Results from the T2K Experiment

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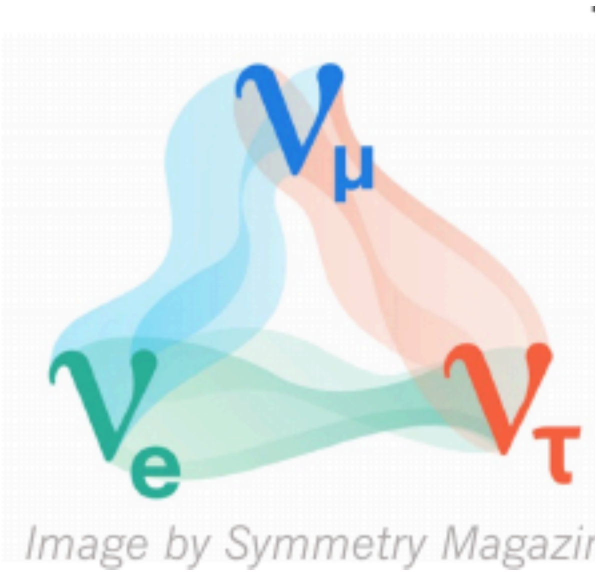
for the T2K Collaboration

7 July 2025

Neutrino Oscillation

flavour eigenstates



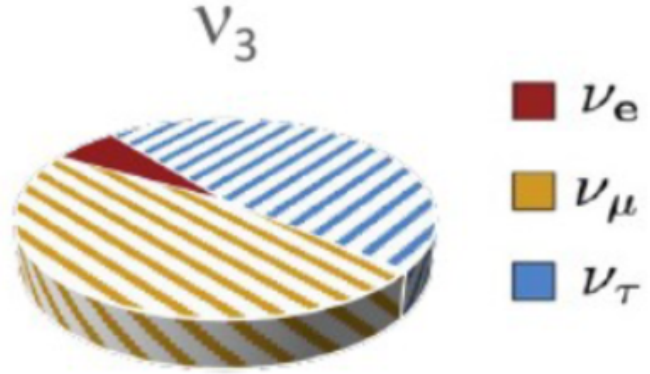
LBL experiments sensitive to these parameters

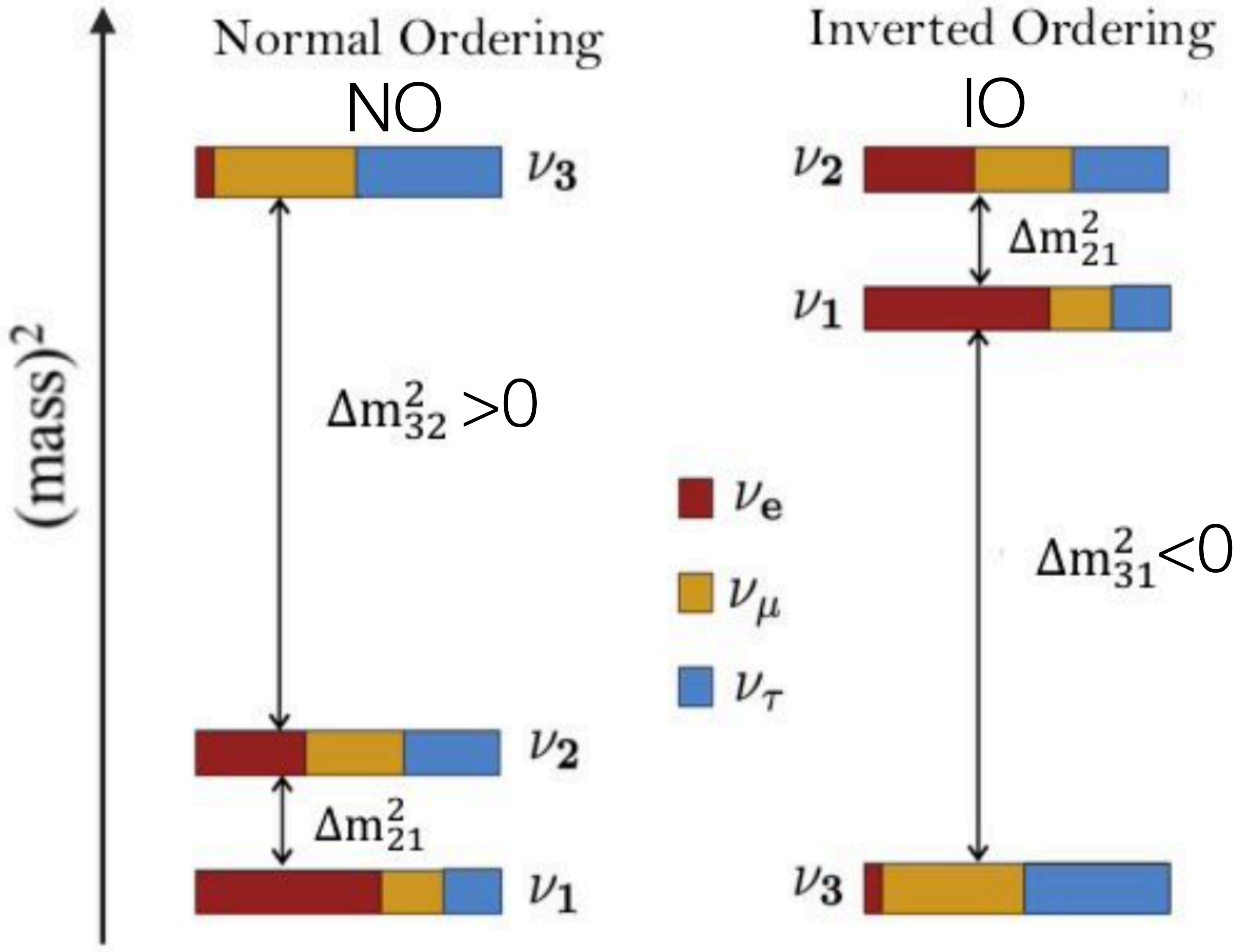
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

mass eigenstates

Atmospherics and LBL	Reactors	Solar and Reactors
$\theta_{23} \sim 45^\circ$	$\theta_{13} \sim 10^\circ$	$\theta_{12} \sim 35^\circ$
$\lvert\Delta m^2_{32}\rvert \sim 2.5\times10^{-3}eV^2$	δ_{CP} unknown	$\Delta m^2_{21} \sim 7.5\times10^{-5}eV^2$

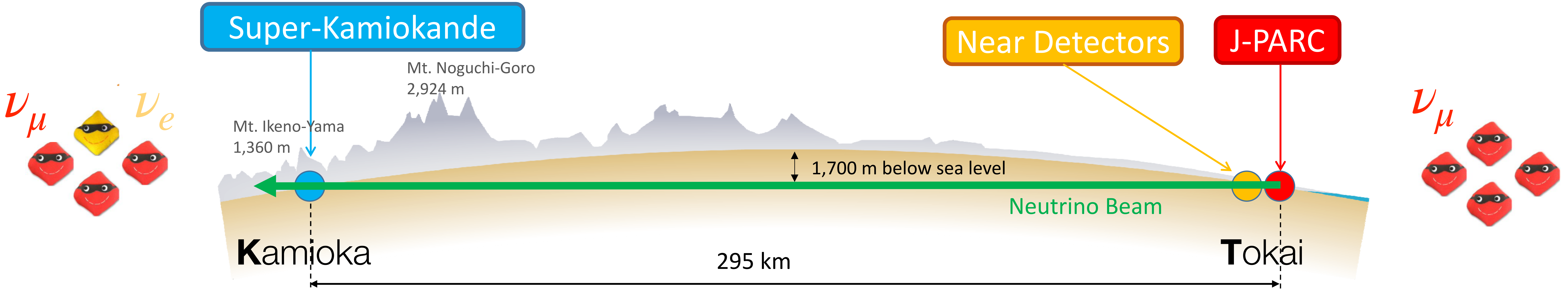
- Do neutrinos violate CP symmetry via δ_{CP} phase ?
- Which way are neutrino mass states ordered ? NO vs IO
- Do ν_μ/ν_τ mix equally into ν_3 ? What is the octant of θ_{23} ?



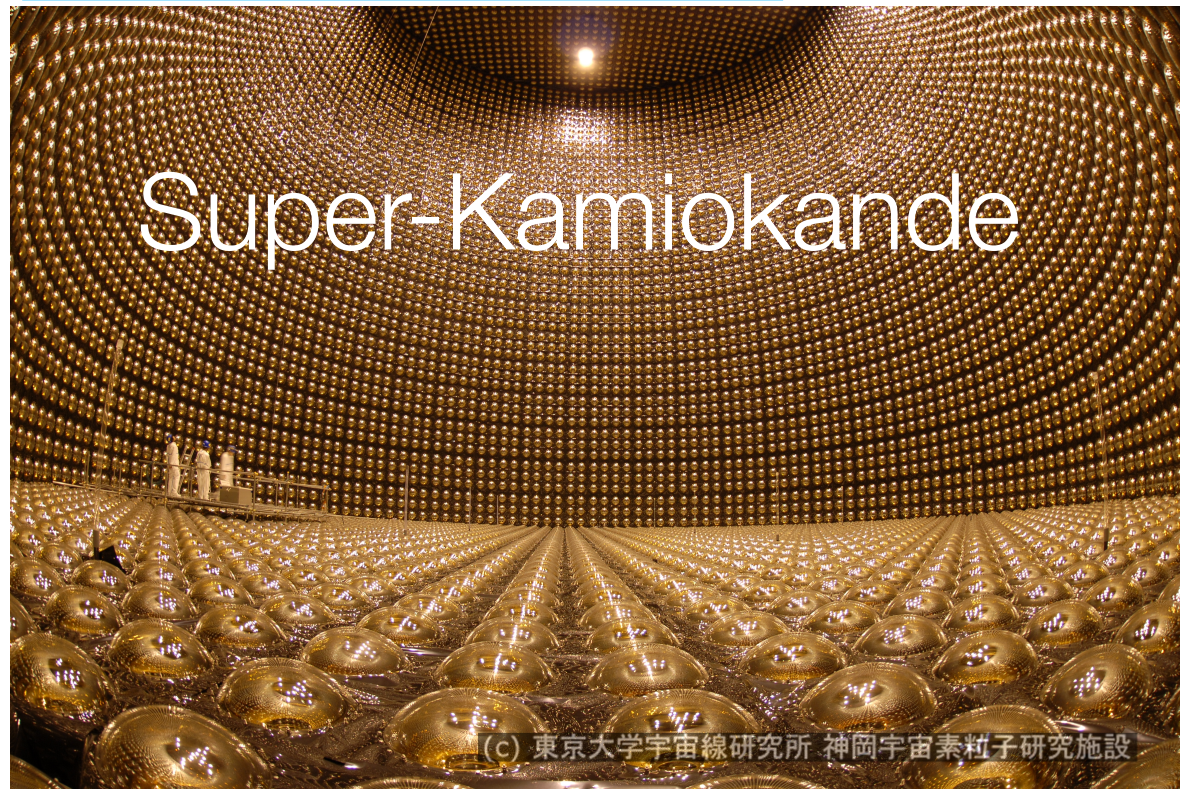


T2K Experiment

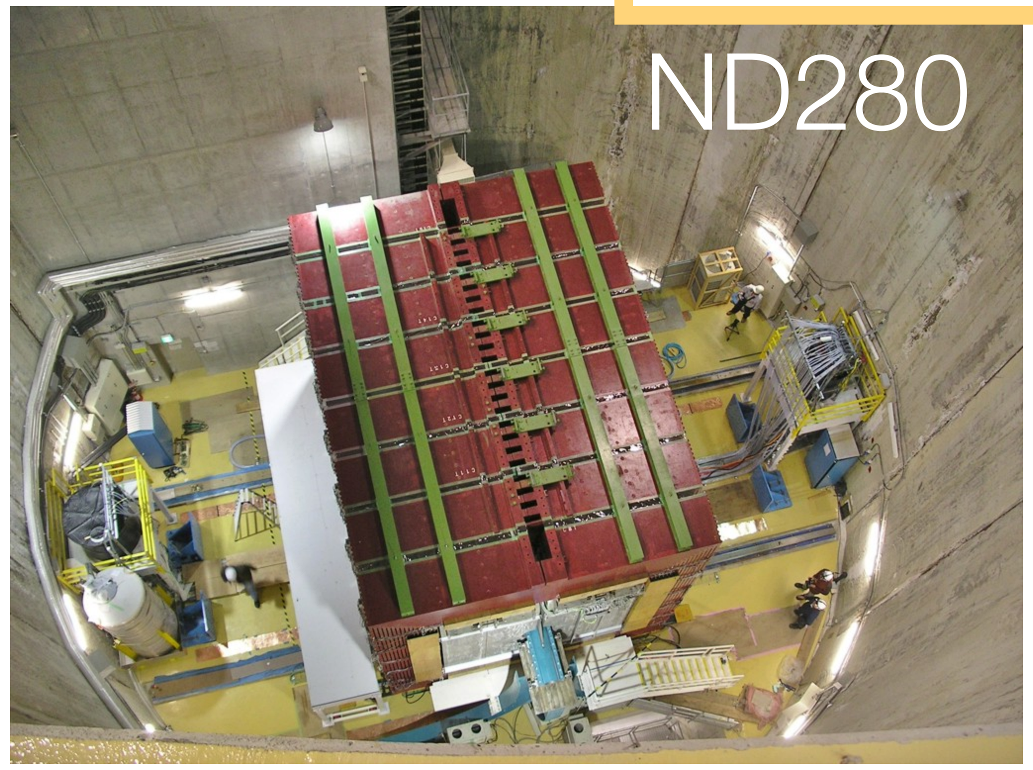
- Uses high intensity $\nu_\mu(\bar{\nu}_\mu)$ accelerator beam to study oscillations of neutrinos
- Measures disappearance $\nu_\mu \rightarrow \nu_\mu$ and appearance $\nu_\mu \rightarrow \nu_e$

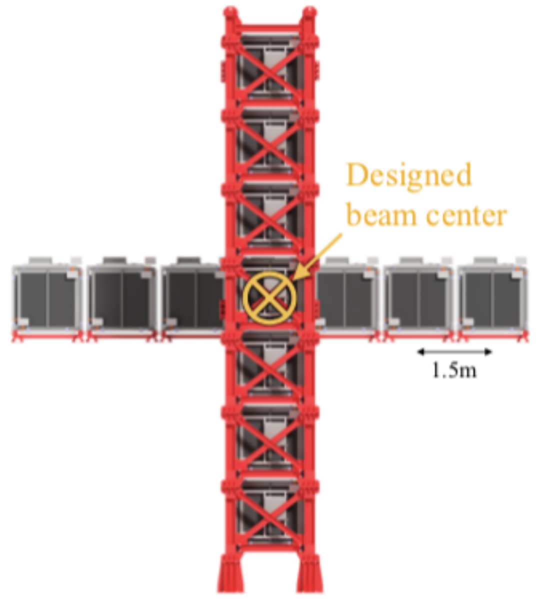


Far Detector

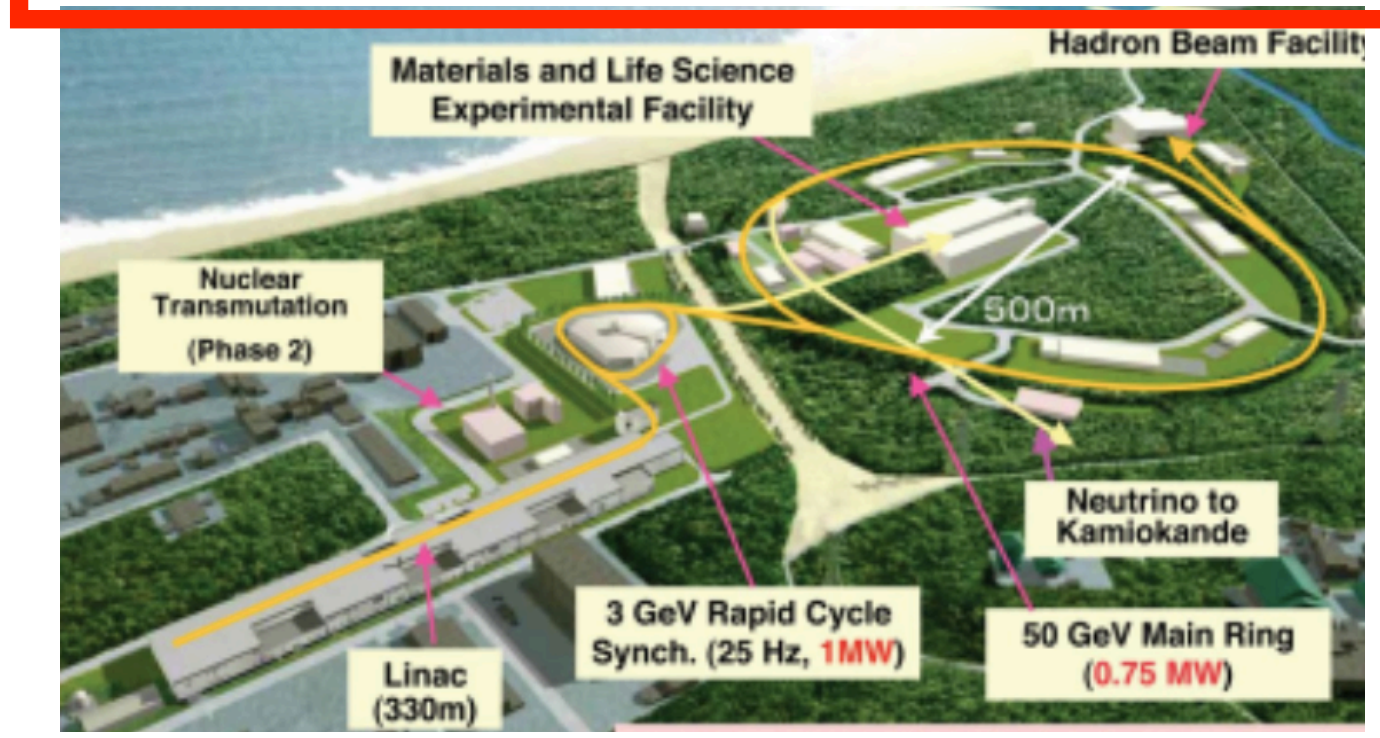


Near Detectors





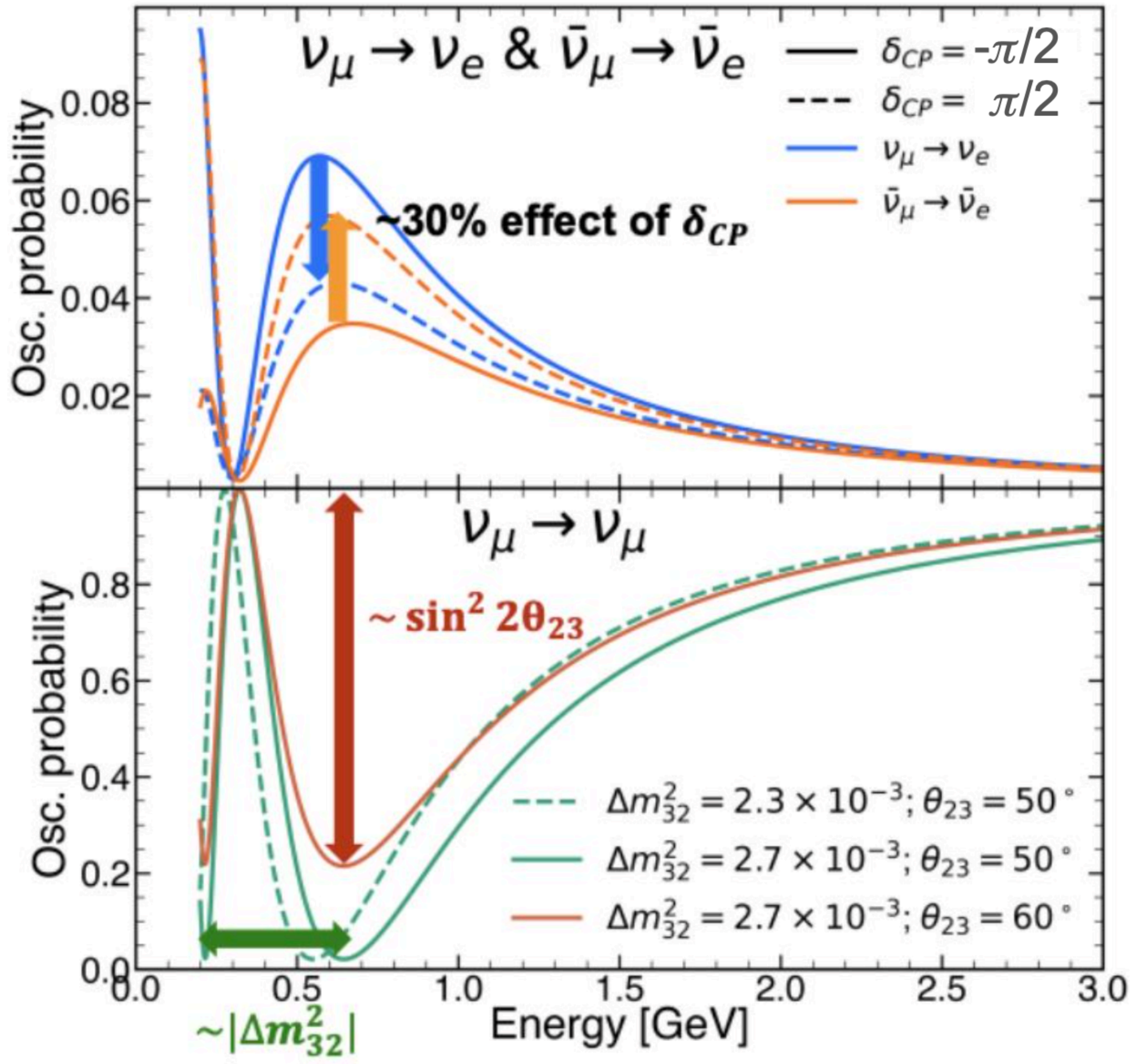
JPARC Accelerator Complex



Oscillation Probability

Probability that produced ν_μ will interact as neutrino of $\nu_e(\nu_\mu)$ type

It depends on
- Neutrino energy
- Baseline distance
- Oscillation parameters



Appearance $P(\nu_\mu \to \nu_e)$

- Sensitivity to CP phase δ_{CP}, opposite effect for ν and $\bar{\nu}$
- Also sensitivity to mass ordering (~10% effect) and θ_{23} octant

