T2K and T2K+SK Oscillation Analyses

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NOW 2024 - Plenary Talk

3rd September 2024

On behalf of the **T2K Collaboration**

UNIVERSITY OF OXFORD

NOW 2024
Neutrino Oscillation Workshop

T2K

Neutrino Oscillations

LBL experiments sensitive to these parameters

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

Atmospherics and LBL
$\theta_{23} \sim 45^\circ$
$|\Delta m^2_{32}| \sim 2.5\text{x}10^{-3}\text{eV}^2$

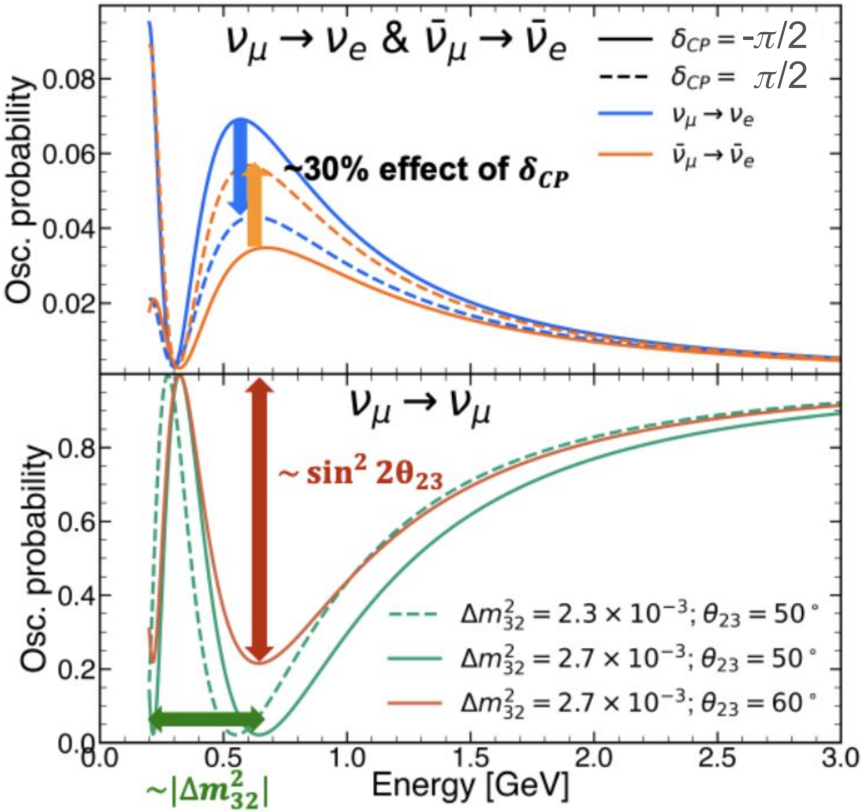
Reactors
$\theta_{13} \sim 10^\circ$
δ_{CP} unknown

Solar and Reactors
$\theta_{12} \sim 35^\circ$
$\Delta m^2_{21} \sim 7.5\text{x}10^{-5}\text{eV}^2$

Long baseline accelerator (LBL) experiments:

- Make the most precise measurements of $\boldsymbol{\theta_{23}}$, $|\boldsymbol{\Delta m^2_{32}}|$
- Sign of $|\boldsymbol{\Delta m^2_{32}}|$ and $\boldsymbol{\delta_{CP}}$ still unknown and accessible to LBL

Accelerator Neutrino Oscillations



Example oscillation probability for T2K:

- Baseline, L = 295km

$\boldsymbol{\delta}_{\mathbf{CP}}$ modifies neutrino/antineutrino appearance ($\nu_\mu \rightarrow \nu_e$) probability:

- Circular modulation over 2π period
- Asymmetric effect

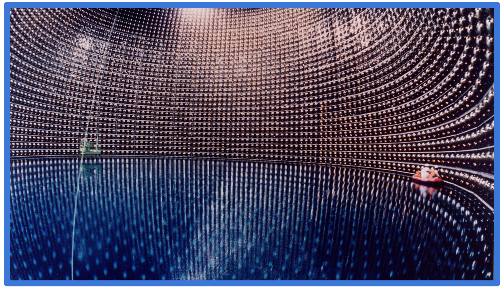
Disappearance probability ($\nu_\mu \rightarrow \nu_\mu$):

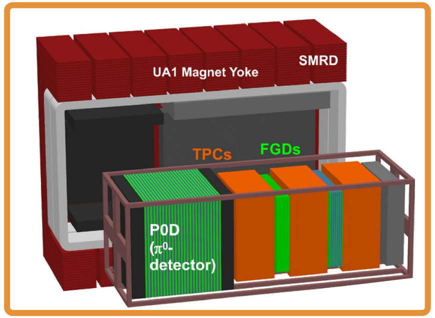
- **$\sin^2 2\theta_{23}$** modulates amplitude
- Frequency of oscillation ~ **$|\Delta m^2_{23}|$**

