assuming either M.O.

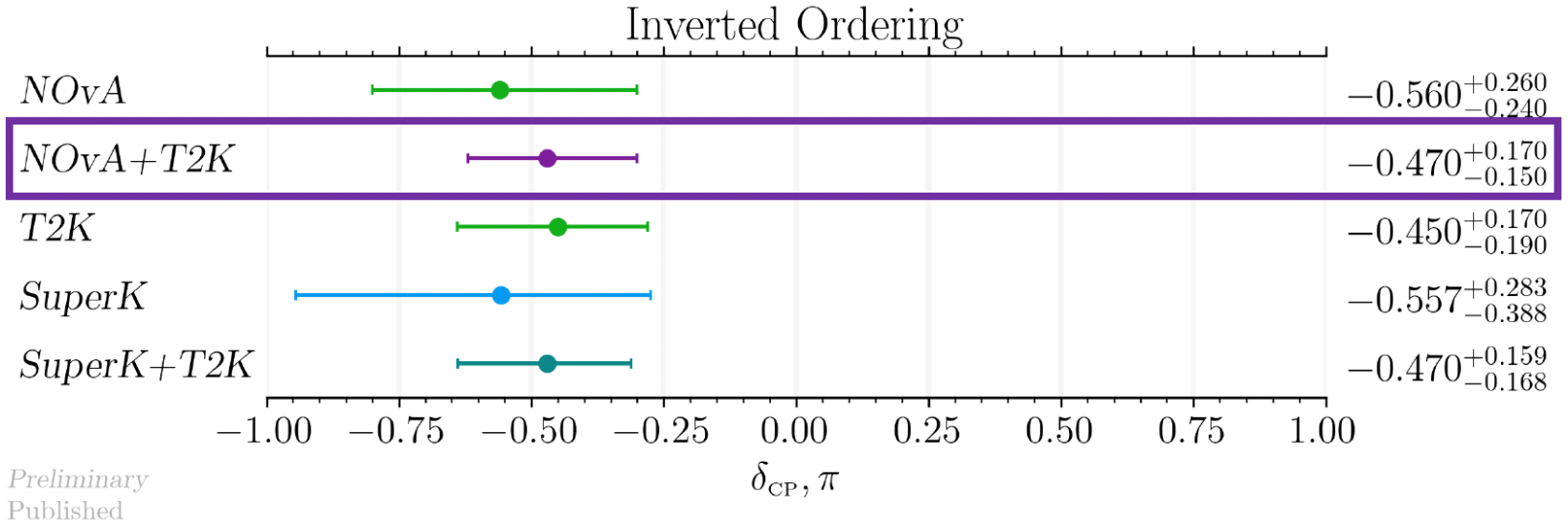
CP-conserving $\delta_{CP} = 0, \pm\pi$ ruled out at 3σ assuming Inverted M.O.

CP-conservation permitted assuming Normal M.O.