Disappearance $P(\nu_\mu \to \nu_\mu)$

- Same for ν and $\bar{\nu}$
- $sin^2(2\theta_{23})$ modulates amplitude
- Position of "dip" $\sim |\Delta m^2_{32}|$

Incoming neutrino flux

Far detector selection efficiency

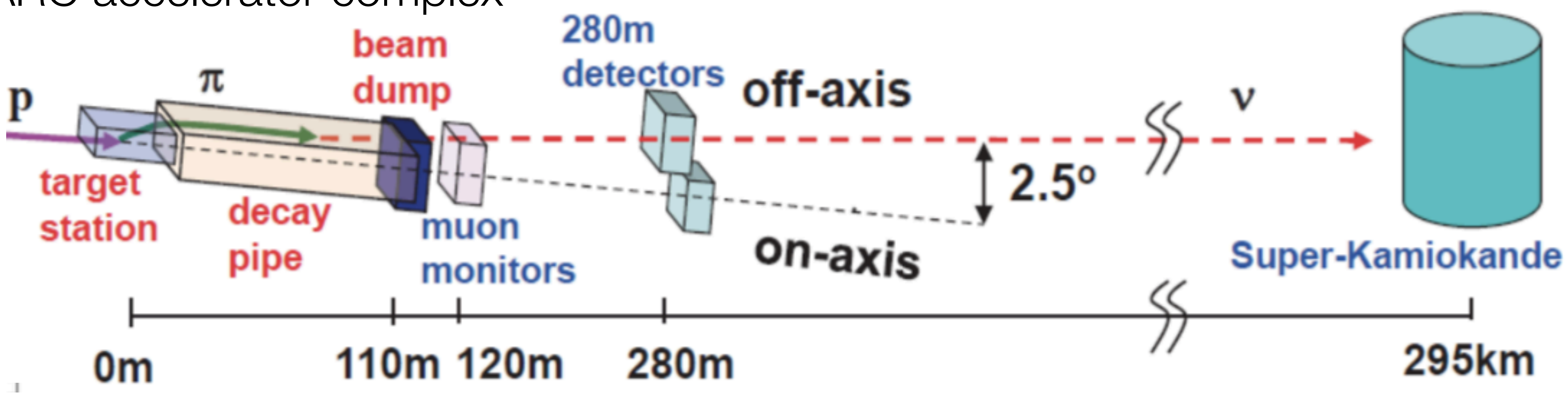
Oscillation Probability

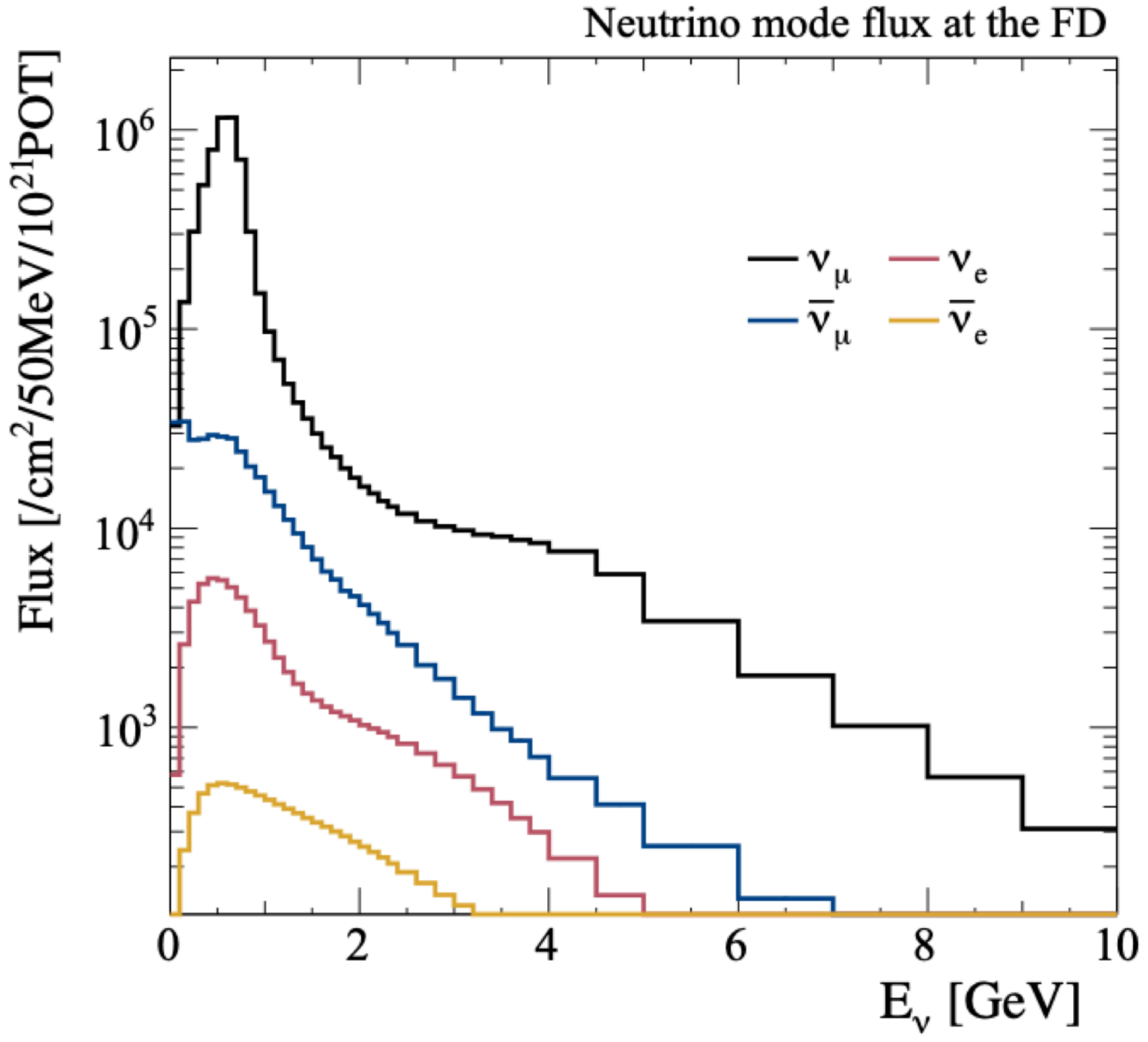
Measured event rates at Super-K : $N^\beta_{FD}(E_\nu) \sim \Phi_{FD}(L, E_\nu)\, \sigma(E_\nu)\, \epsilon_{FD}(E_\nu)\, P(\nu_\mu \to \nu_\beta)$

Neutrino cross section model

T2K Beam and Flux Predictions

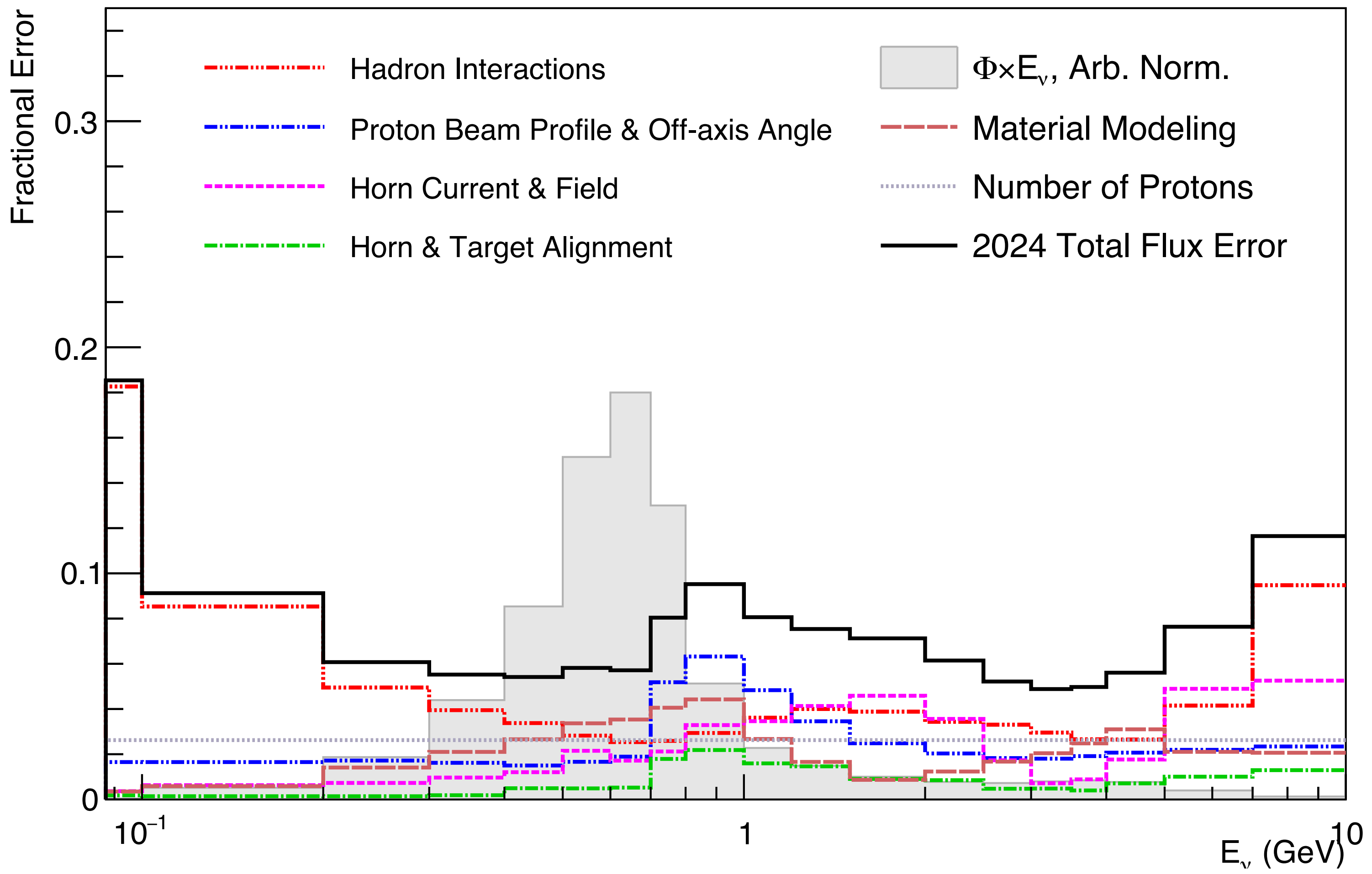
JPARC accelerator complex





- 30 GeV protons scatter off graphite target producing $\pi^{\pm}$, $K^{\pm}$
- π^{+}, K^{+} decay in flight producing ν_{μ} (π^{-}, K^{-} for $\bar{\nu}_{\mu}$)

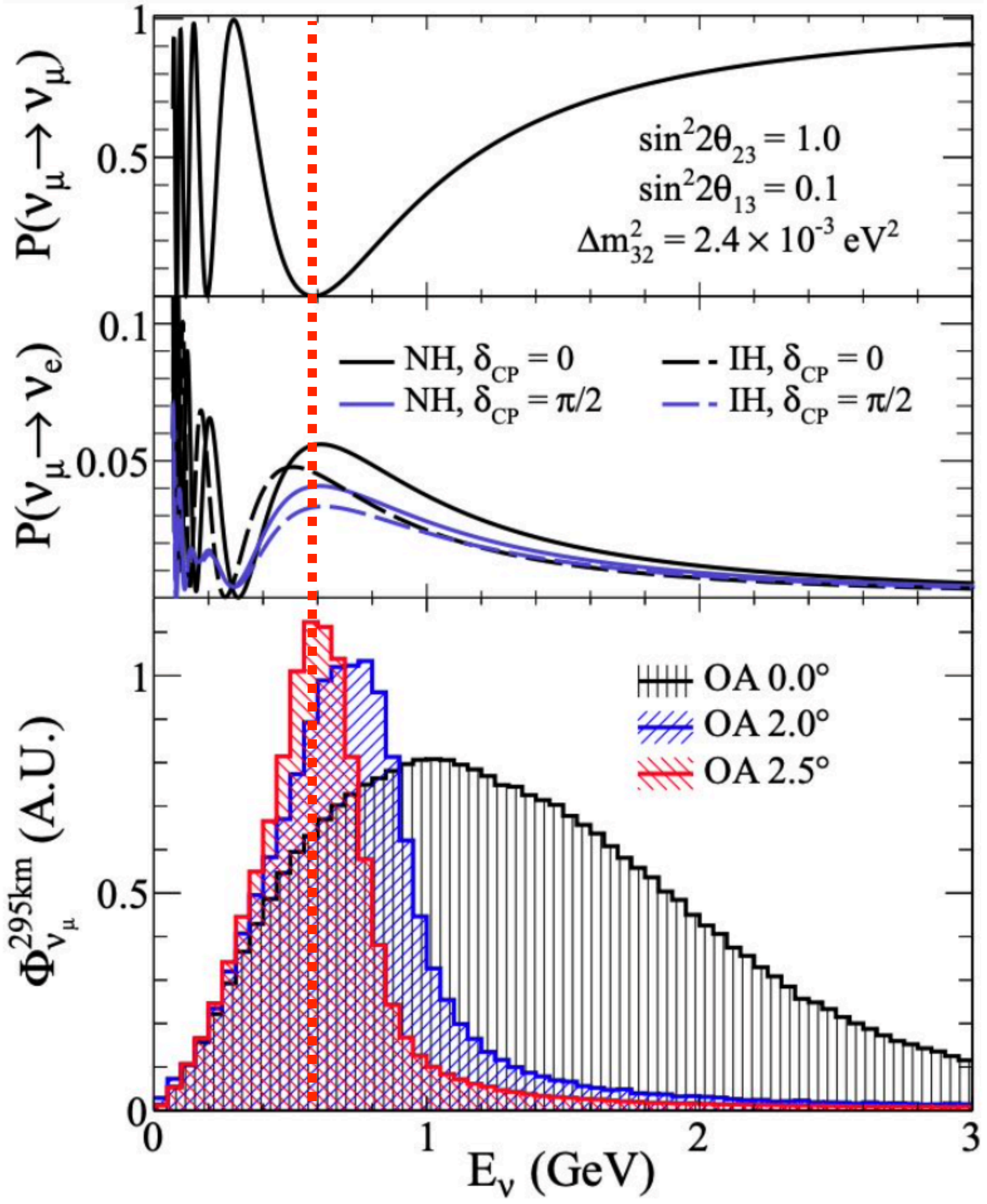
SK: Neutrino Mode (250kA), ν_{μ}



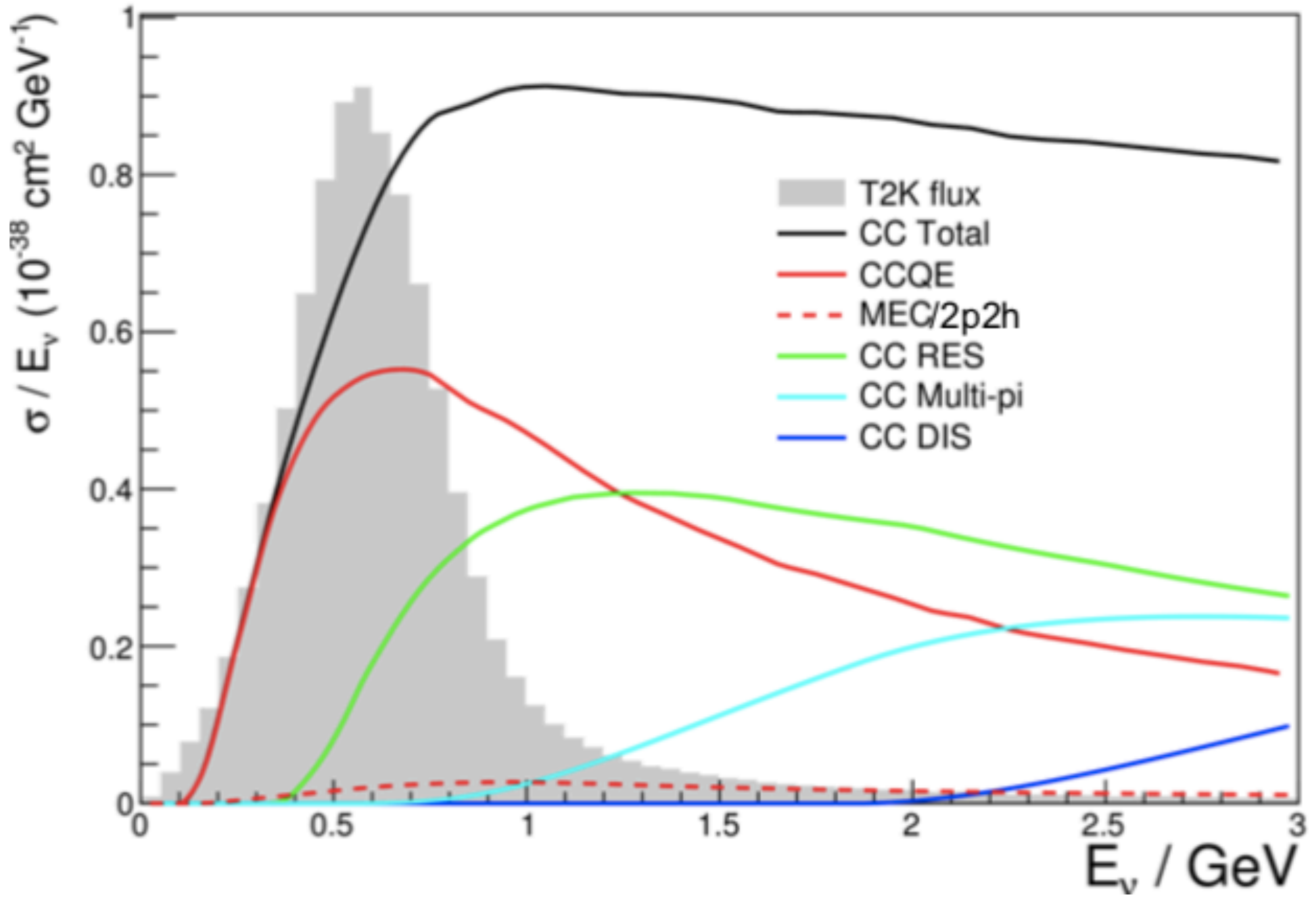
- Systematic error on flux is dominated by hadron-production cross section in p+C collisions
- Thanks to NA61/SHINE systematic error is reduced to 5%
- Using 2.5^{0} off-axis beam results in narrow beam band