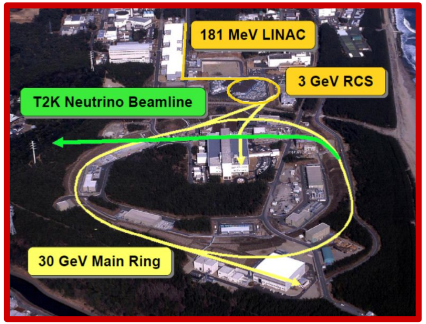
T2K Experiment

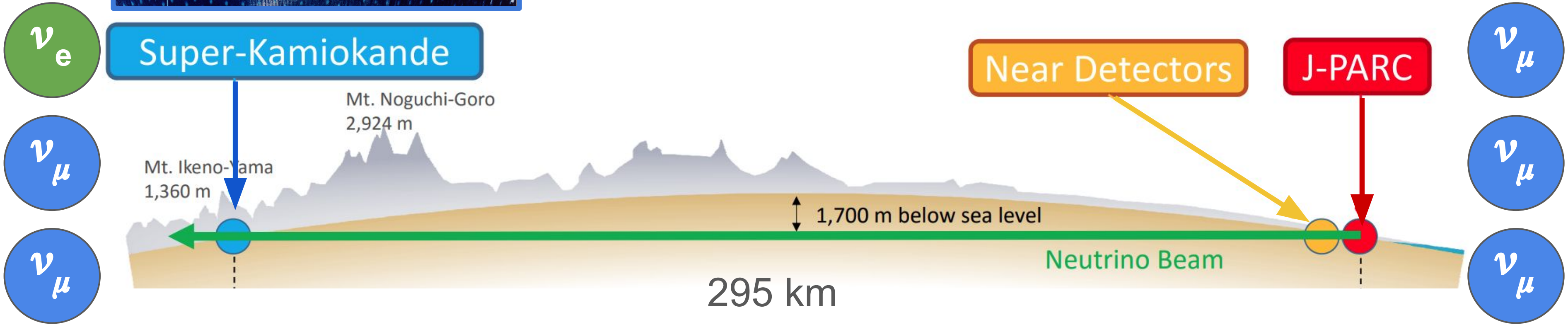
High intensity neutrino(antineutrino) beam produced at **J-PARC**:

- Use **Near** and **Far** detector







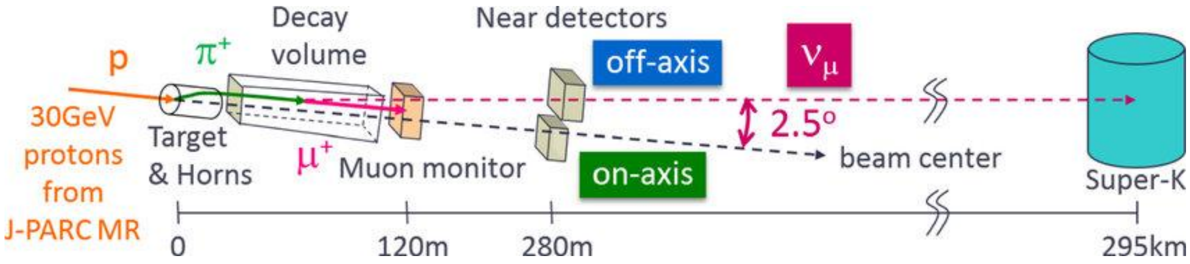


T2K Collaboration

Large collaboration: ~560 members from 74 institutes

- Oscillation analysis (this talk)
- Joint analyses with SK (this talk) and NOvA (see L. Kolupaeva talk)
- Cross-section measurements (see L. Bathe-Peters' talk)
- Detector R&D and upgrades (see L. Magaletti's talk)