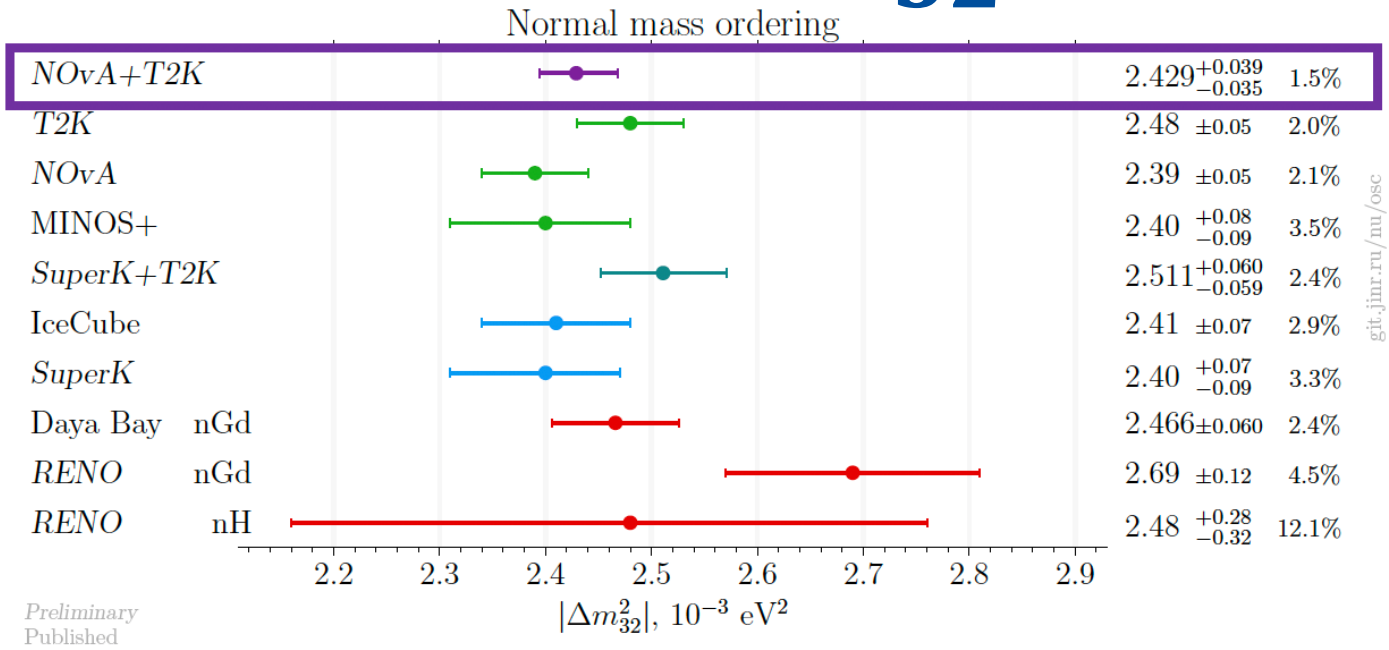
Similar story for Jarlskog-invariant
Phys. Rev. D 100, 053004 (2019)