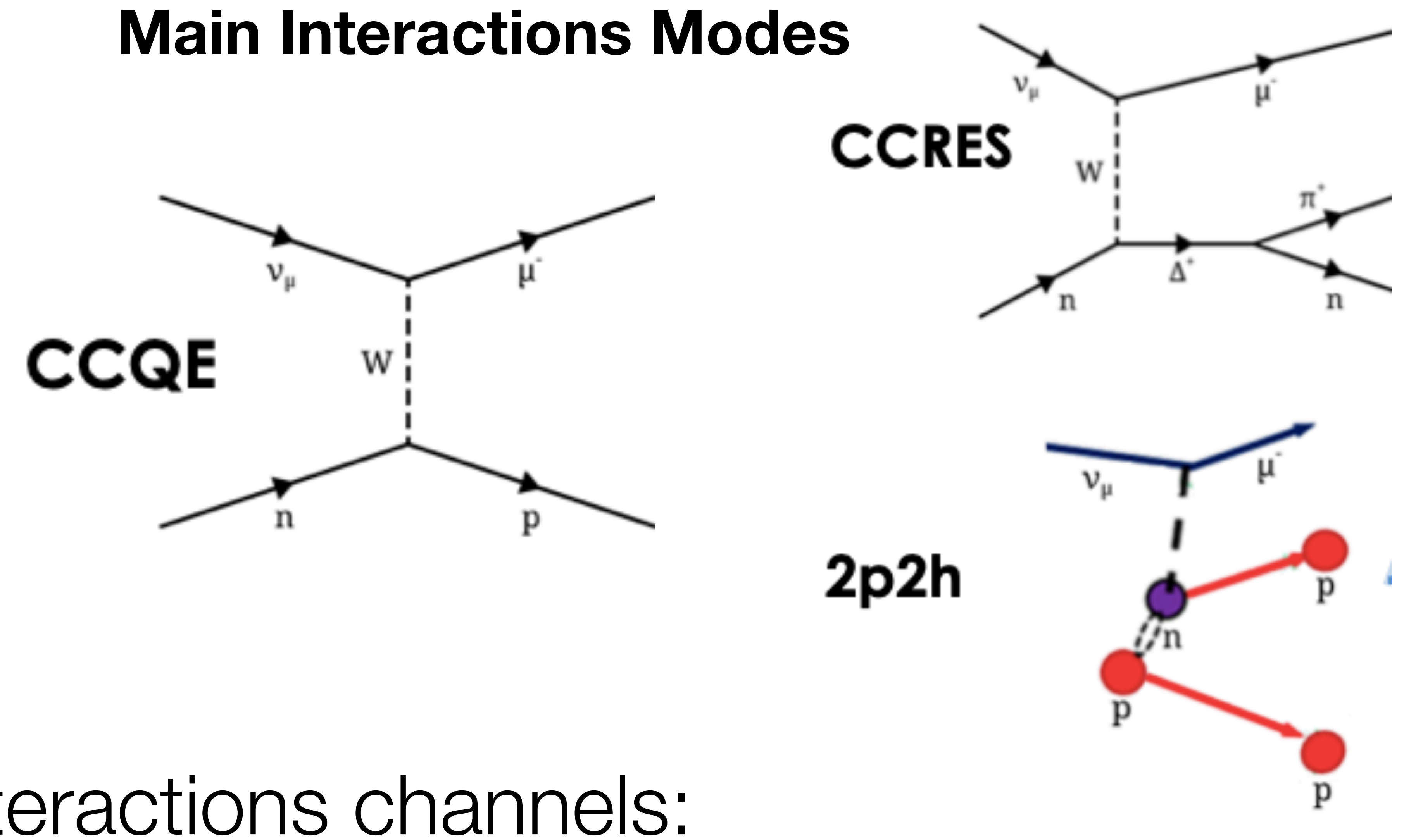
Neutrino Interactions

Off-axis beam enhances sensitivity to oscillation effects and the contribution of CCQE



Eν~0.6GeV



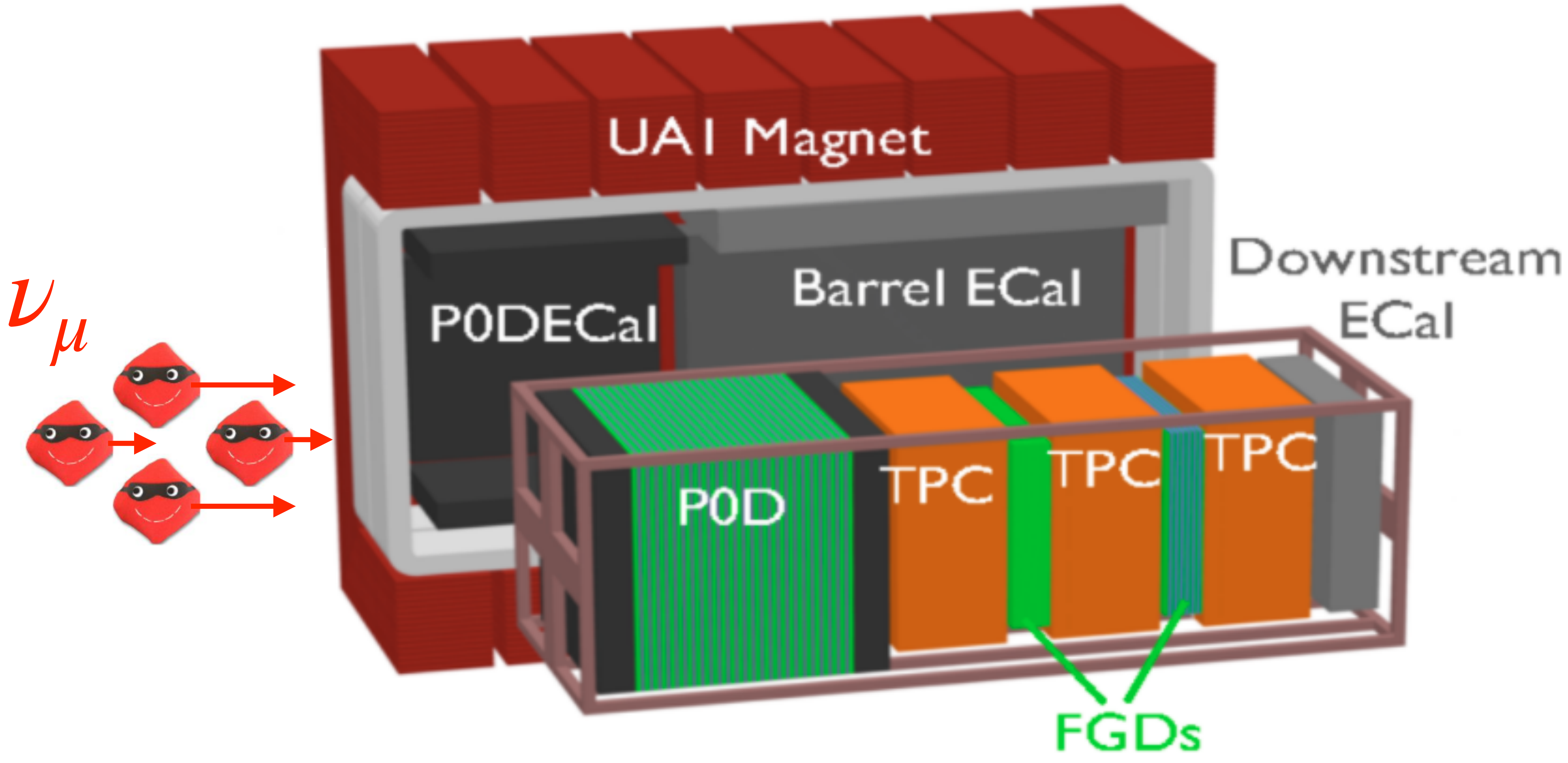


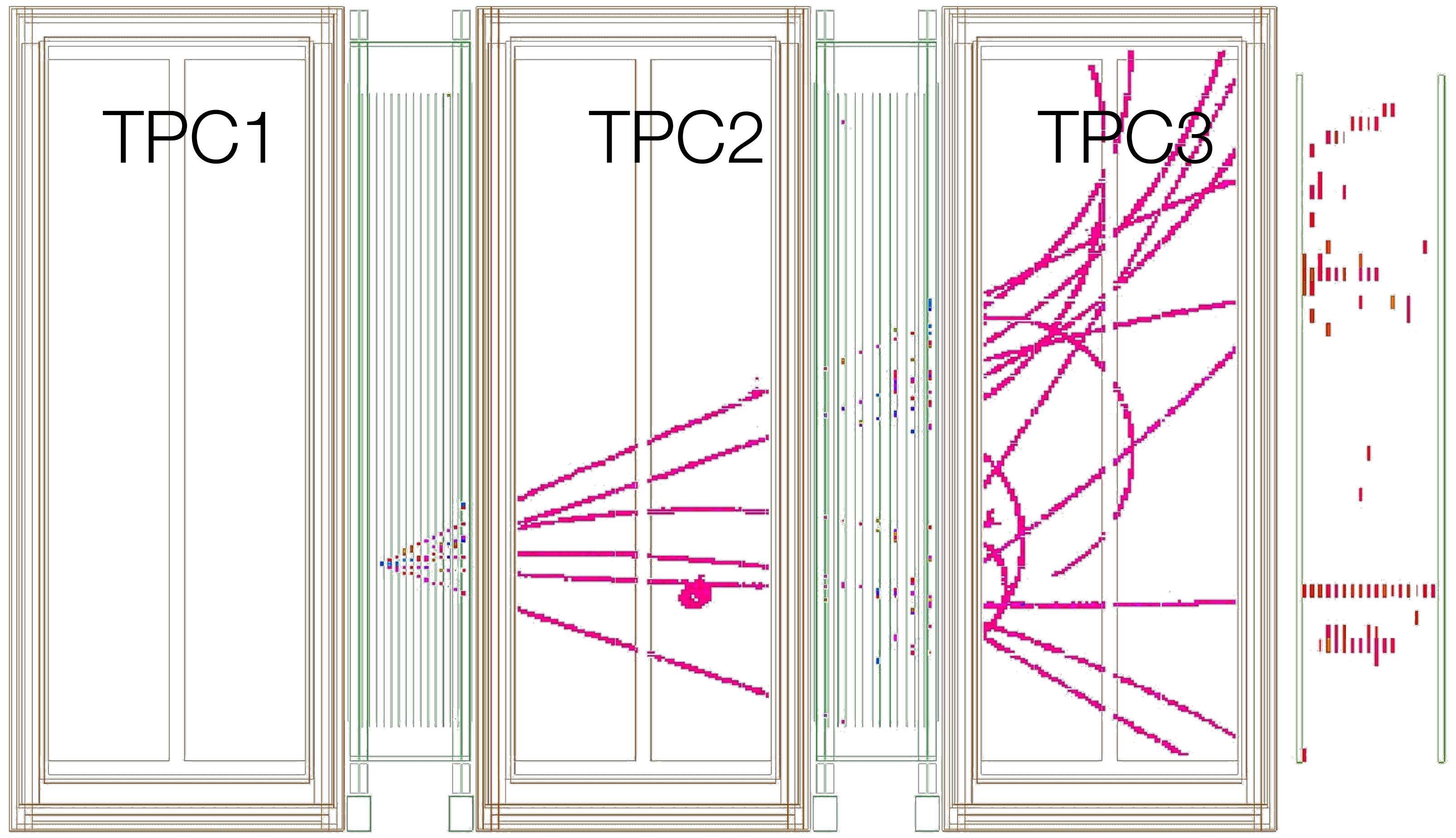
- At T2K energies the main interactions channels:
  - CCQE - Charged Current Quasi Elastic (+2p2h)
  - CCRES - Charged Current Resonant
- Important to have correct model to minimize the bias in E_ν reconstruction

ND280 Near Detector

Before upgrade in 2024

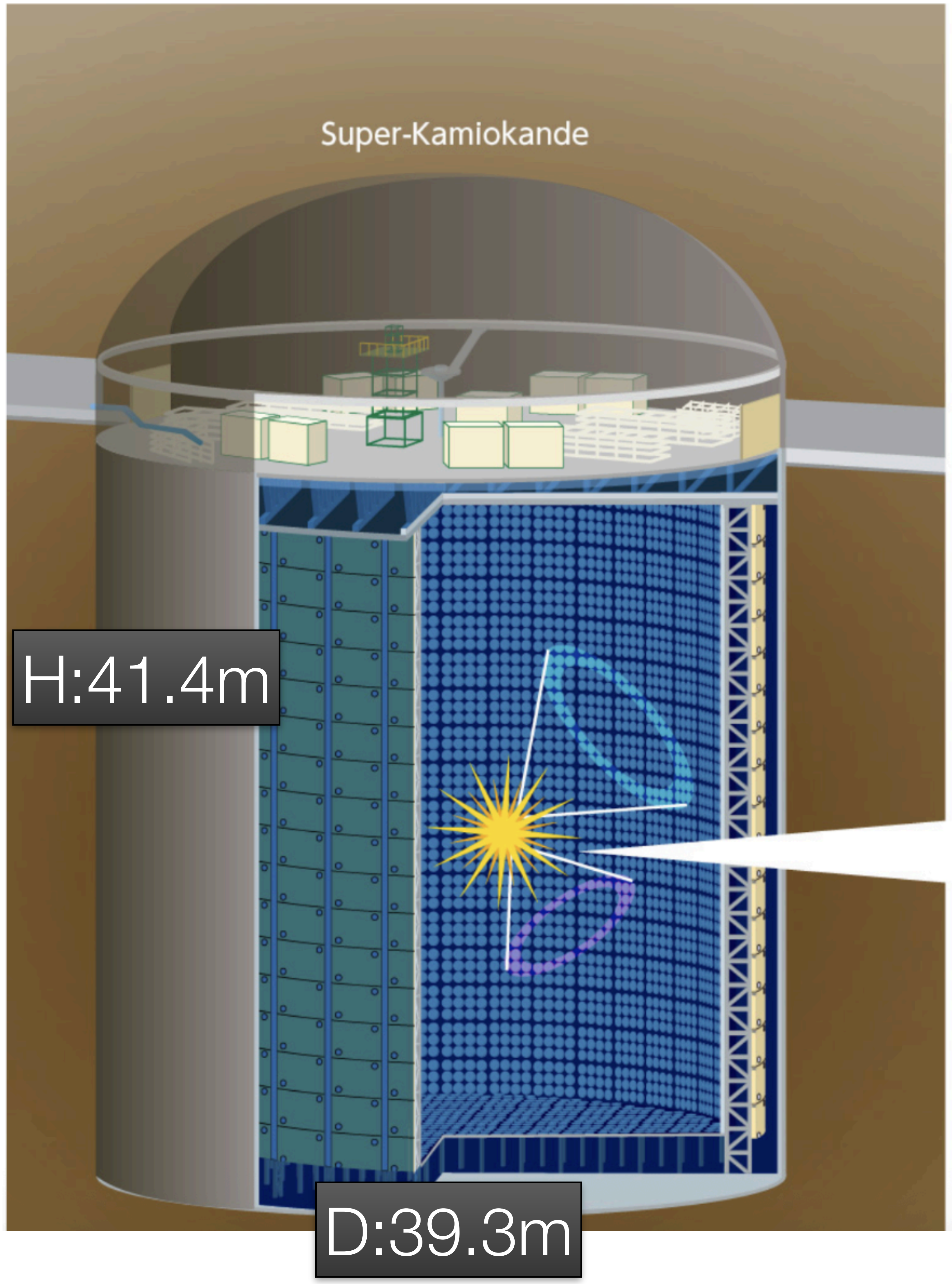
- Off-axis 2.5 deg to measure $\nu(\bar{\nu})$ interactions before oscillation occurs
- Refurbished UA1 magnet, field 0.2T
  - Momentum and charge measurement
- Upstream π^0 detector (POD)
- **T**ime **P**rojection **C**hambers (TPC)
  - Tracking detector
  - Particle identification
- **F**ine **G**rained **D**etectors (FGD)
  - FGD1: CH scintillator tracker
  - FGD2: CH and H_2O layers
  - Both used as target for ν
- Inner tracker surrounded by electromagnetic calorimeter (ECal) and muon detector





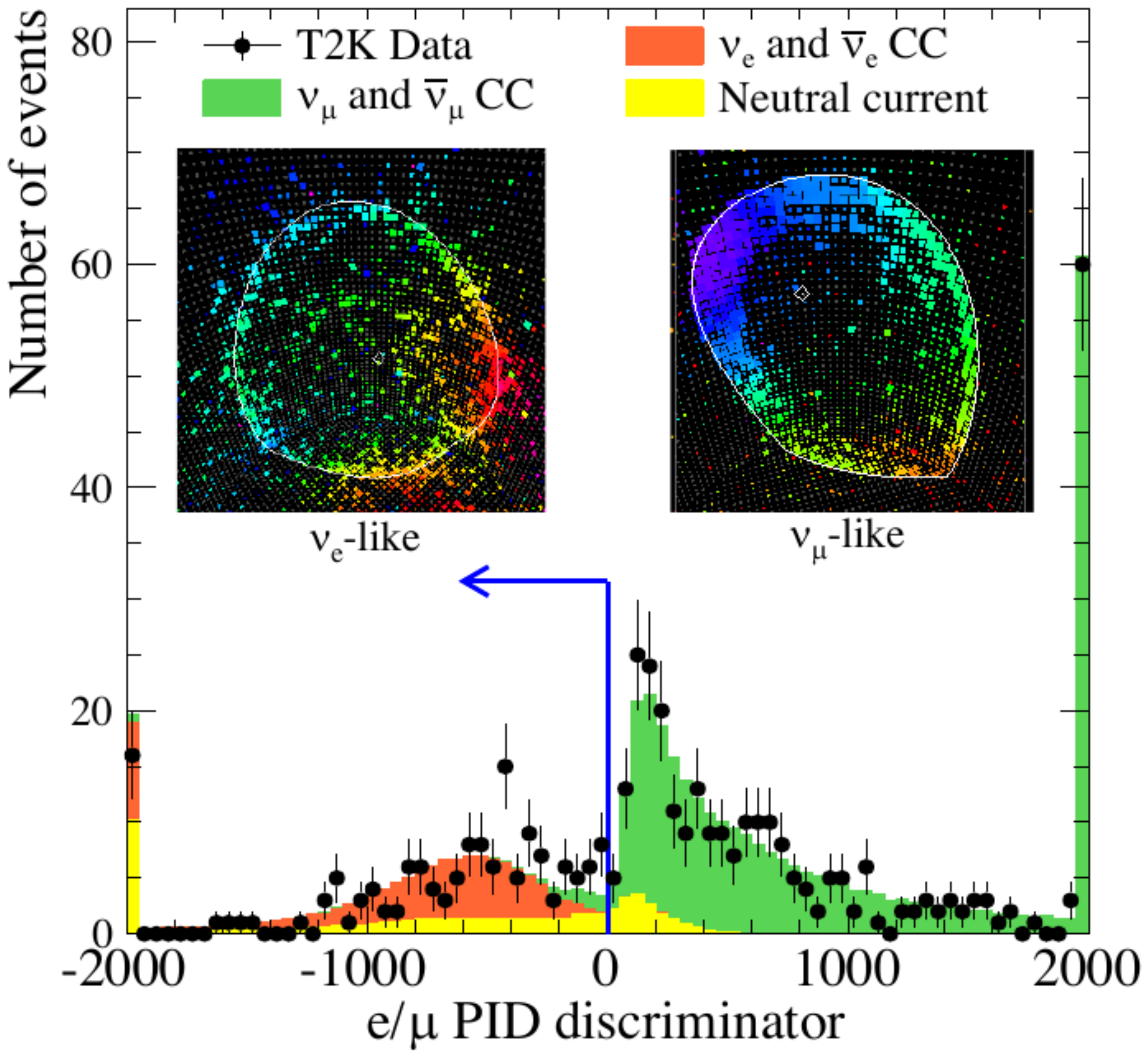
Talk by X.Zhao, Recent T2K neutrino-nucleus cross-section results