Beamline



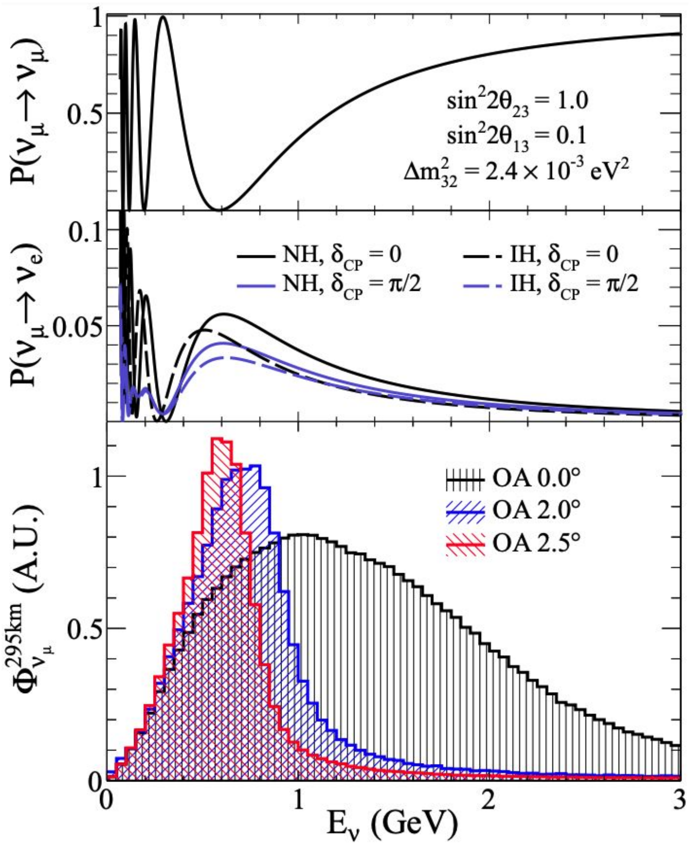
30 GeV proton beam extracted onto graphite target:

- p+C interactions produce hadron beam ($\pi^{\pm}$ and $K^{\pm}$)

Hadrons focused by 3 electromagnetic horns:

- Focusing π^{+} produces ν_{μ} via $\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$
- Changing horn current produces antineutrino beam

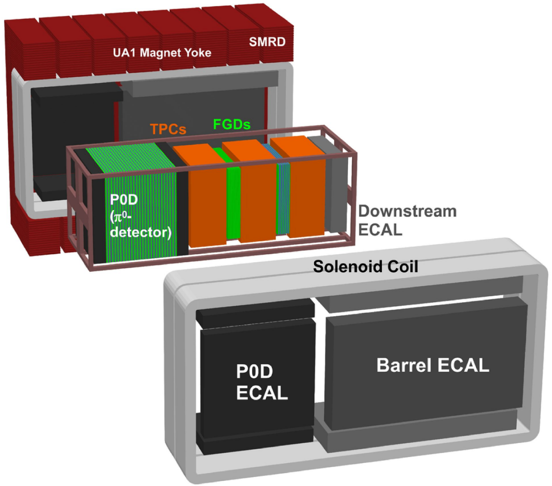
Off axis technique produces narrow-band beam

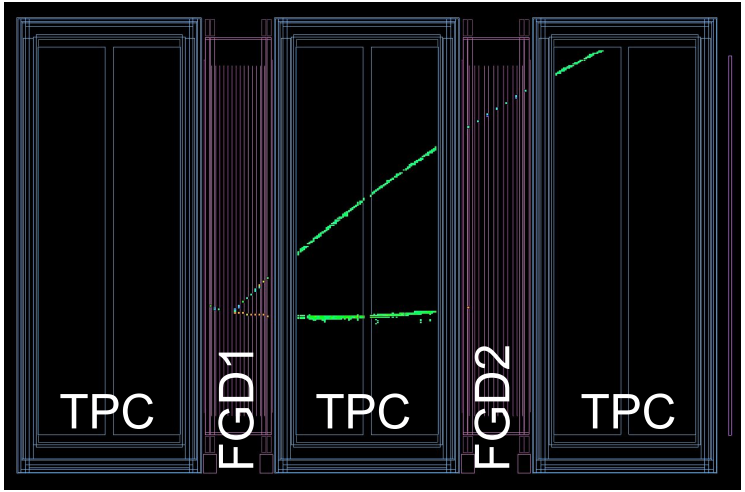


Near Detector (ND280)

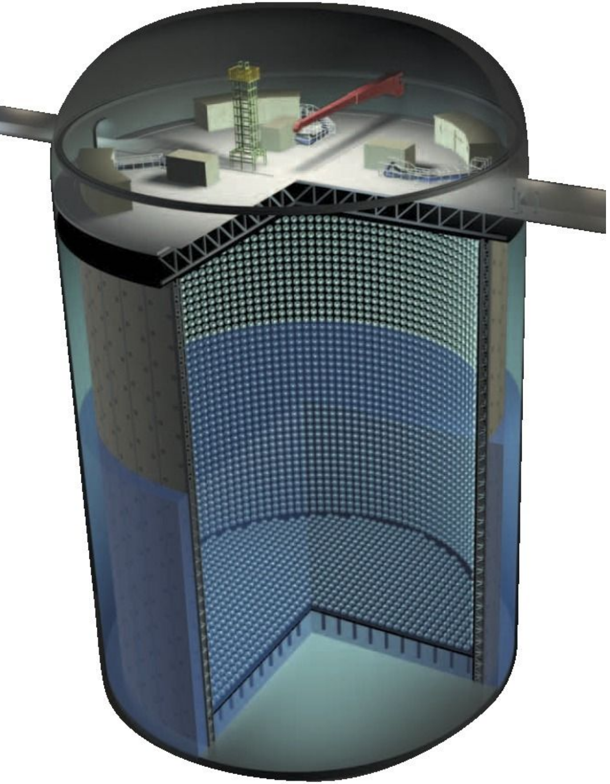
Measure beam spectrum and flavour composition pre-oscillation:

- 0.2T magnetic field
- Electromagnetic calorimeter to distinguish showers/tracks
- 2 Fine Grain Detectors (FGDs): Primary neutrino target
- 3 Time Projection Chambers (TPCs): Reconstruct momentum, charge and PID
- Recent upgrades (SFGD, high-angle TPCs, time of flight): **<u>Not</u>** used within analyses shown





Super Kamiokande (SK)

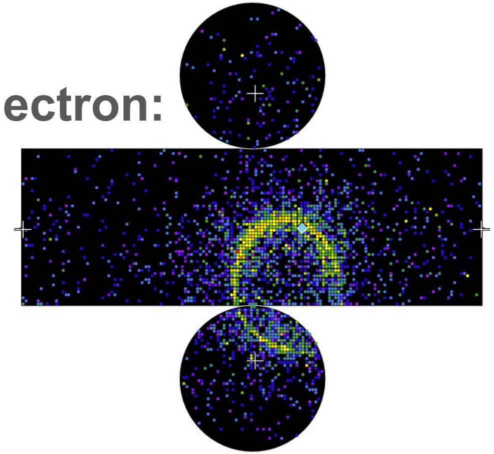


Large underground 50 kton water Cherenkov detector:

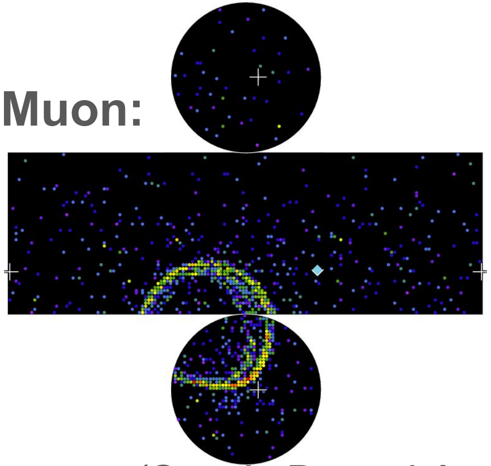
- ~11k 20” PMTs in the inner detector
- ~2k 8” PMTs in the outer detector, used as veto

Doped with 0.03% Gd in 2022 for improved neutron tagging efficiency: **Not** used within analyses shown

Electron:

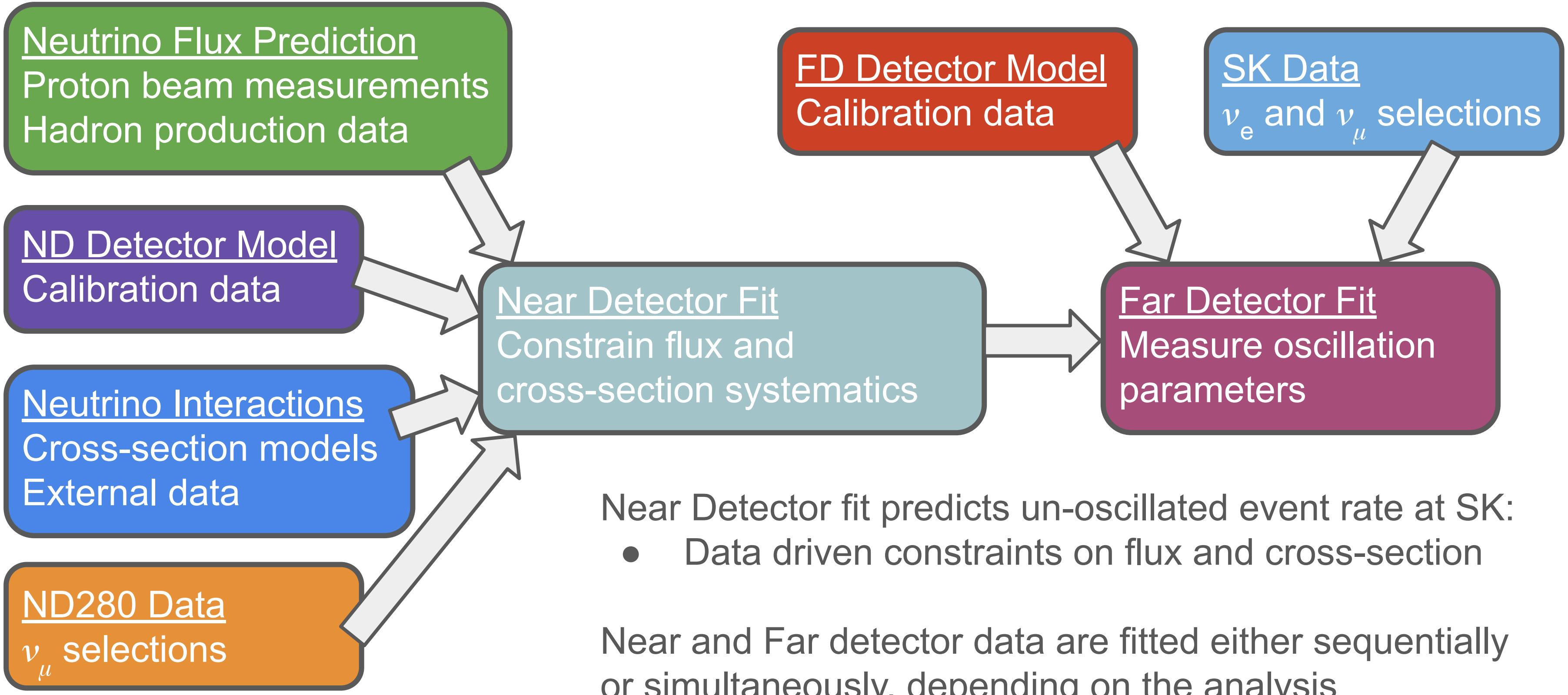


Muon:



(See A. Beauchêne’s talk)

Oscillation Analysis Methodology



Near Detector fit predicts un-oscillated event rate at SK:

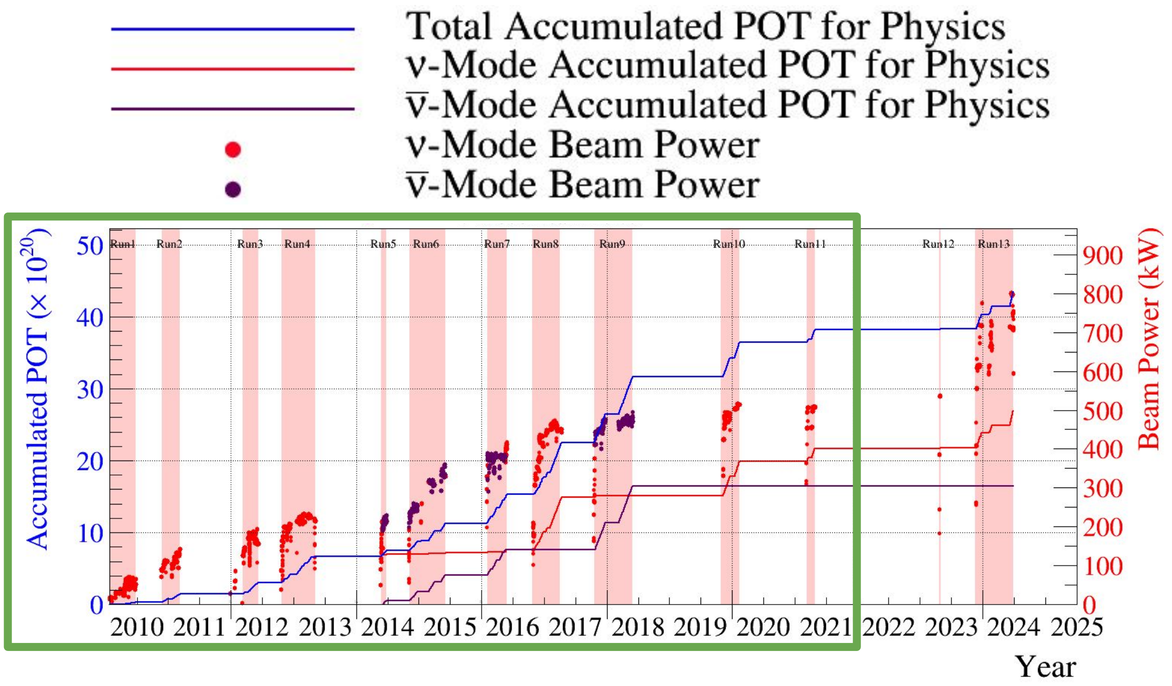
- Data driven constraints on flux and cross-section