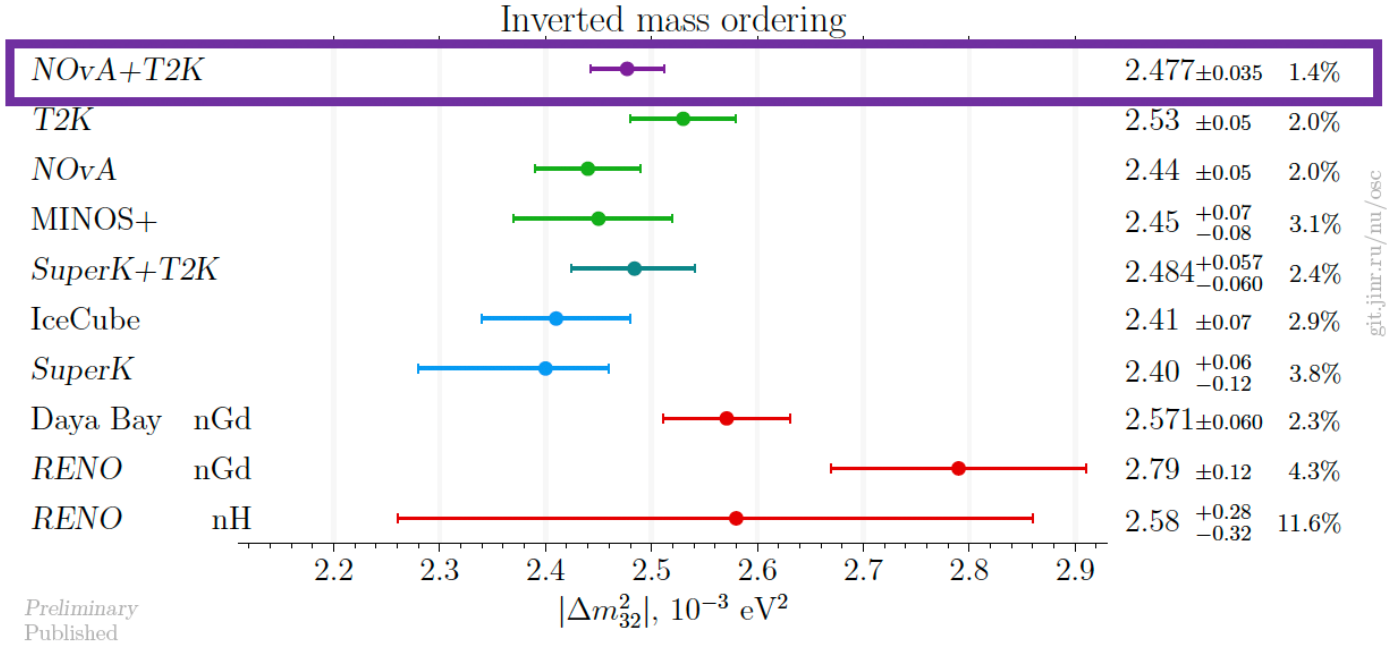
Comparisons to others – δ_{CP}





Comparisons to others – Δm^2_{32}





Summary & Outlook

T2K and NOvA data compatible with each other

Joint fit results

Strong constraint on $\left|\Delta m^2_{32}\right|$

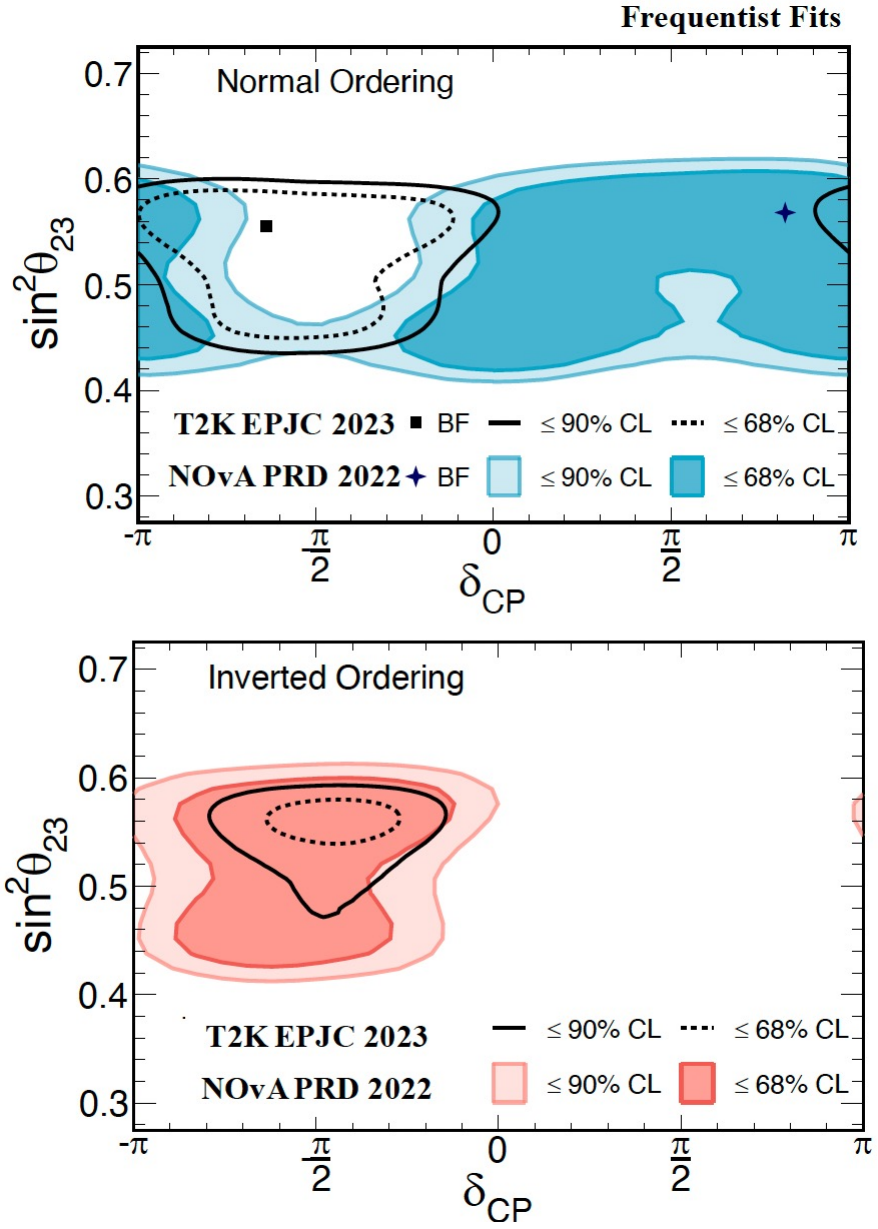
$\delta_{CP} = \frac{\pi}{2}$ ruled out at 3σ for either Mass Ordering