Super Kamiokande



- 50 kton water Cherenkov tank used as T2K far detector with Gd added starting from 2020
- Located 1000m underground in Kamioka mine
- ~11 000 20” PMTs for inner detectors and ~2000 8” PMTs for outer detector

Adapted from arXiv:1910.03887v2



Good μ/e separation based on ring shape

$\nu/\bar{\nu}$ separation uses information about the beam mode

Oscillation Analysis Strategy

using external constrains

Neutrino Flux Model

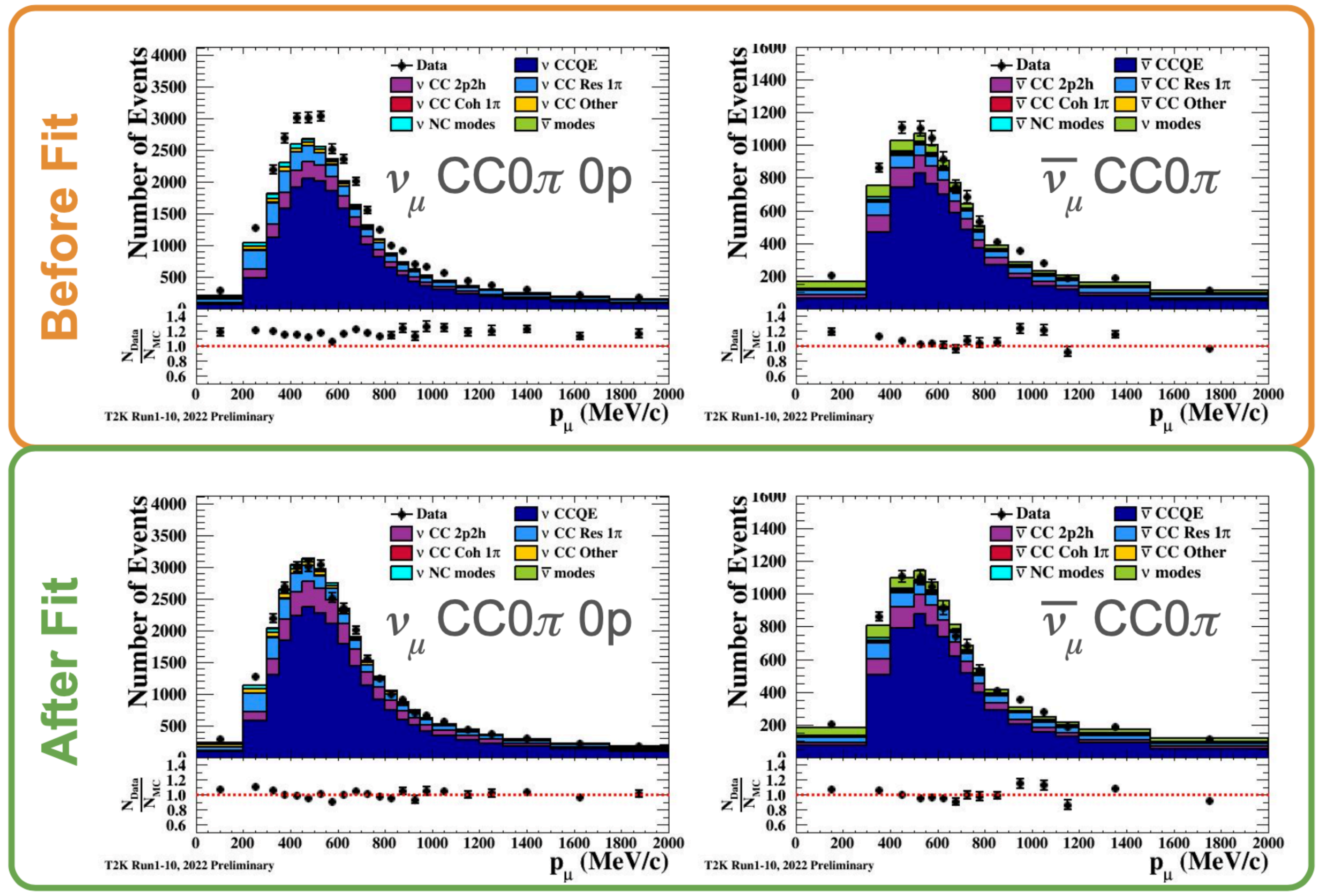
ND280 Detector Model

Cross section Model

ND280 Near Detector Fit
Constrain flux and cross section uncertainities

ND280 Data

22 samples based on
- Beam configuration
- Taget CH/H20
- Number pions, protons, photons

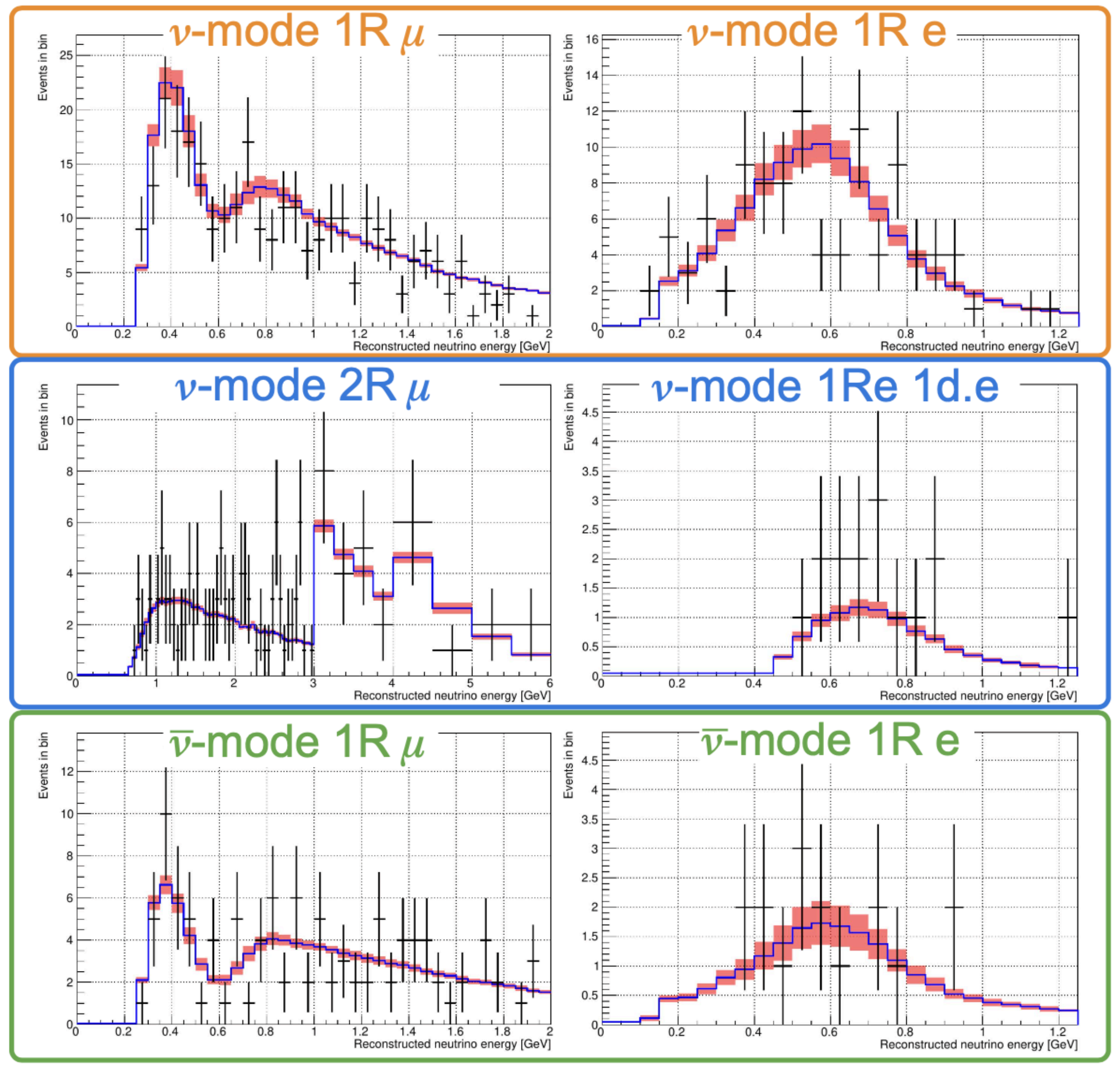


Far Detector Model

Far Detector Fit
Combine flux, cross section and ND280 to predict expected event rates at FD

Super-K Data

6 samples

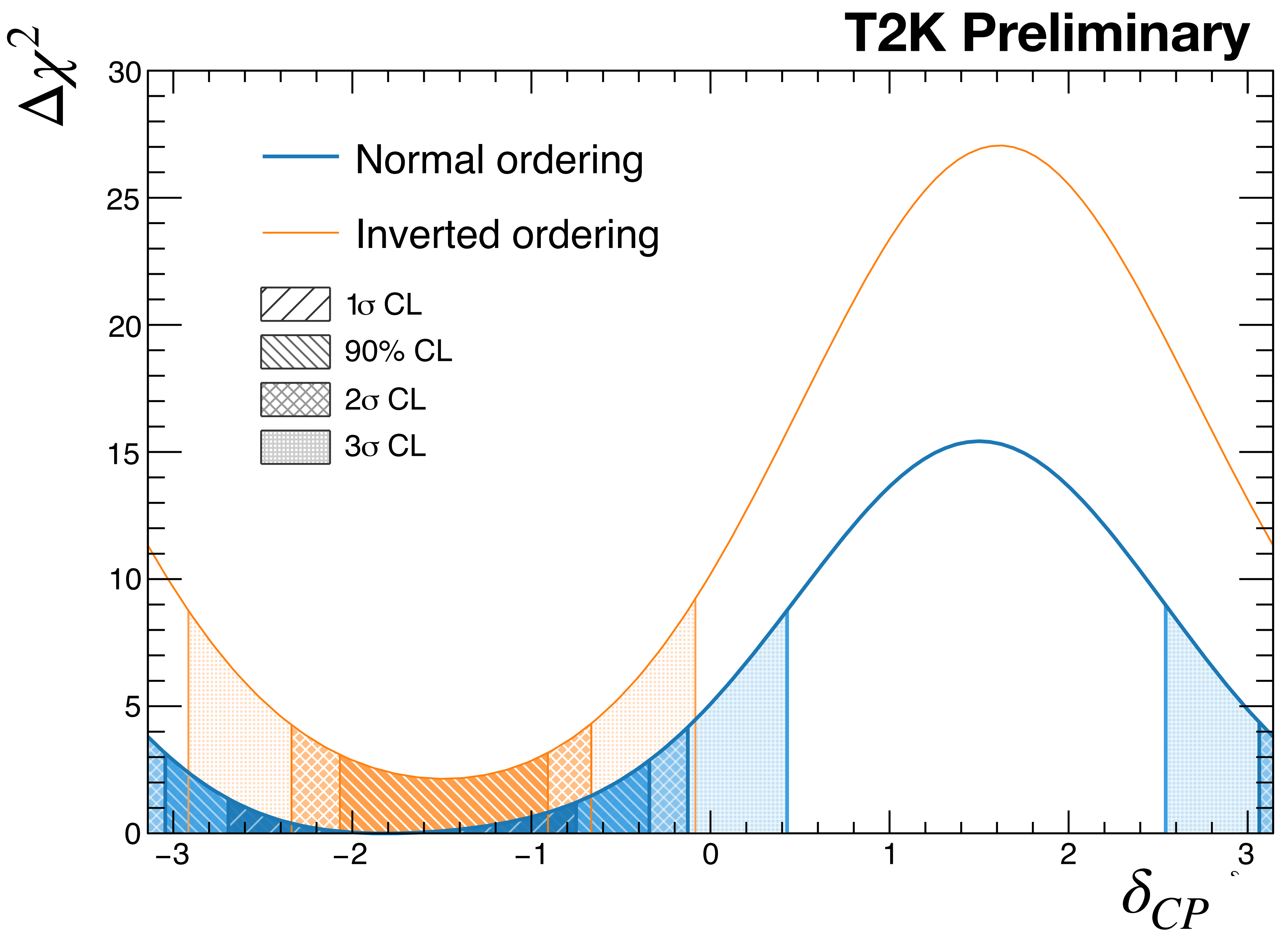


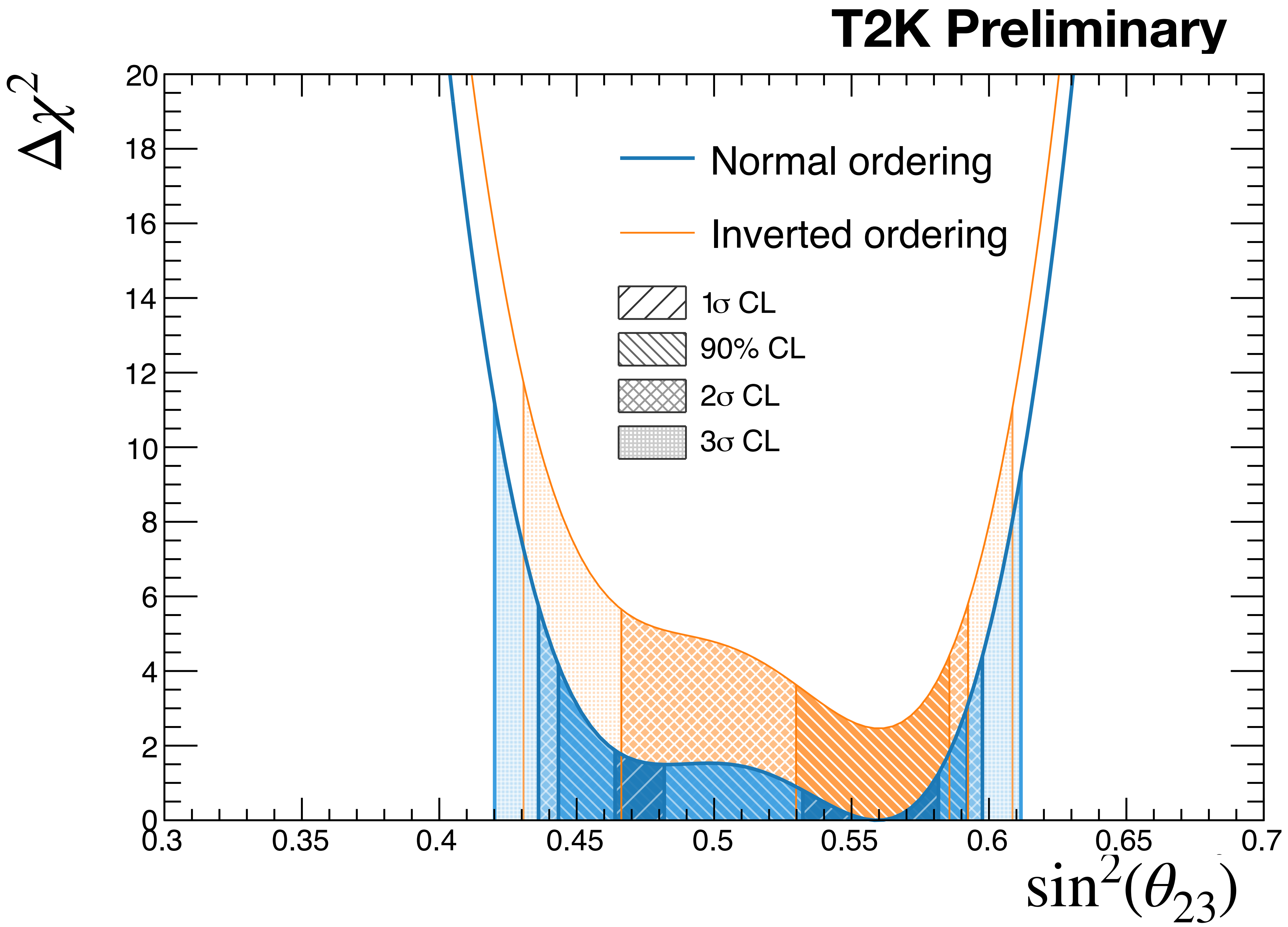
Oscillation Parameters

Two analyses :
Frequentist- ND280 and FD fits are done separately after each other
Bayesian - ND280 and FD are fitted together at the same time

T2K Oscillation Analysis Results

~10% Increased statistics for $\bar{\nu}$ mode compared to the previous analysis





Total :

ν: 2.17 x 10^{21} POT

$\bar{\nu}$: 1.65 x 10^{21} POT

Confidence level	Interval NO	Interval IO
1σ	[-2.69,-0.75]	
90%	[-3.04,-0.34]	[-2.07,-0.91]
2σ	[-π,-0.13] ∪ [3.06,π]	[-2.34,-0.67]
3σ	[-π,0.43] ∪ [2.54,π]	[-2.92,-0.08]

Feldman-Cousins confidence intervals for δ_{CP}

- Best fit value close to maximal CP-violation $\delta_{CP} \sim -\pi/2$
- CP conservation values $\delta_{CP}=0,\pm\pi$ outside 90% CL
- Weak preference for upper octant θ_{23} and NO

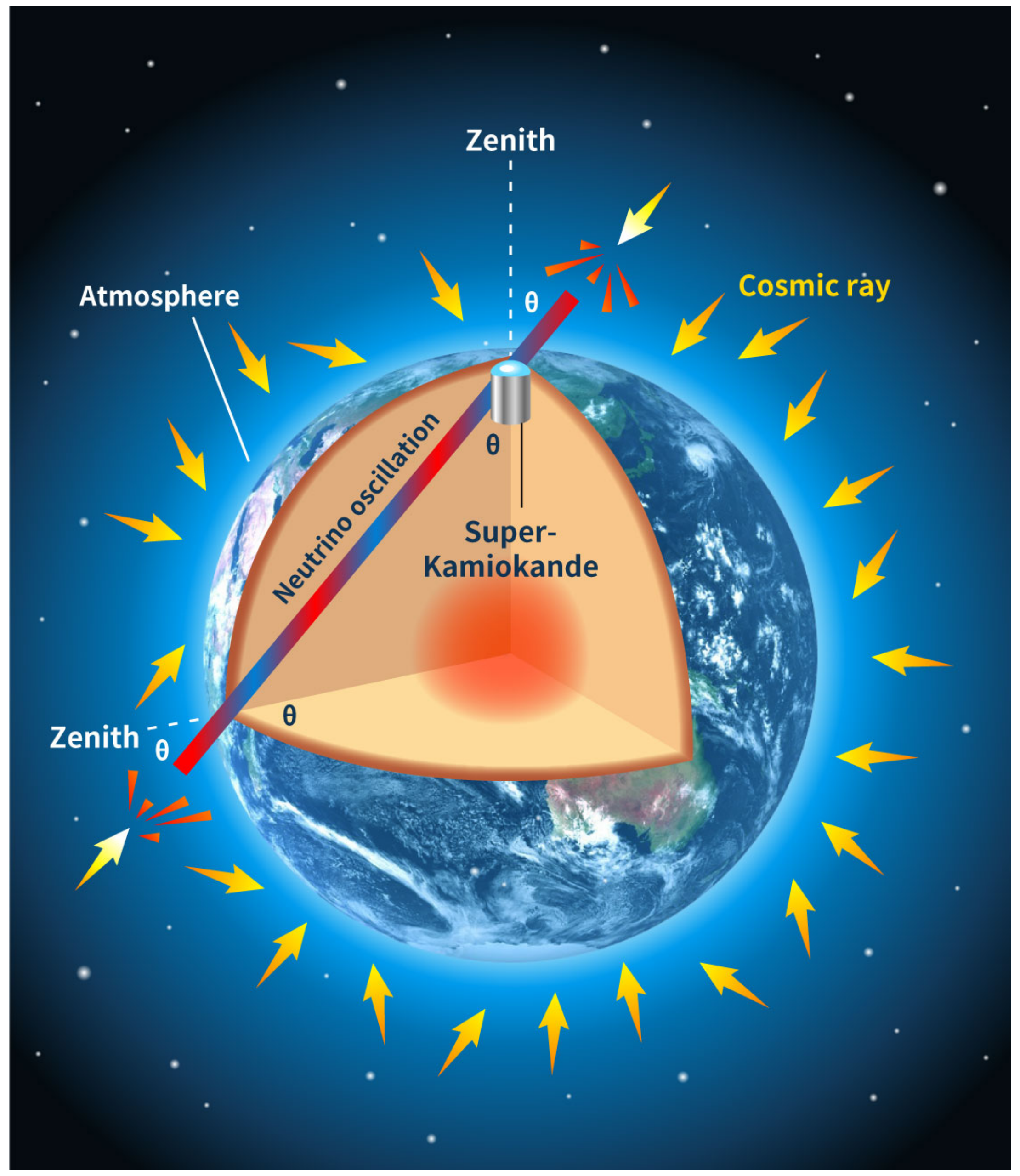
Publication in preparation

Joint T2K and Super-K Analysis

Atmospheric Neutrino Oscillations in Super-K

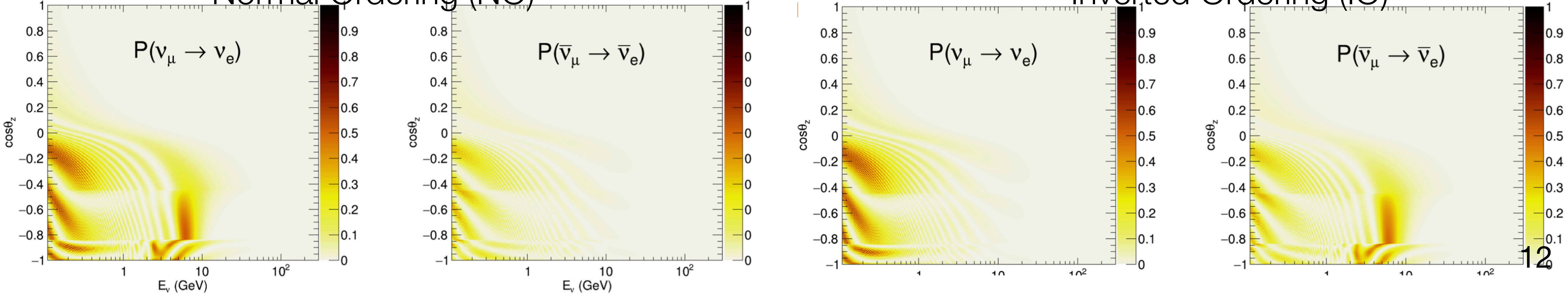
- Neutrinos produced by cosmic rays in upper atmosphere: large range of energies (MeV-TeV) and propagation length (15km-13000km)