Near and Far detector data are fitted either sequentially or simultaneously, depending on the analysis

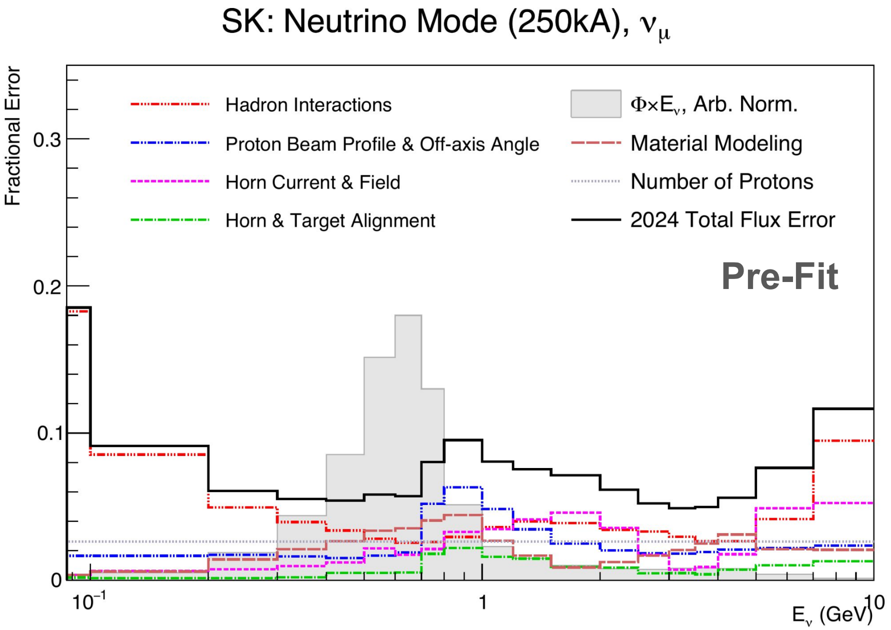
New Improvements for latest Oscillation Analysis

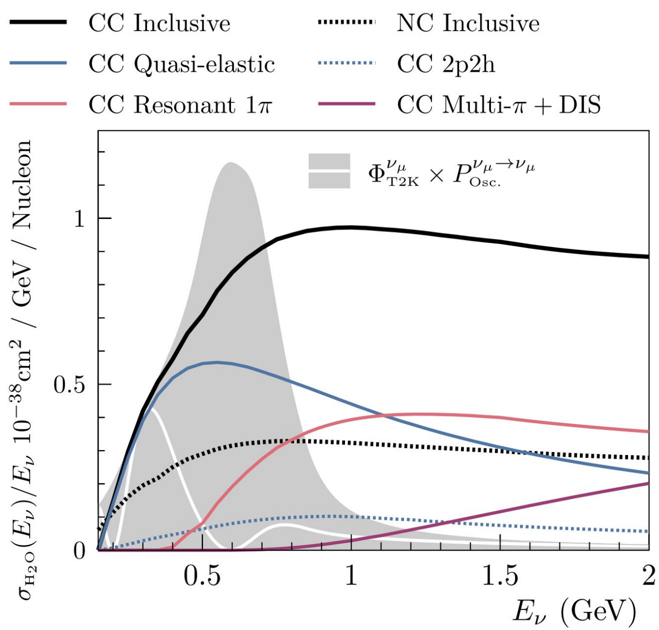
Updates since 2022 analysis: Neutrino 2022

- 10% more data in ν-mode
- Improved SK detector systematics treatment
- Additional selection cuts used to distinguish decay-electrons and neutrons at SK



Neutrino Flux and Cross Section Modelling





Flux uncertainty ~6% at peak of spectrum:

- Improved modelling of horn geometry
- External hadron production data (e.g NA61)

Dominated by CCQE interactions

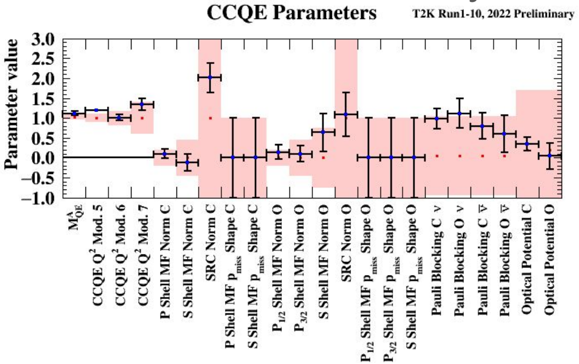
- Significant 2p2h and resonant contributions
- Mis-modelling may bias neutrino energy reconstruction - Near Detector constraint