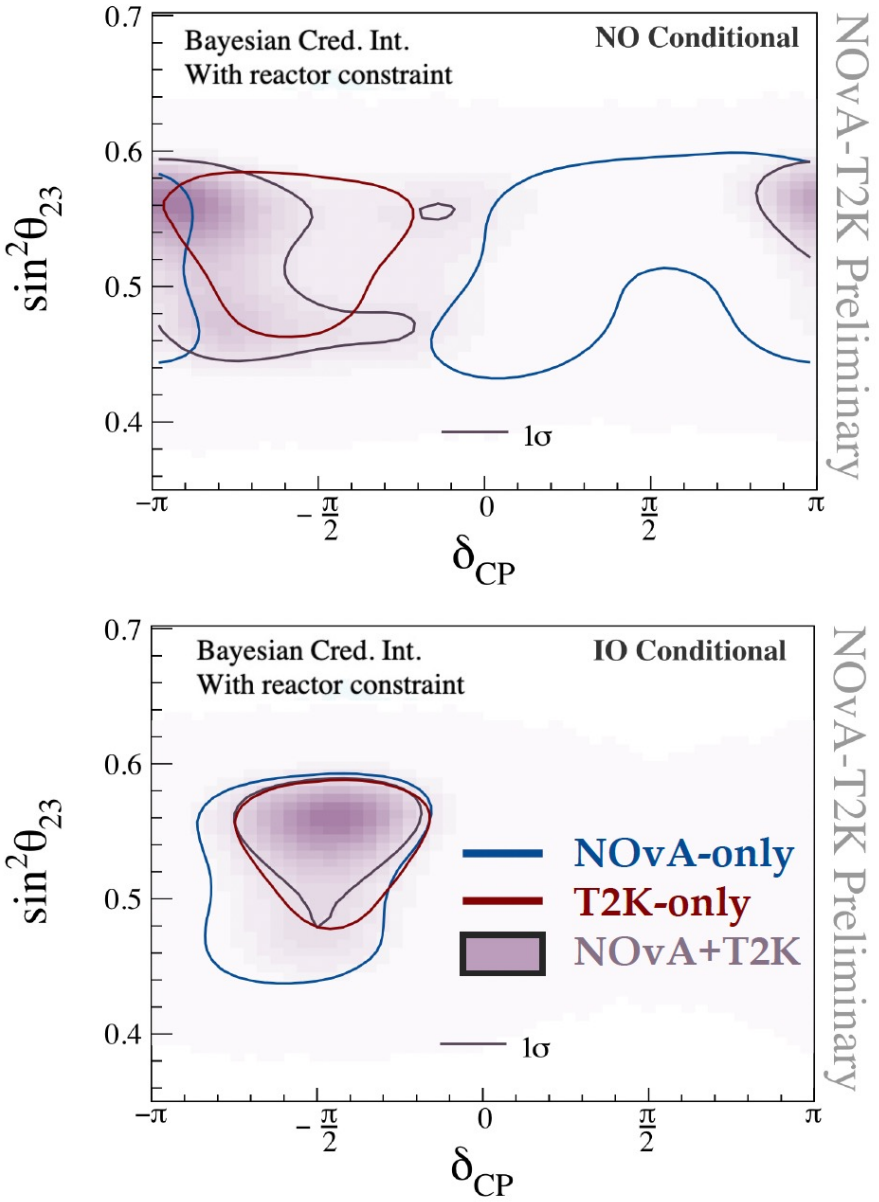
CP-conservation ruled out at 3σ for Inverted Mass Ordering