- **Sensitivity to mass ordering** due to matter effects for upward going 2-10 GeV neutrinos
- In NO enhancement of ν_e appearance and no effect for $\bar{\nu}_e$. For IO effect is opposite



Phys.Rev. D 109,072014 (2024)

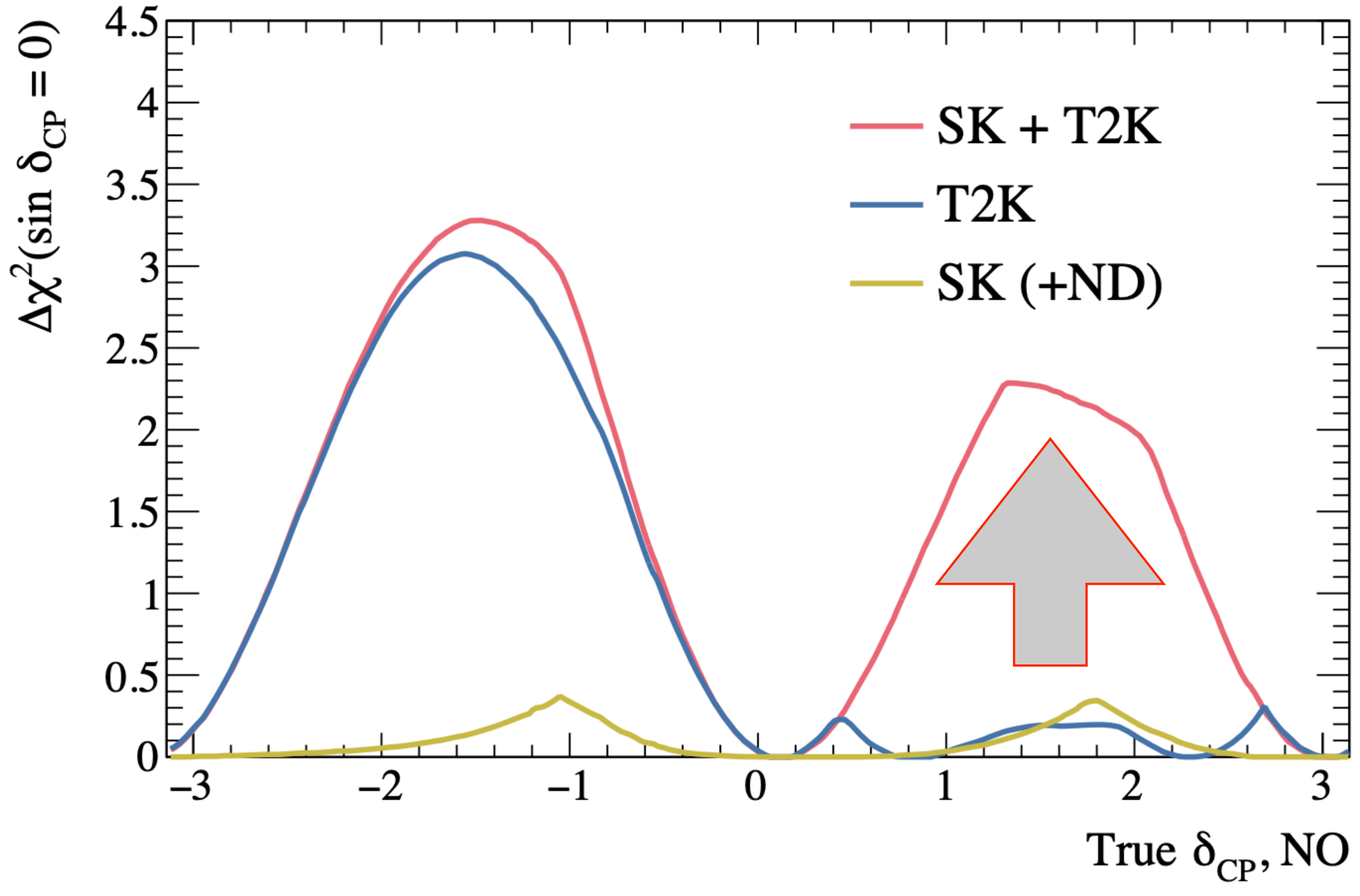
Normal Ordering (NO) | Inverted Ordering (IO)

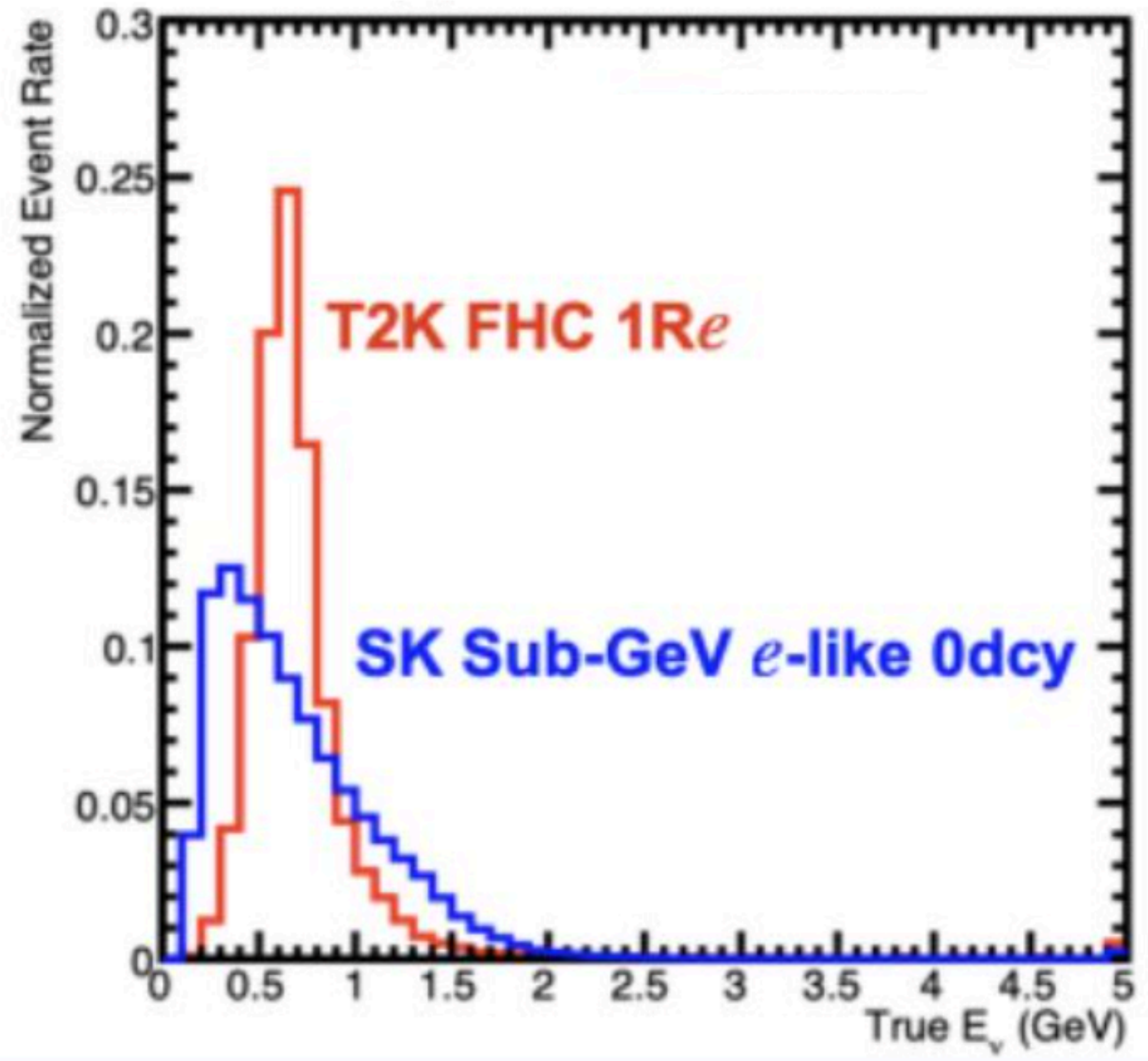


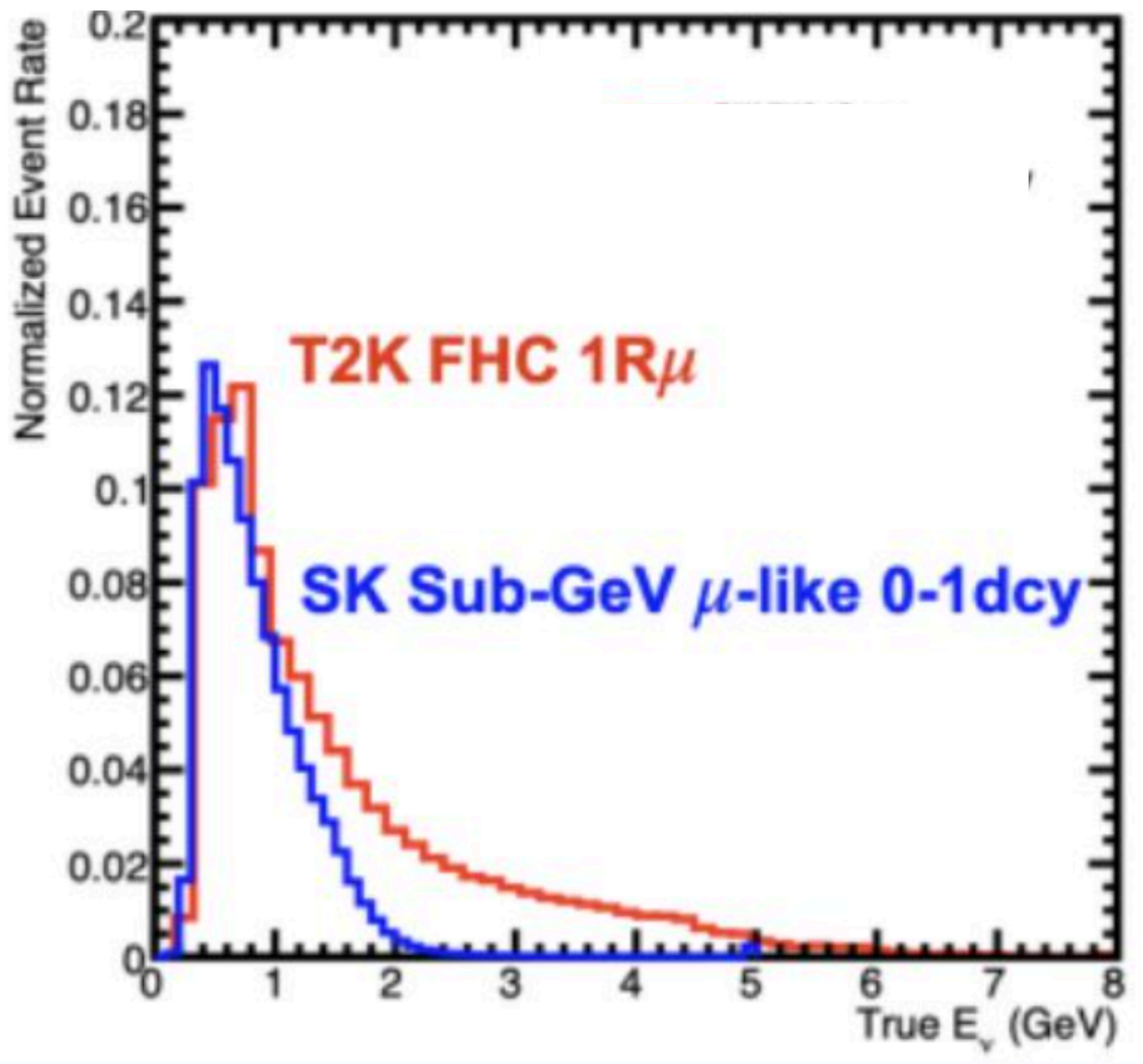
Motivation for Joint T2K+Super-K Analysis

- Adding Super-K atmospheric samples help to break degeneracies between δ_{CP} and mass ordering → boost sensitivity to CP
  - T2K has good sensitivity to δ_{CP} but not to mass ordering
  - Super-K has good constraint on mass ordering but not on δ_{CP}

Sensitivity to reject CP-conserving hypothesis





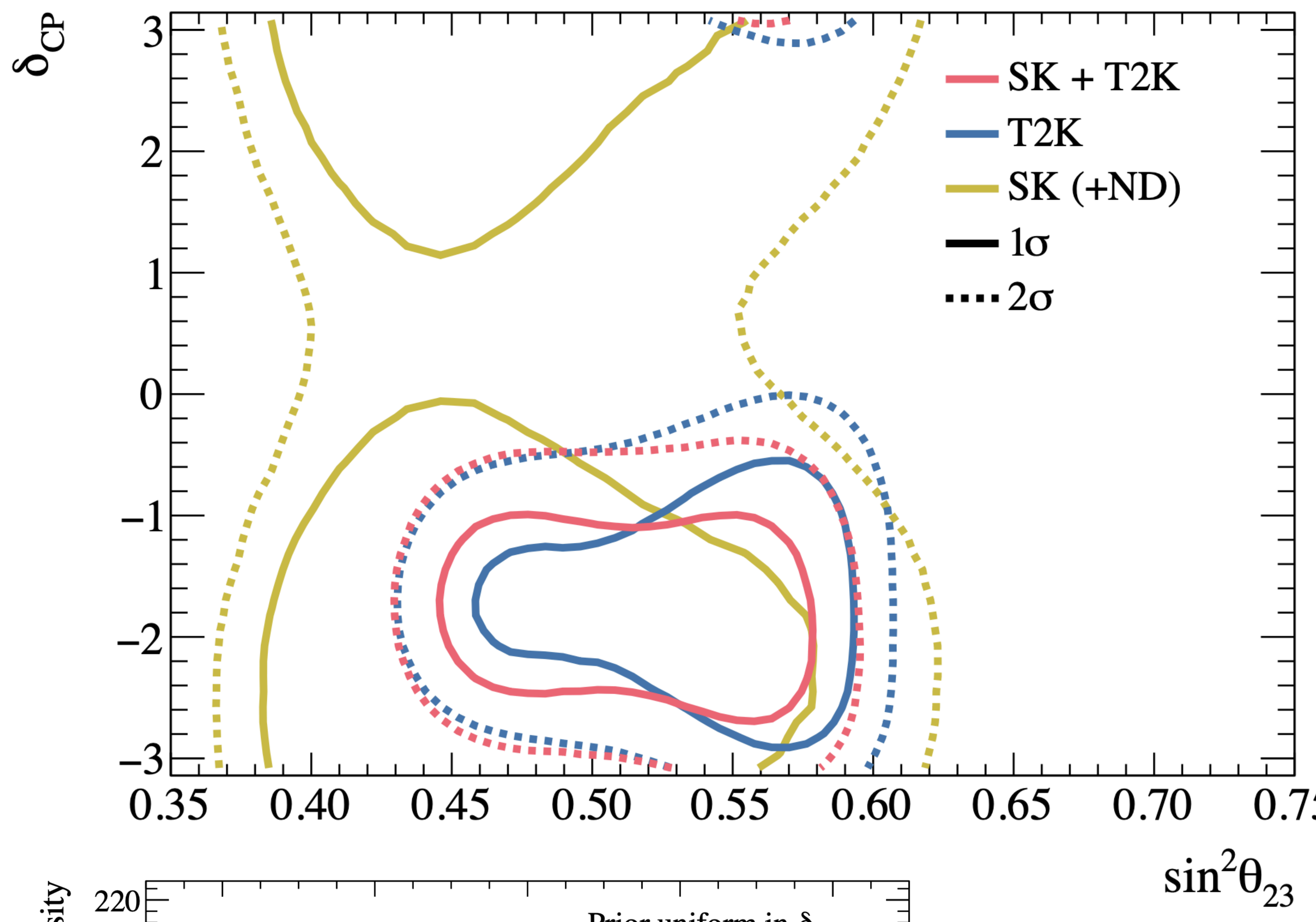


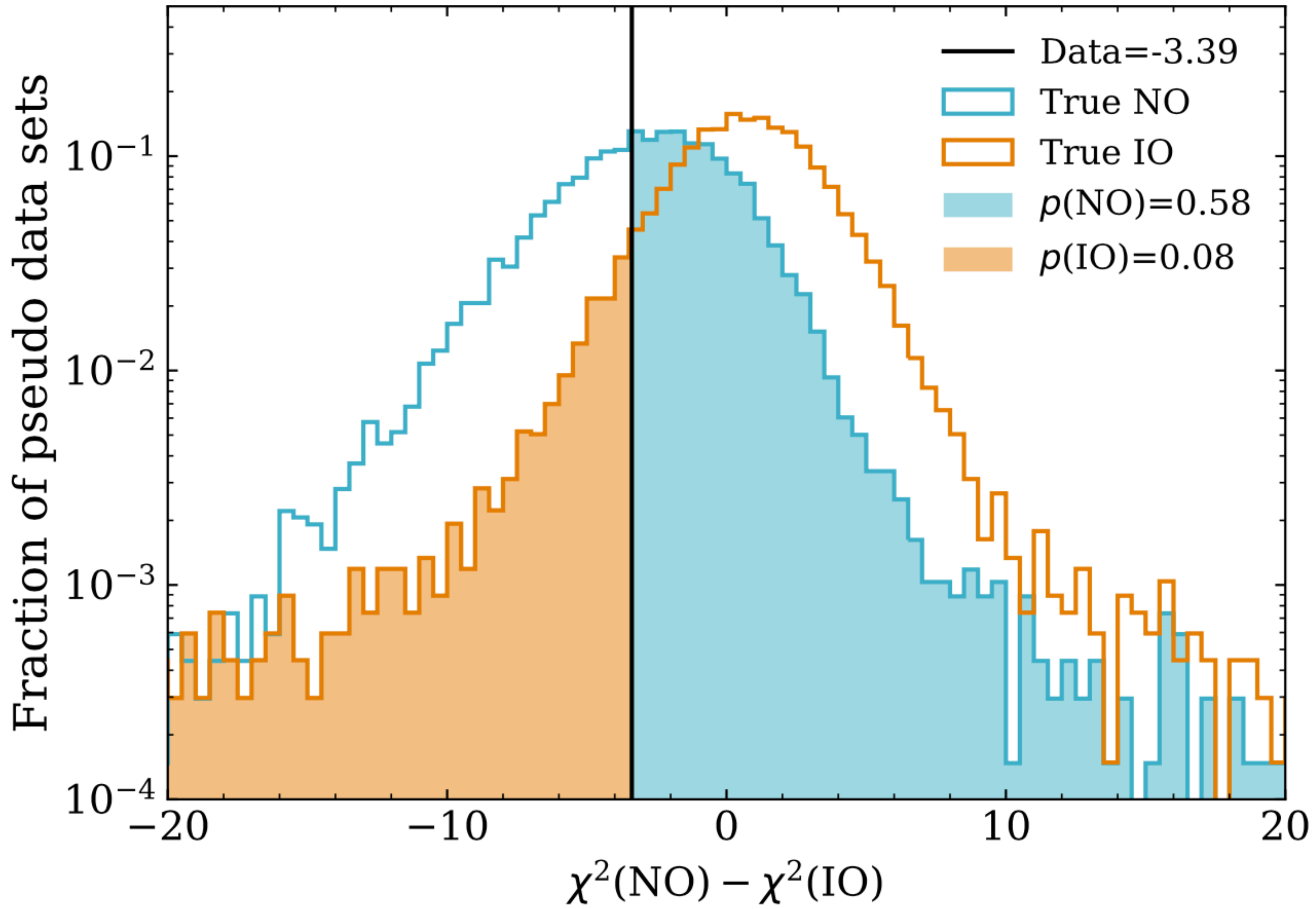
- Share same detector and have overlapping energy spectrum
  - Developed common interaction model for T2K-beam and Super-K low energy sample
  - Common detector model with correlated systematics included into joint fit

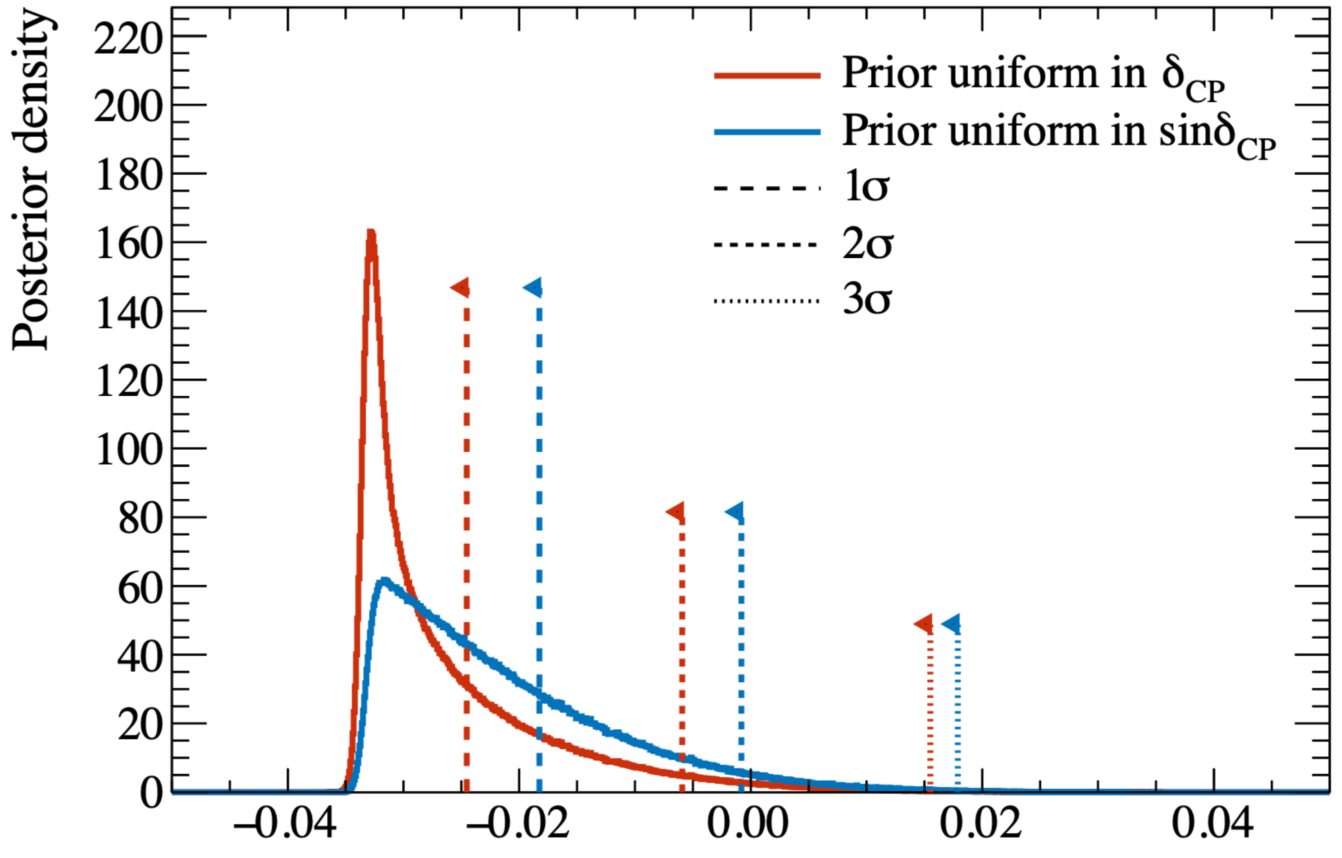
Joint T2K+Super-K Oscillation Results

PRL 134, 011801(2024)

- Super-K and T2K have different preferences for θ_{23} octant → no strong preference for θ_{23} octant in joint fit
- Jarlskog invariant CP conserving value (J_{CP}=0) is excluded at 1.9-2.0σ
- Limited preference for NO (rejecting IO at 1.2σ)







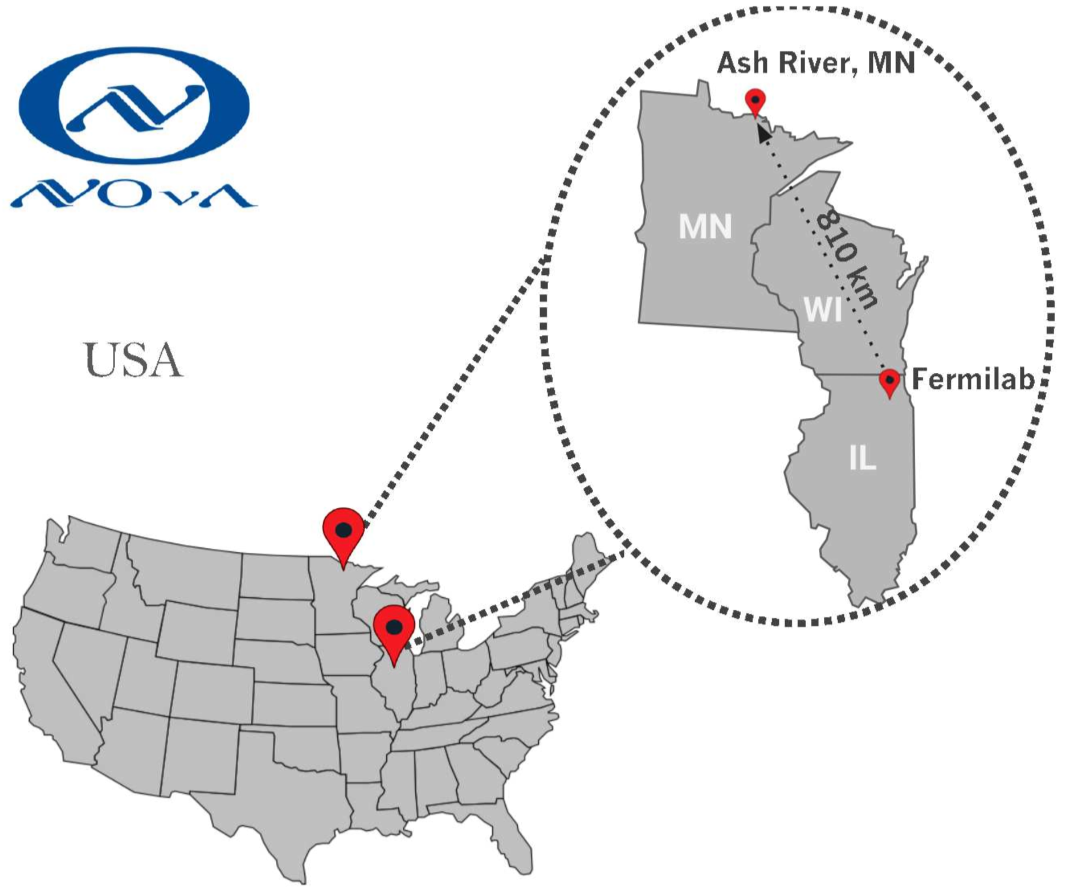
$J_{CP} = sin\theta_{13}cos^2\theta_{13}sin\theta_{12}cos\theta_{12}sin\theta_{23}cos\theta_{23}sin\delta_{CP}$

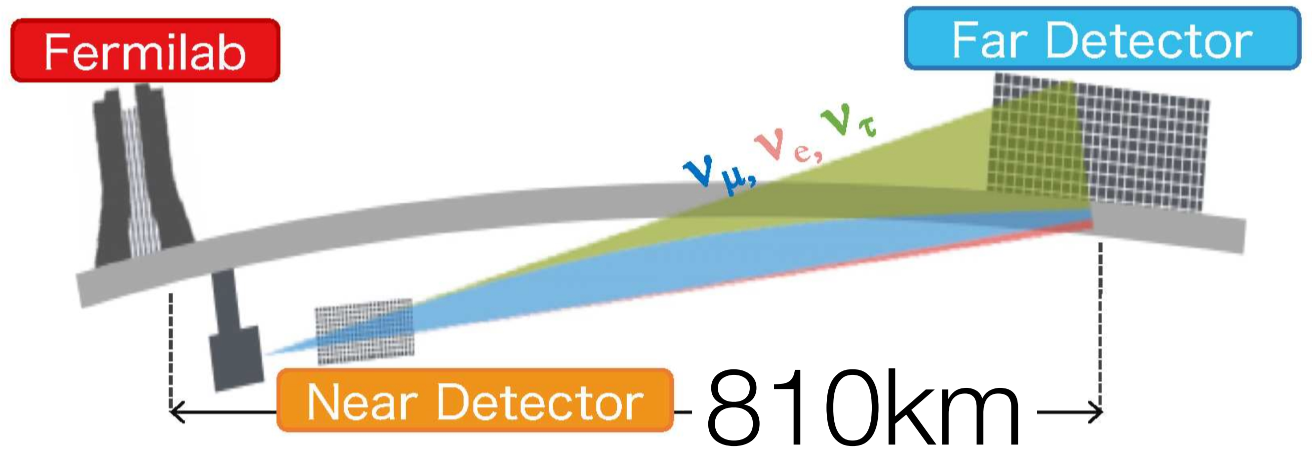
Joint T2K and NOvA Analysis

T2K and NOvA Experiments

Complementary experiments with different baseline, flux, detector technologies

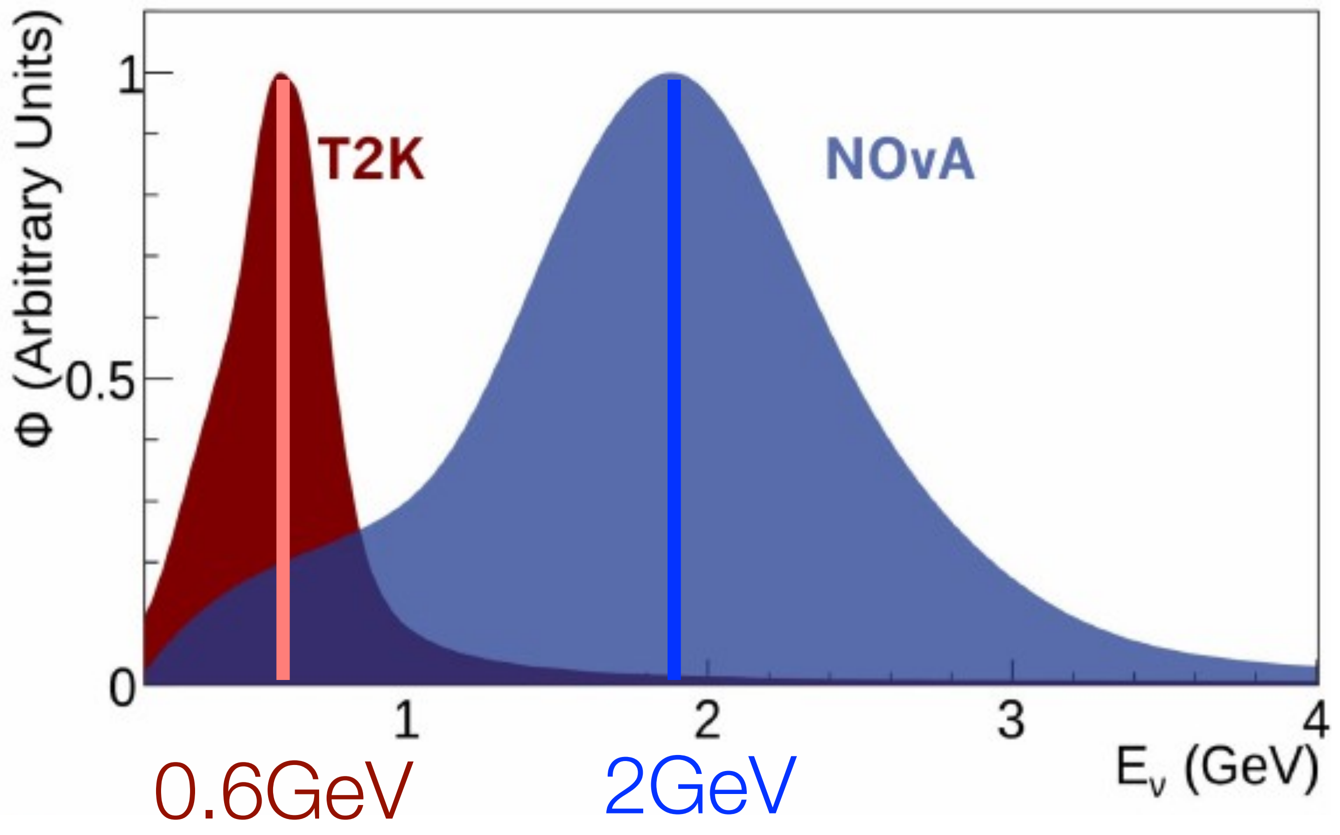
In T2K ND different from FD share uncertainties fitted and constrained via model

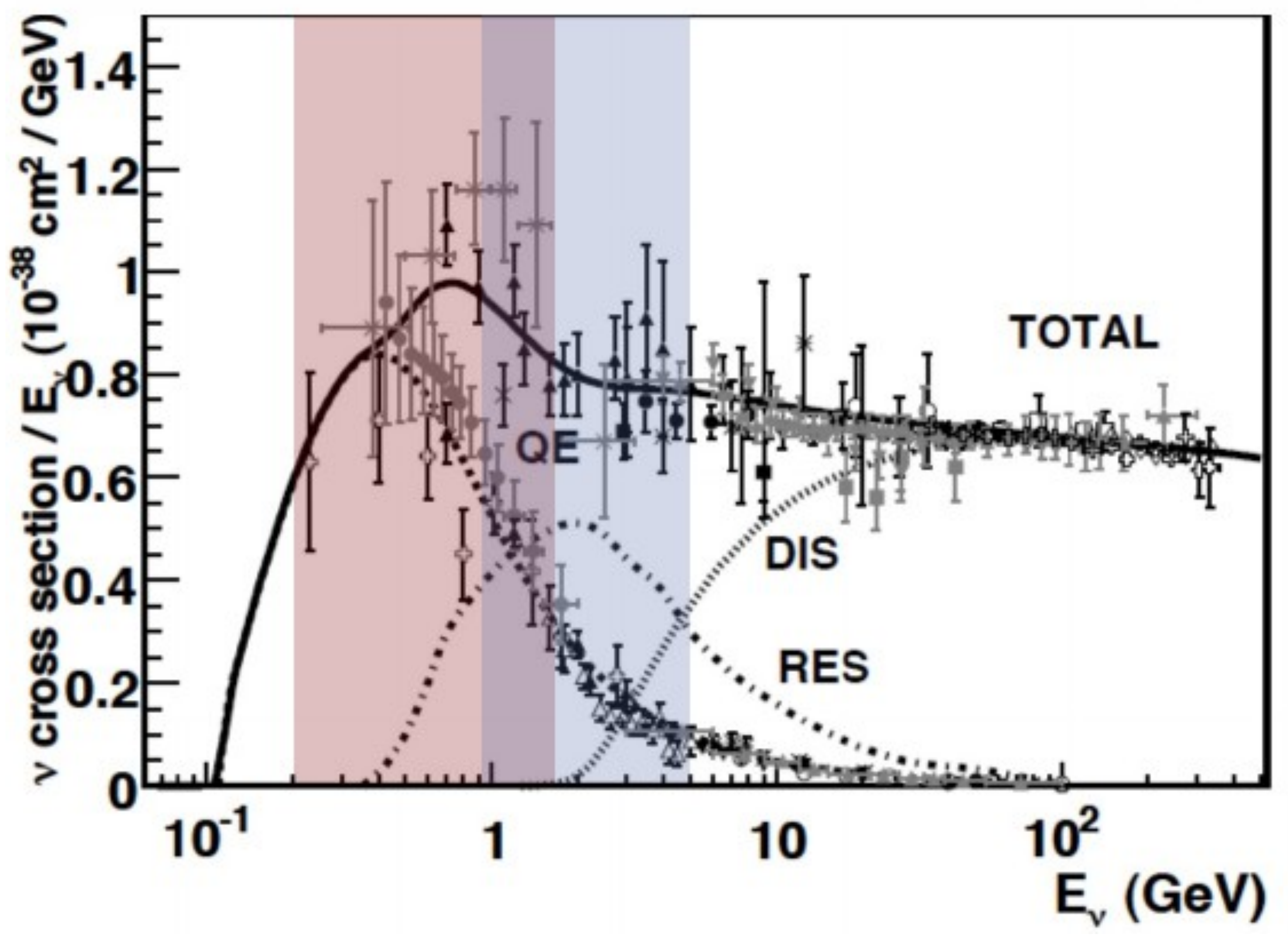




NOvA ND and FD are both active scintillator trackers (cancelation of uncertainties)