Both Experiments are expected to double data set before end of operations

Potential future collaboration

Current Measurements from NOvA and T2K



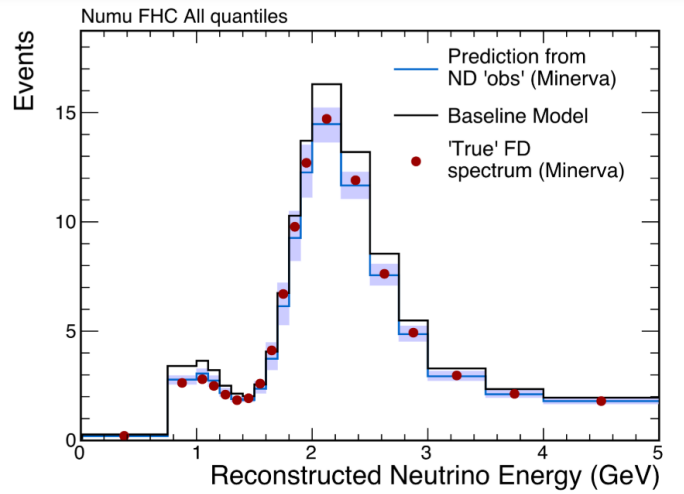


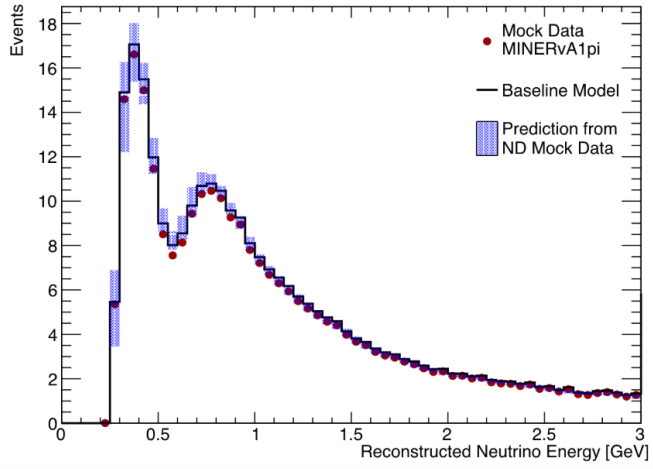
Joint Fit – Cross-section Modeling