NOvA has higher E_ν





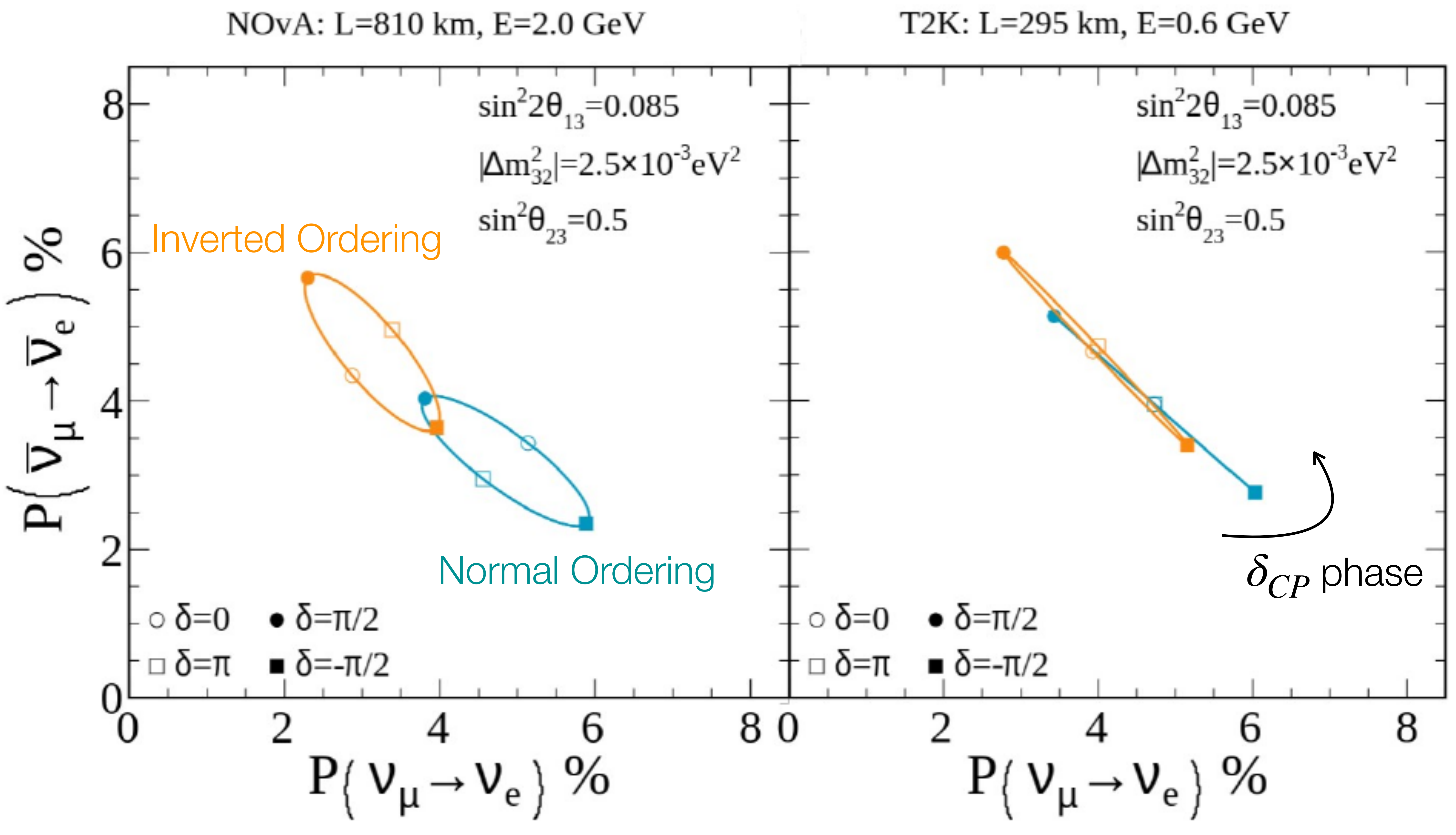
Motivation for Joint T2K+NOvA Analysis

- Different energies and baselines provide different oscillation probabilities and sensitivity to oscillation parameters

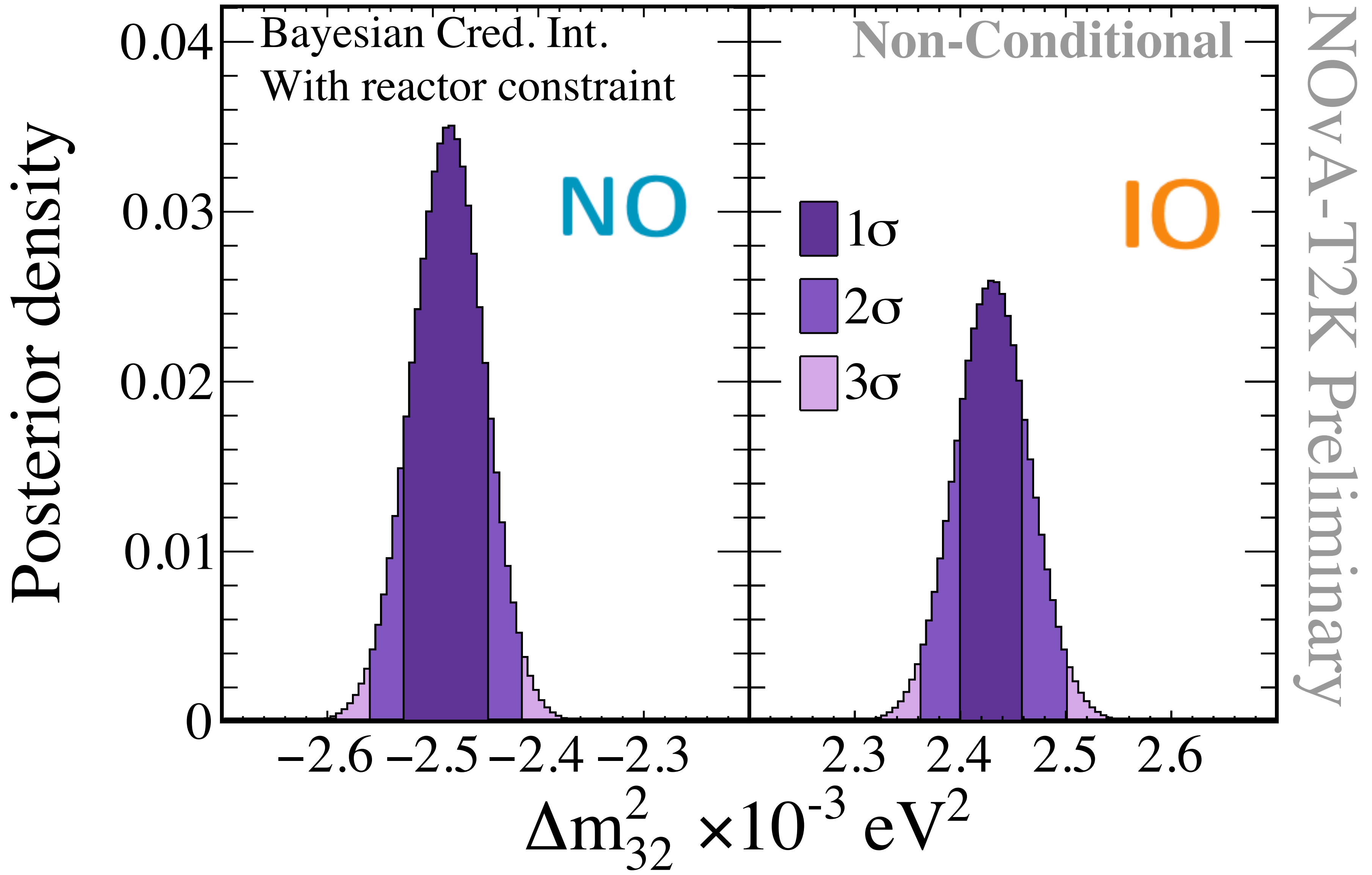
- Lifting degeneracies in each experiment between δ_{CP} and mass ordering

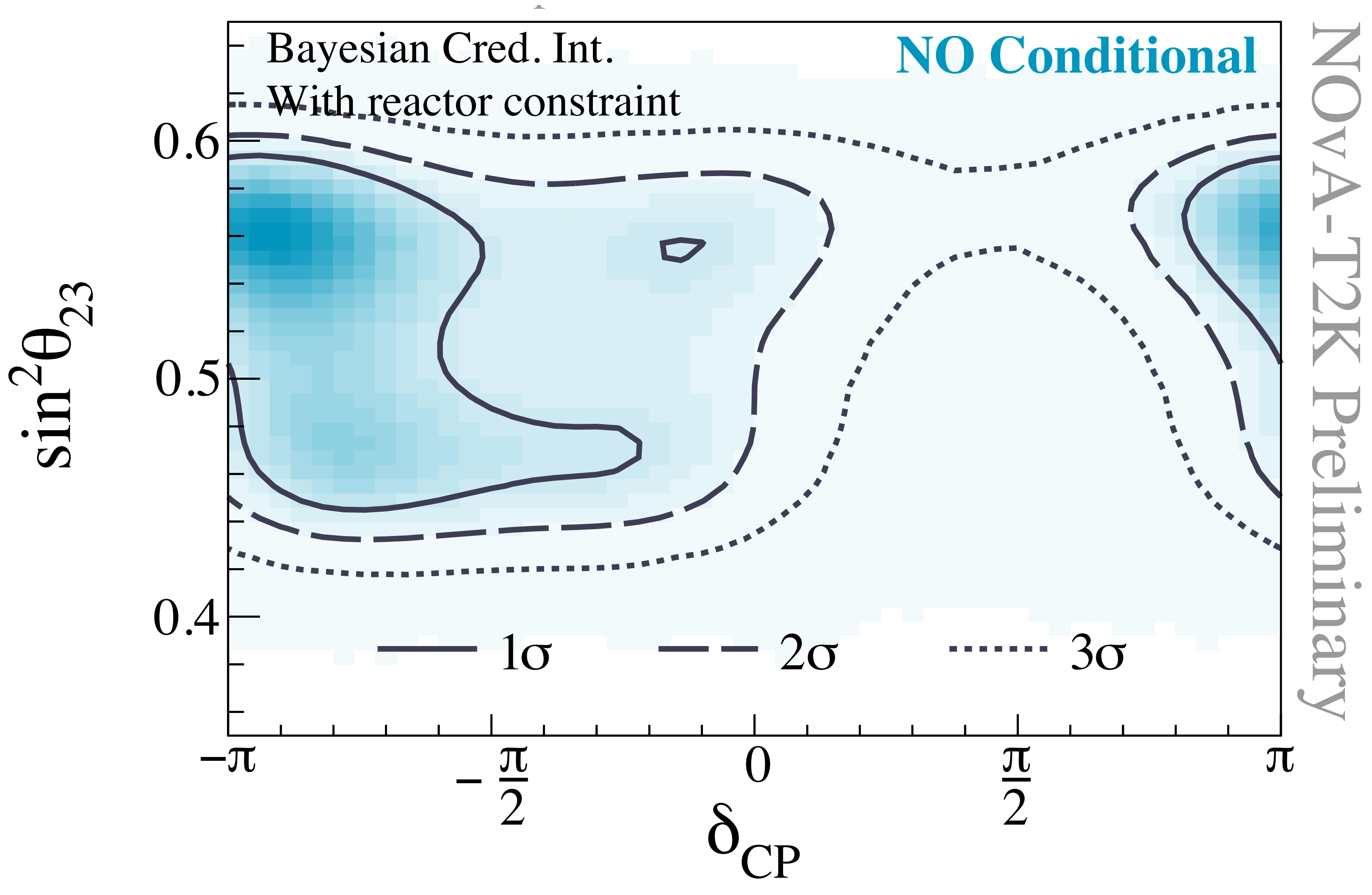
- NOvA has better mass ordering sensitivity due to longer baseline
- Degeneracy around $\delta_{CP} = \pm\pi/2$ CPV

- T2K more sensitivity to δ_{CP}
- Degeneracy around $\delta_{CP} = 0,\pi$ no-CPV



Joint T2K+NOvA Oscillations Results





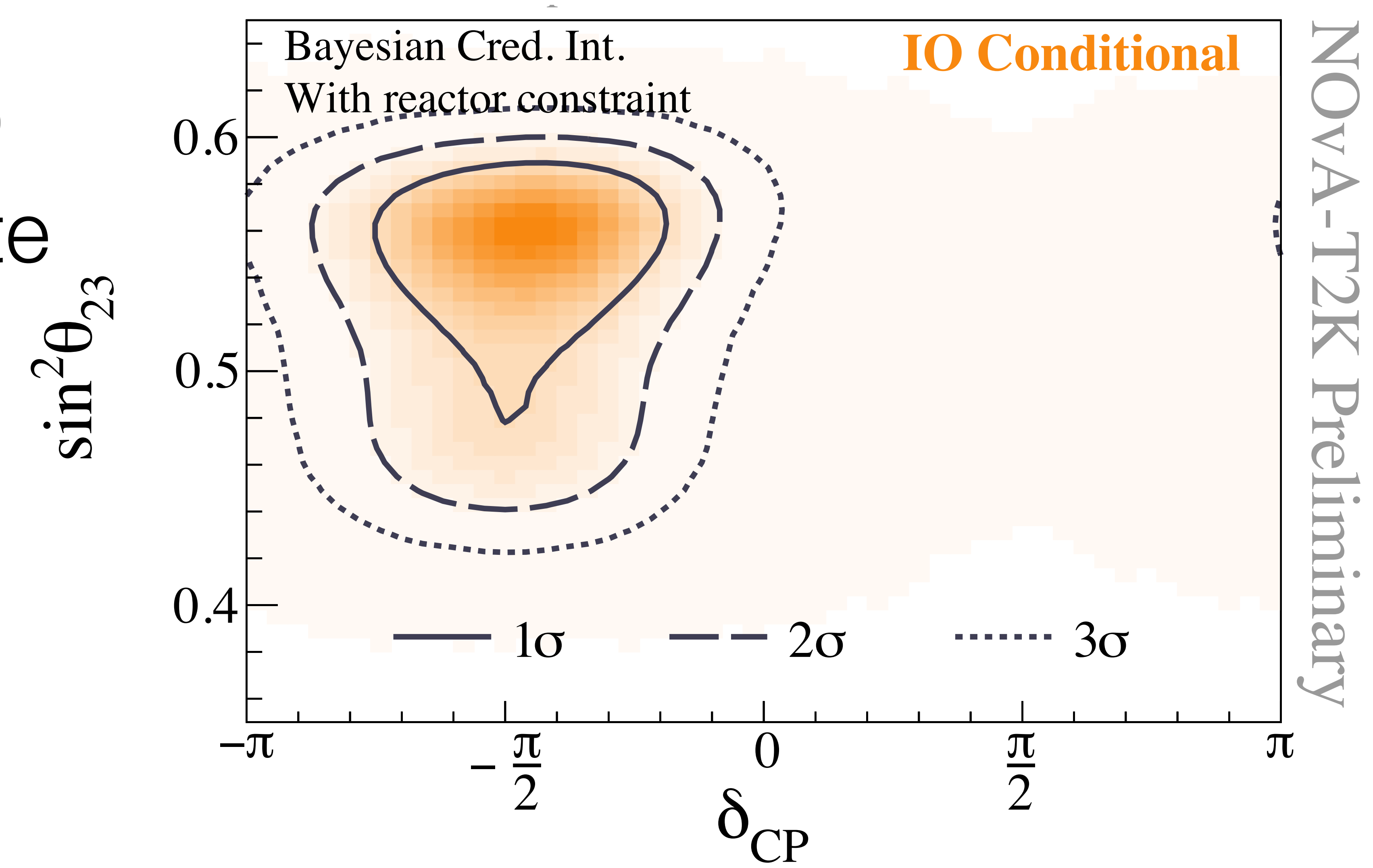
Normal ordering (NO)

- Broad range of δ_{CP} allowed
- No preference for $\delta_{CP} = \pi/2$ (outside 3σ)

- Slight preference IO (θ_{13}dependent) but statistically insignificant (separate fits prefer NO)
- High precision for $|\Delta m^2_{32}| < 2\,\%$

$\Delta m^2_{32}|_{\mathrm{NO}} = 2.43^{+0.04}_{-0.03} \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{32}|_{\mathrm{IO}} = -2.48^{+0.03}_{-0.04} \times 10^{-3}\ \mathrm{eV}^2$

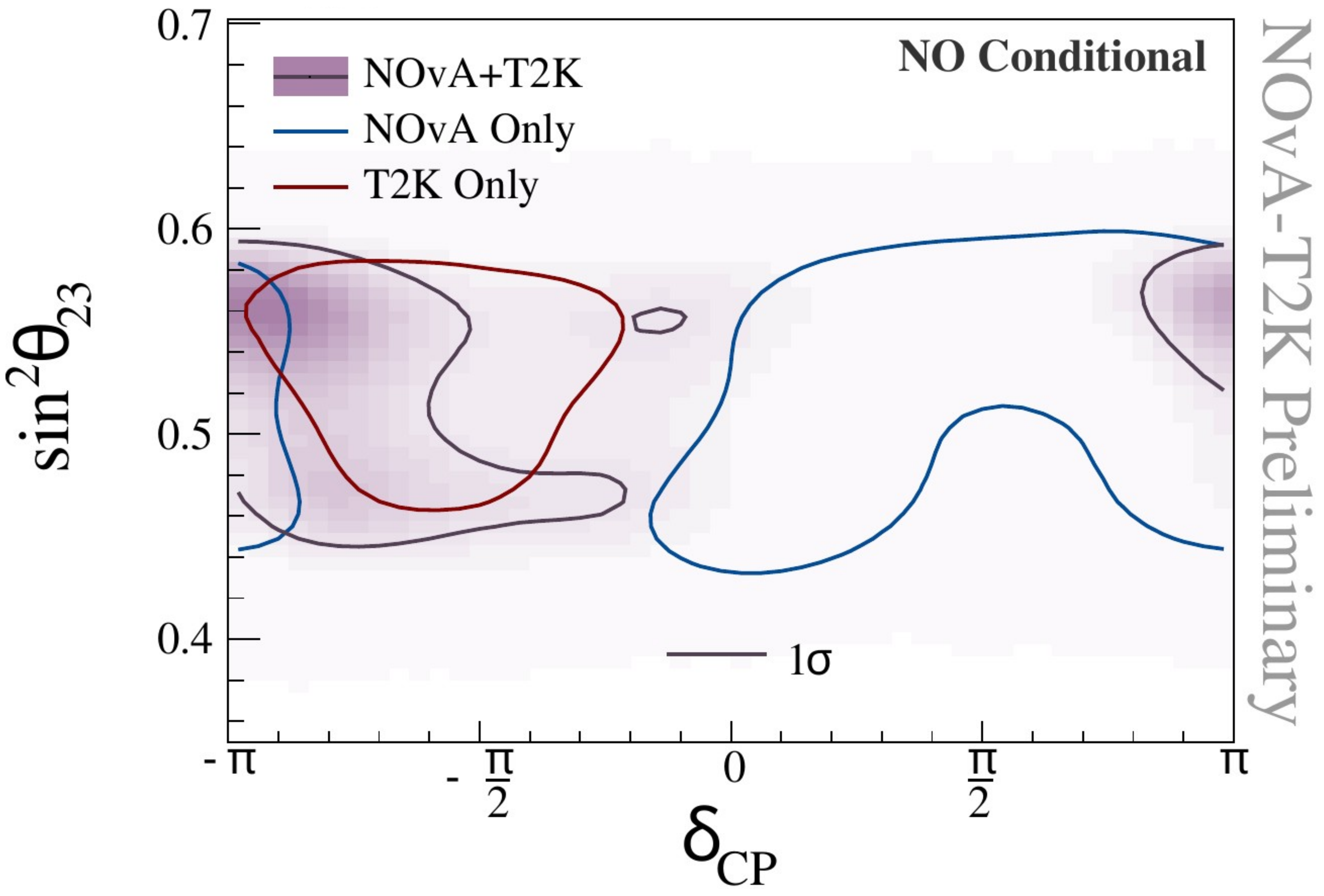


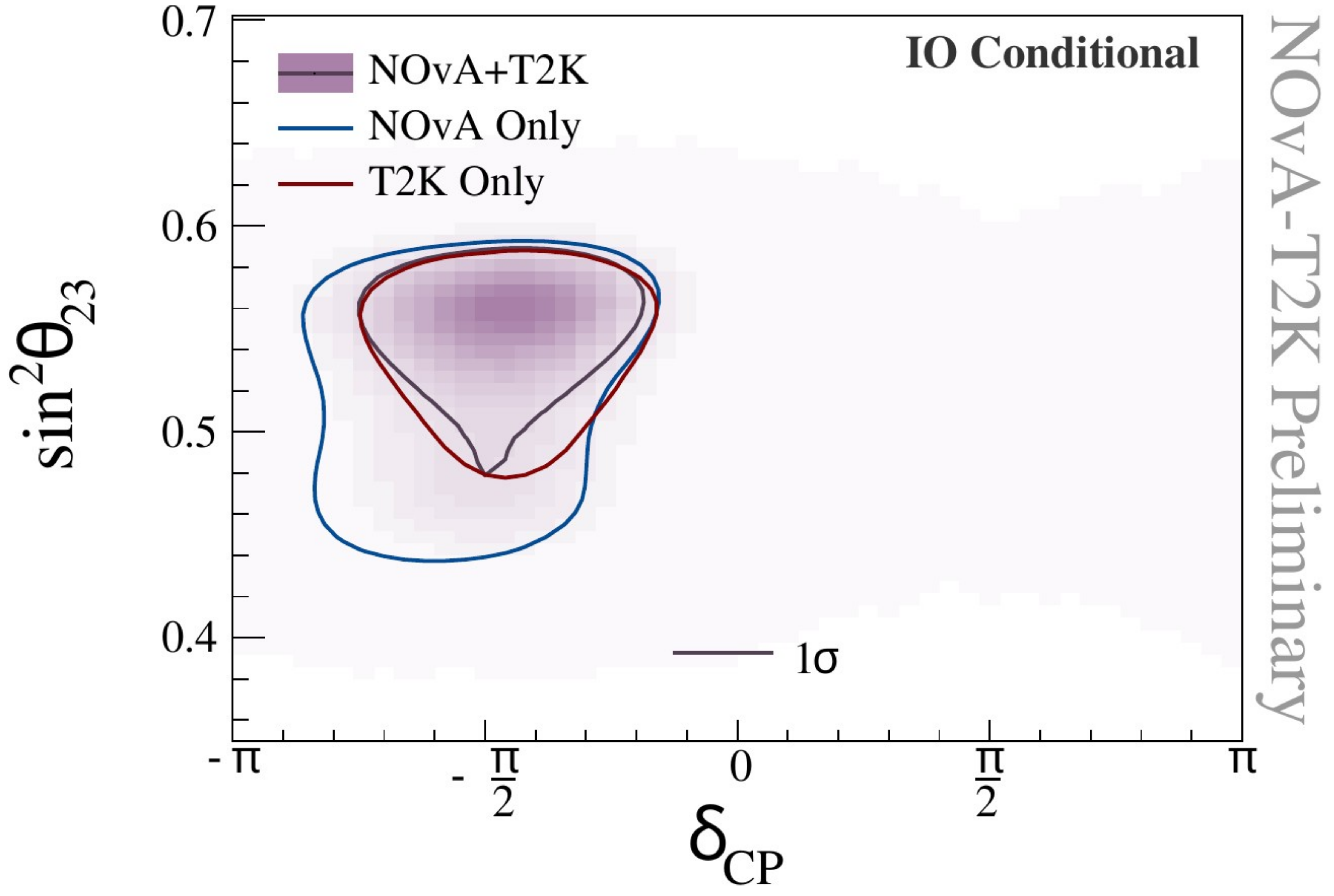
Inverted ordering IO

- CP conserving values $\delta_{CP} = 0,\ \pi$ excluded at 3σ

Publication in preparation

Comparison to NOvA and T2K Results

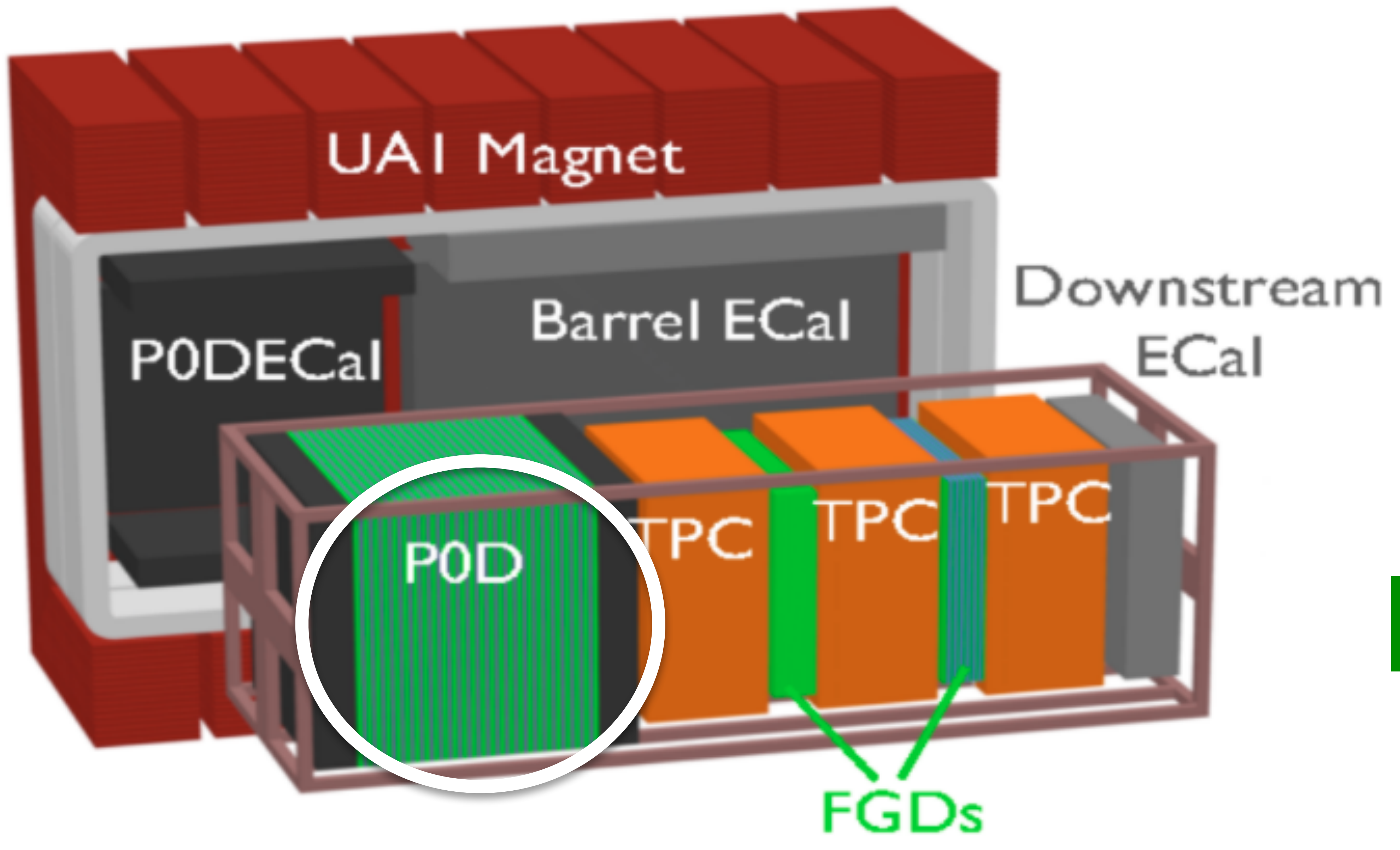




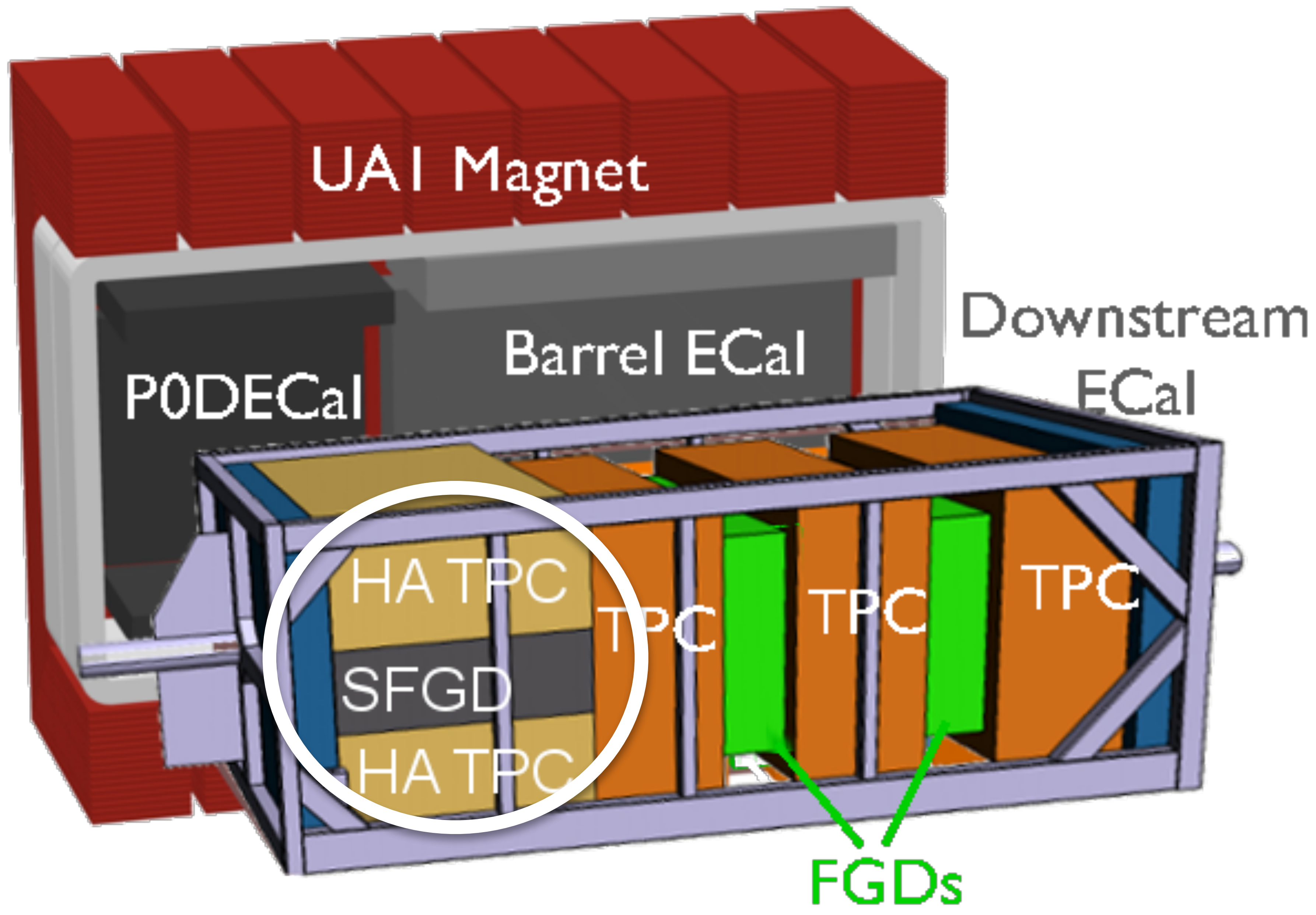
Joint fit agrees with individual fits from T2K and NOvA and improves constrains for inverted mass ordering

ND280 Near Detector Upgrade

2010-2022



Completed in May 2024



- POD detector replaced with Super FGD, 2 High Angle TPCs and Time of Flight

- Improved acceptance and efficiency
- Lower detection thresholds
- Better sensitivity to neutrons
- Larger mass (neutrino target)

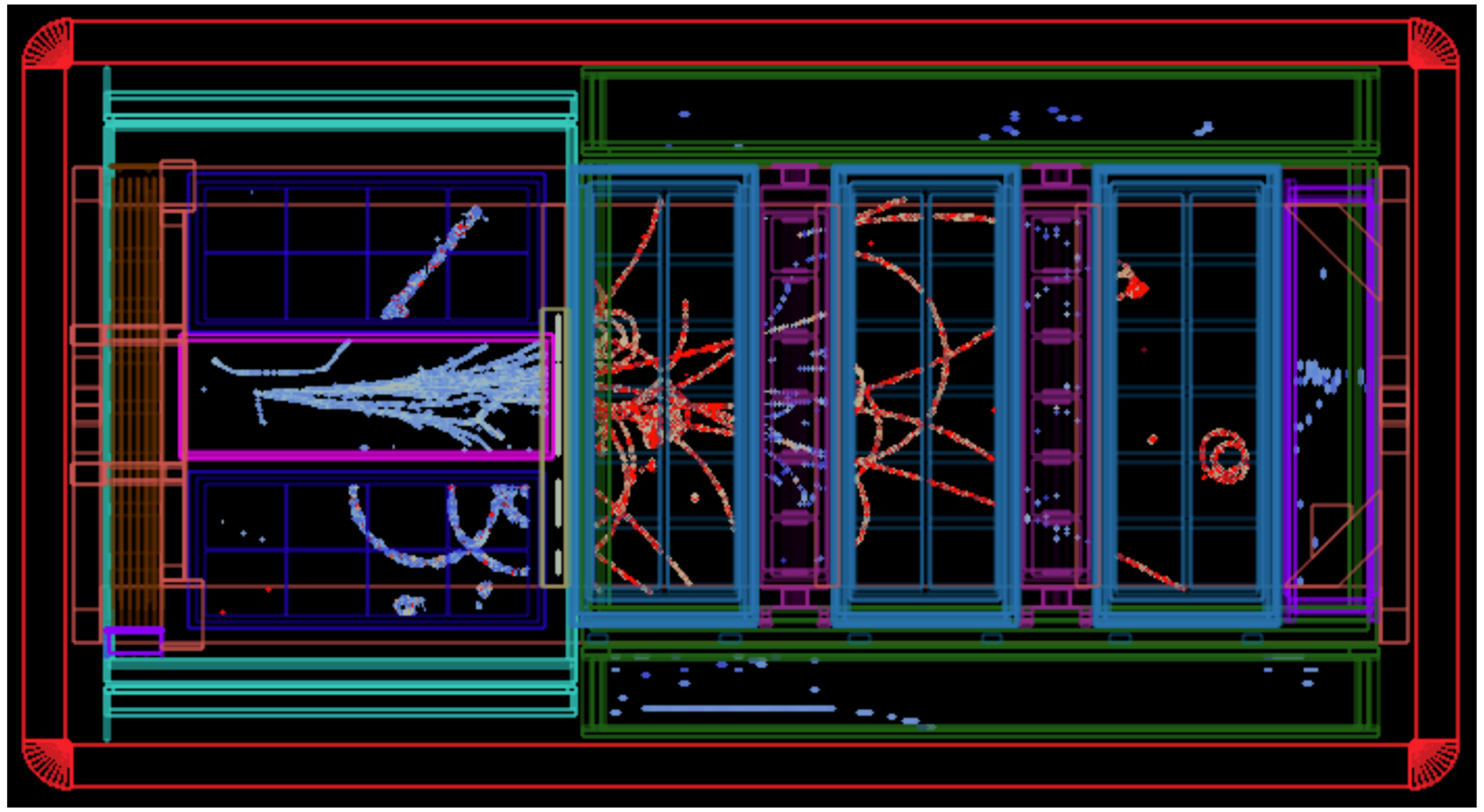
ND280 Near Detector Upgrade

Talks

- 148 L.Giannessi, Super Fine-Grained Detector for the T2K long-baseline neutrino experiment
- 441 A.Chalumeau, AI and Machine Learning Applications at the Near Detector of the T2K Experiment
- 641 M.Varghese, Performance of the High-Angle Time Projection Chamber in the T2K Near Detector Upgrade
- 771 W.Saenz, The T2K ND280 Detector Upgrade

Posters

- 630 L.Giannessi, Commissioning and performance of the TOF detector for the T2K ND280 Upgrade
- 678 U.Virginet, Innovative track reconstruction algorithms and performances of the new High-Angle Time Projection Chambers in the upgraded T2K Near Detector

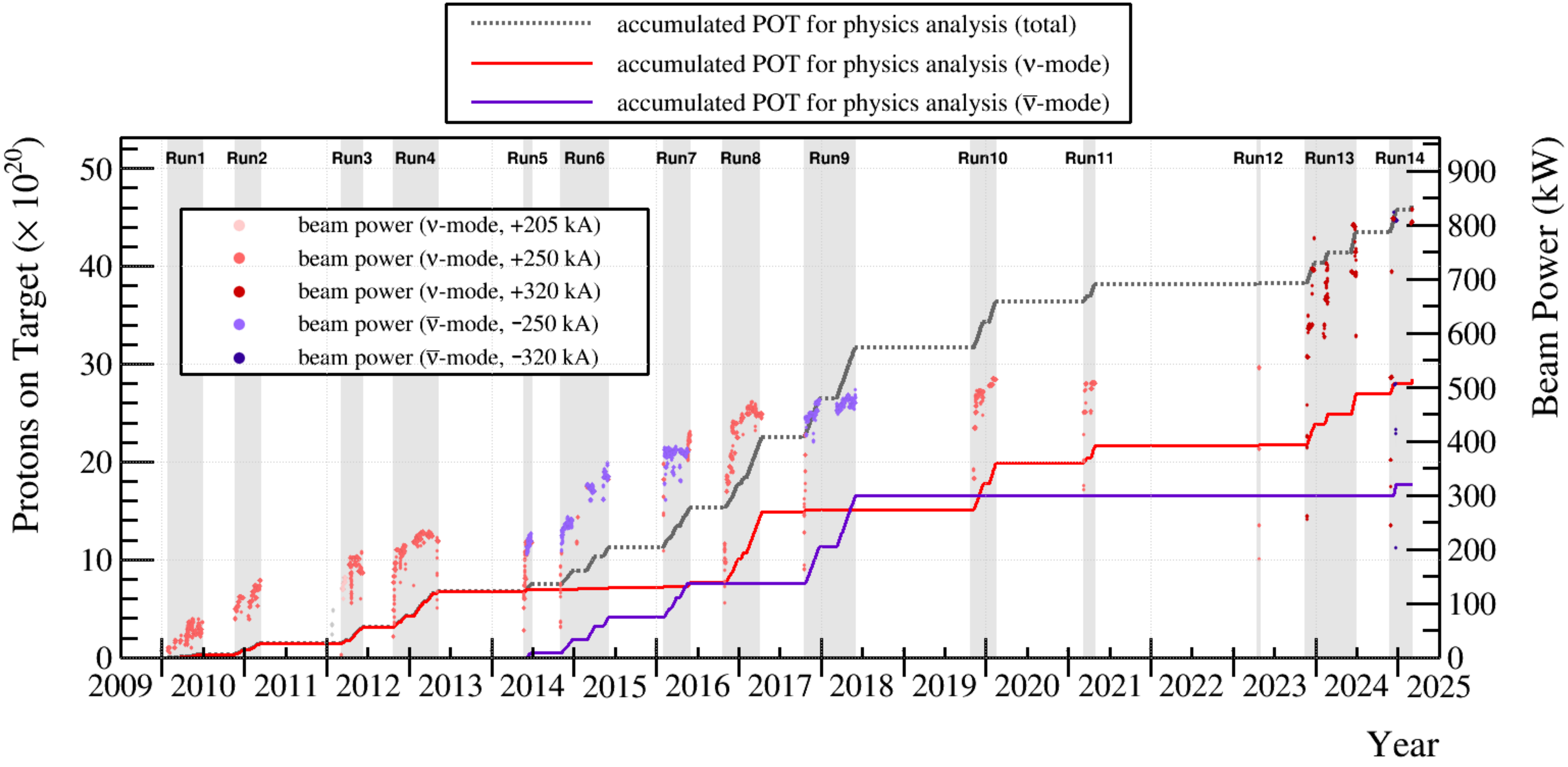


Summary

- New T2K oscillation analysis with 10% additional statistics
  - CP symmetry excluded at 90% CL
  - Preference for normal mass ordering and upper octant of θ_{23}
- We plan to update the analysis with new samples from far and near detector
- Joint analysis with Super-K
  - CP conserving value of the Jarlskog invariant is excluded at 1.9σ - 2.0σ
  - Preference for normal mass ordering
- Joint analysis with NOvA
  - No clear preference for mass ordering
  - Improved precision for $|\Delta m^2_{32}| < 2\%$
  - CP conserving values outside of 3σ for inverted mass ordering
- First data taken with the ND280 upgraded detector!
- Beam power reached 830 kW this year, expected to reach 1.3 MW by 2027
- ND280 detector will be used by Hyper-K (starting in 2028)

Backup Slides

T2K Data POT



accumulated POT for physics analysis (total)
accumulated POT for physics analysis (ν-mode)
accumulated POT for physics analysis (ν̄-mode)
beam power (ν-mode, +205 kA)
beam power (ν-mode, +250 kA)
beam power (ν-mode, +320 kA)
beam power (ν̄-mode, −250 kA)
beam power (ν̄-mode, −320 kA)
Run1 Run2 Run3 Run4 Run5 Run6 Run7 Run8 Run9 Run10 Run11 Run12 Run13 Run14
Protons on Target (× 10^20)
0 10 20 30 40 50
Beam Power (kW)
0 100 200 300 400 500 600 700 800 900
2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025
Year