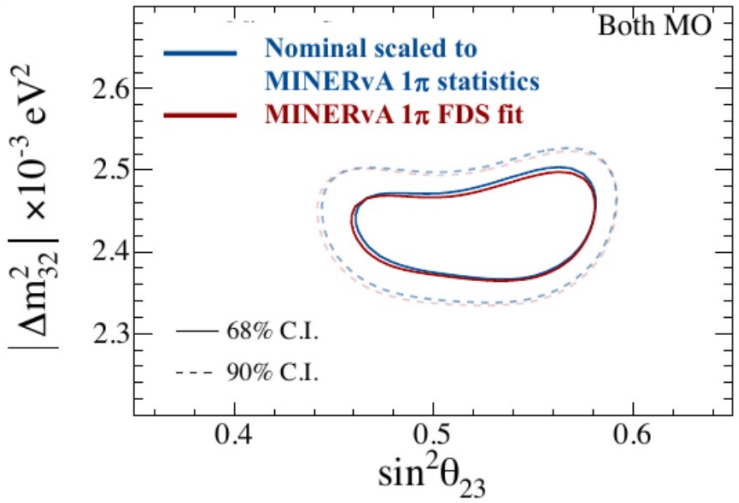
Fit Mock Data

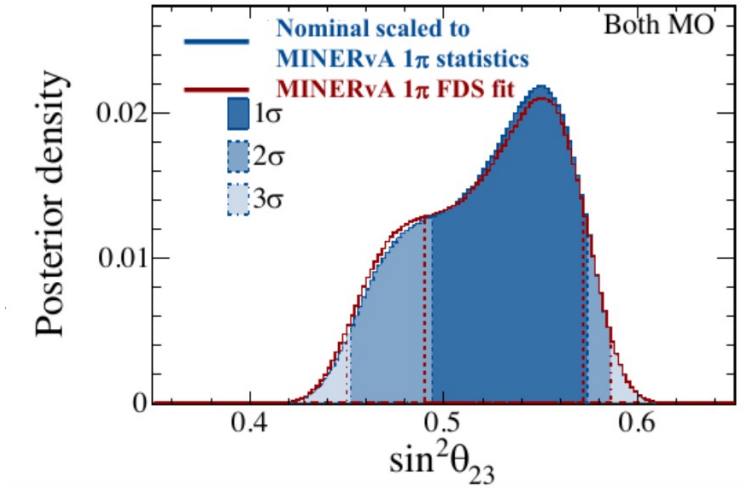
Single Pion Suppression

MINERvA: PRD 100 072005

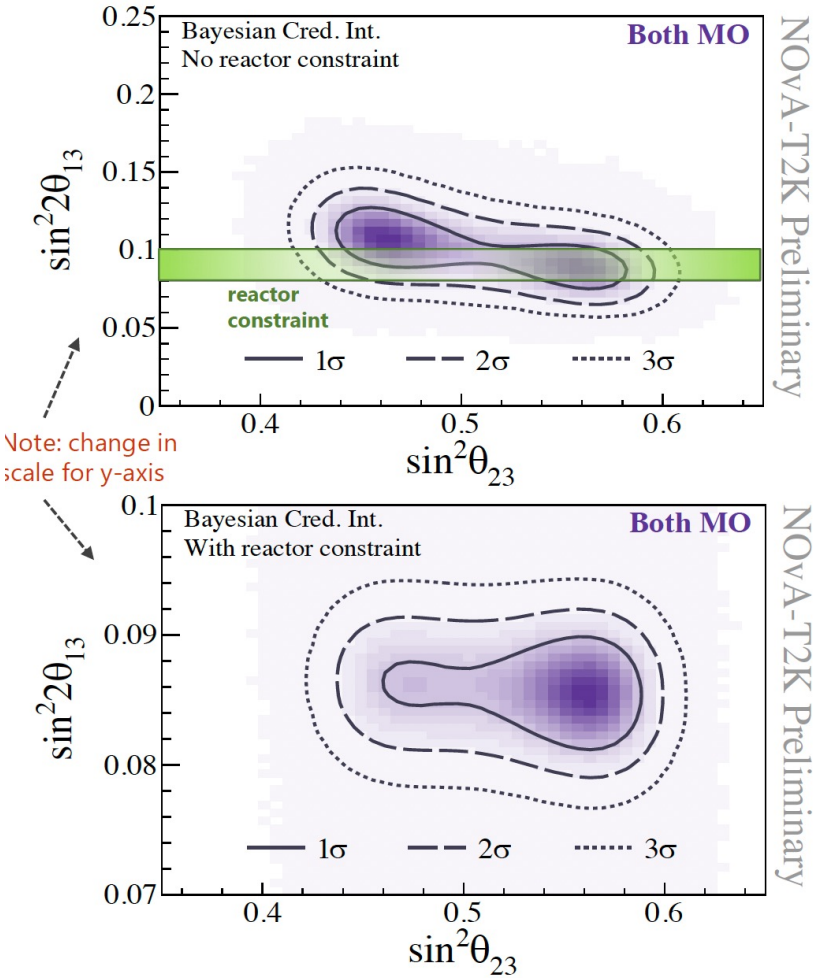


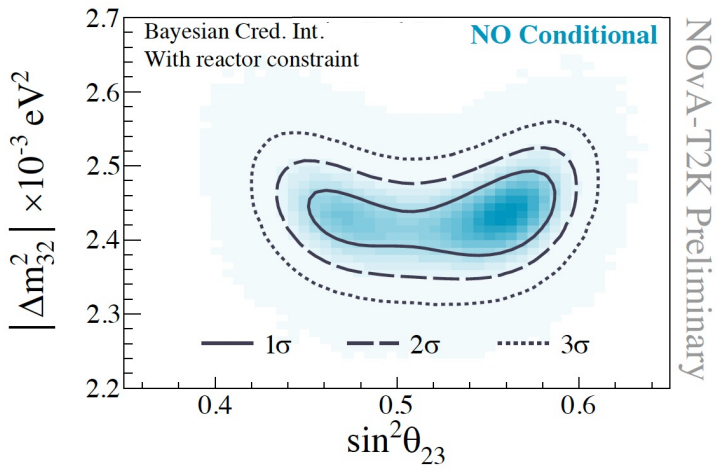


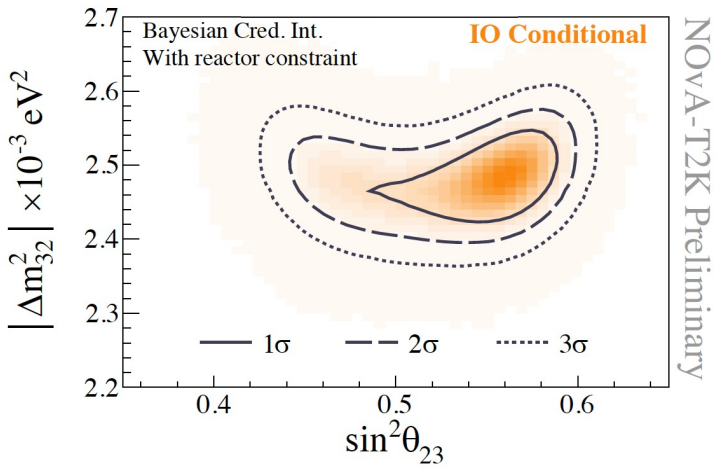




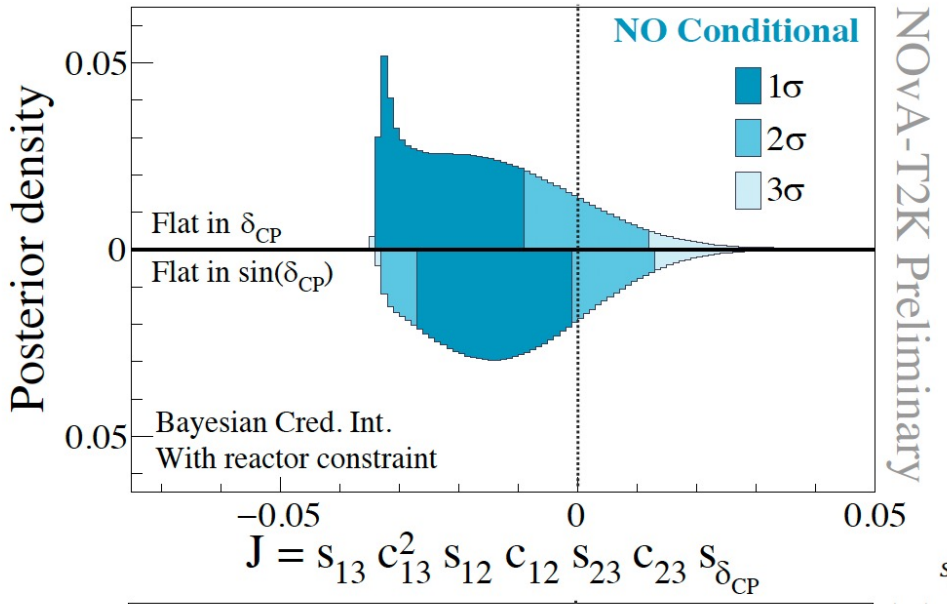
Joint Fit - θ_{13} & θ_{23}

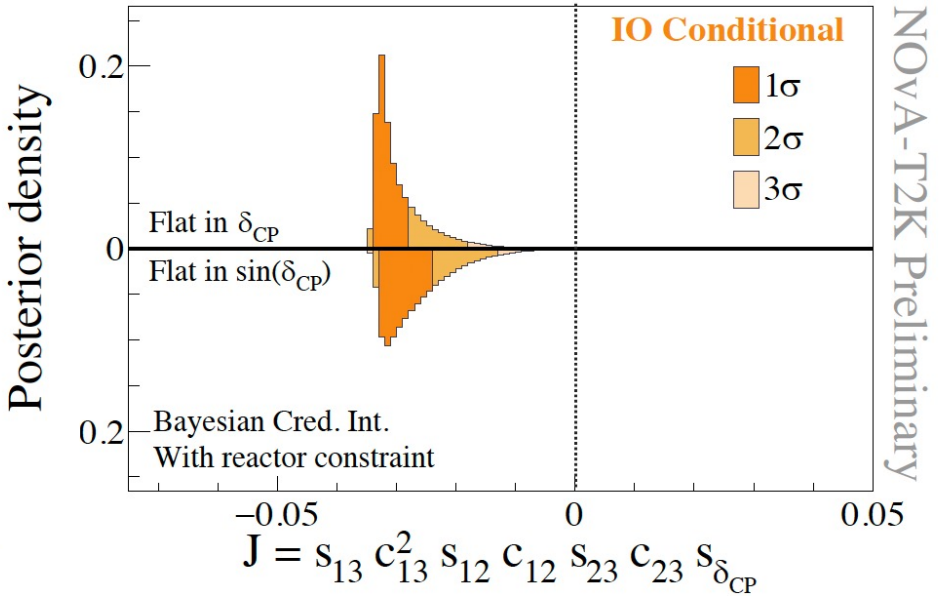






Joint Fit – Jarlskog Invariant





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

Neutrino Interactions