ND280 Fit

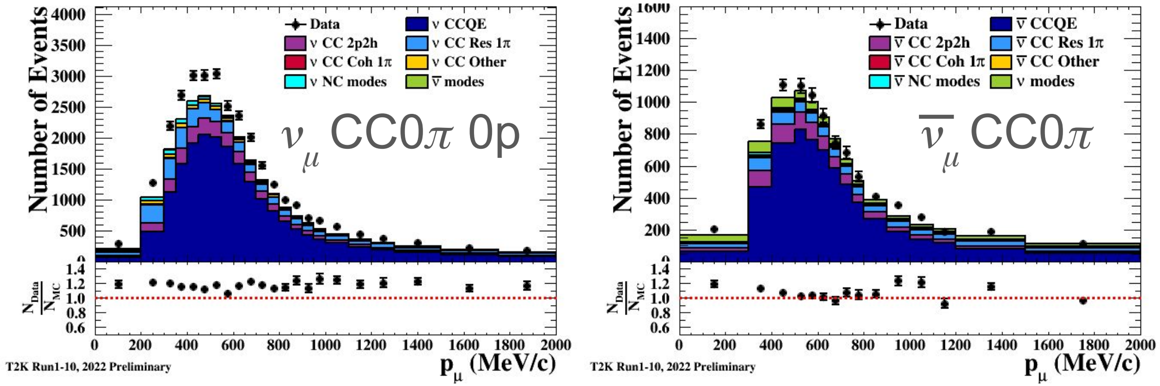
22 Samples based on:

- Beam configuration
- Target (CH/H_2O)
- Number of pions, protons, photons, etc.

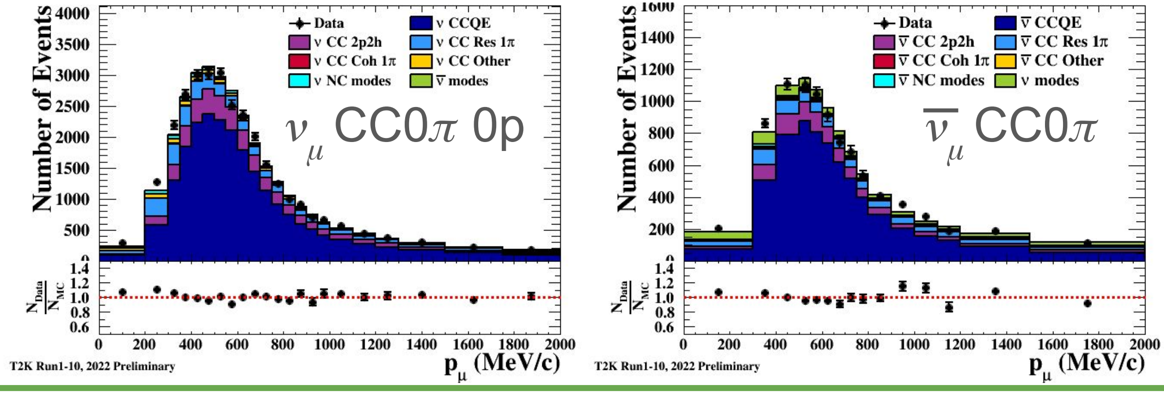
Tune and reduce flux and cross-section uncertainty:



Before Fit



After Fit



SK Selections

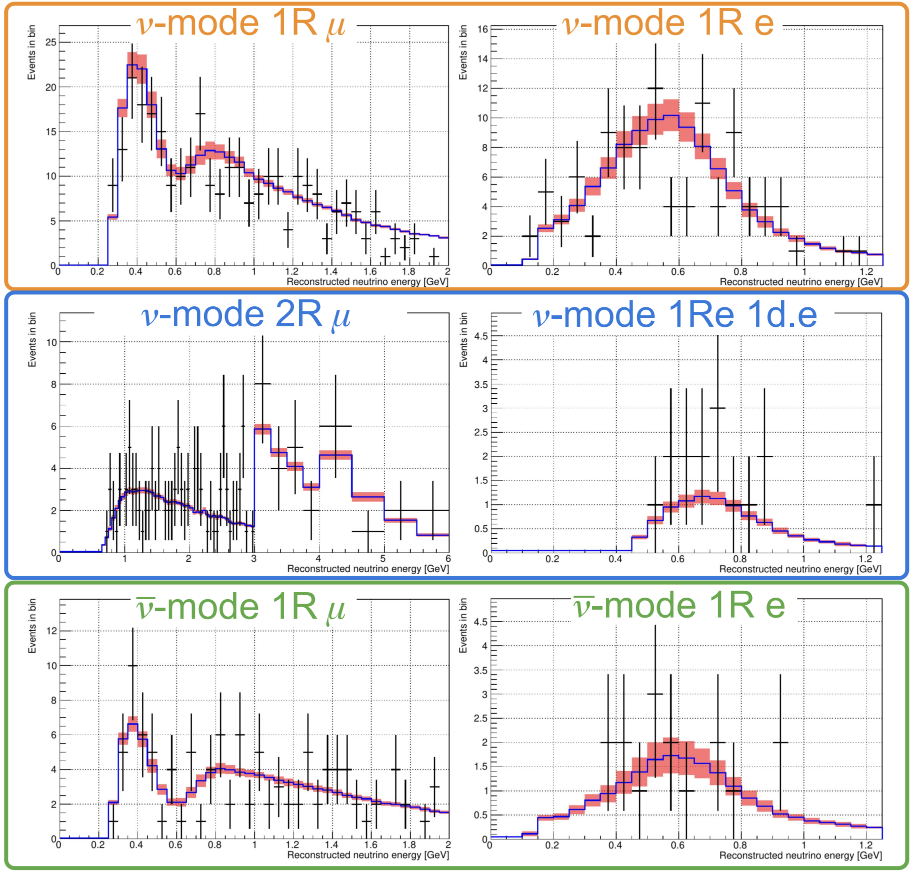
Six samples selected at SK:

- 2 samples: μ-like and e-like in ν-mode: CCQE
- 2 samples CC1π-enhanced (2 rings or additional decay electron)
- 2 samples: μ-like and e-like in $\overline{\nu}$-mode: CCQE

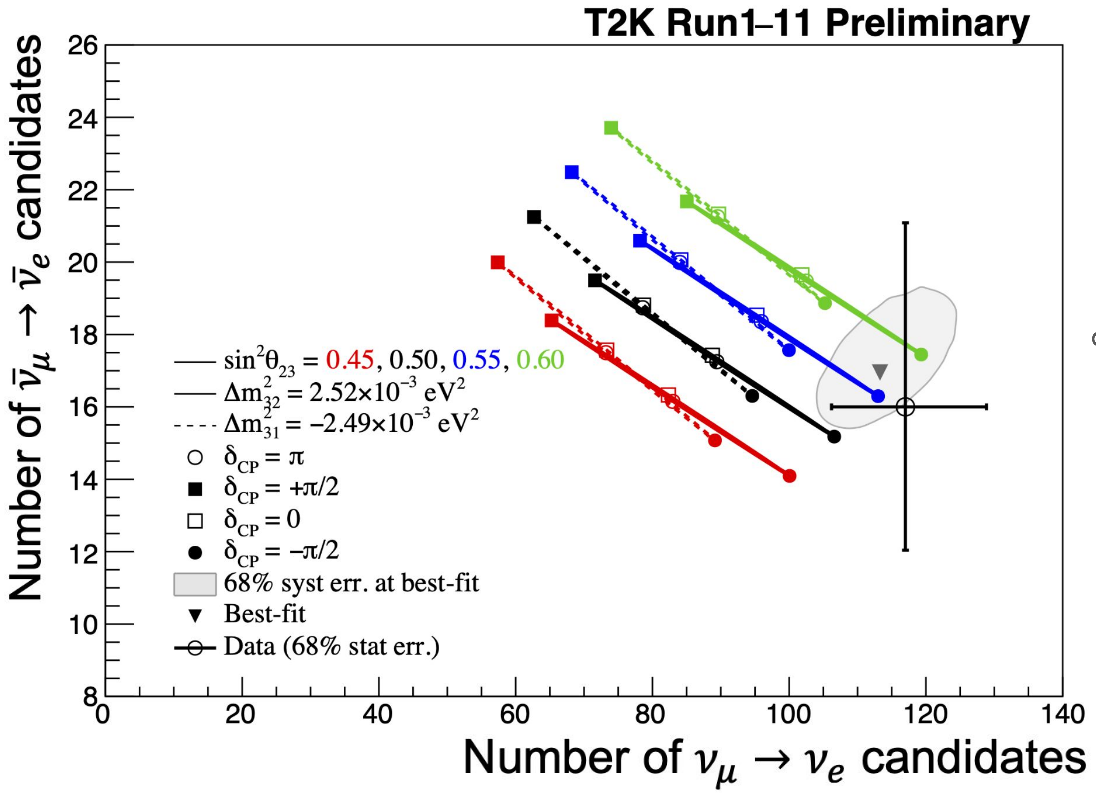
Updated detector modelling at SK:

- Significant reduction in total uncertainty after ND constraints:

Sample	Last Analysis	This Analysis
ν-mode 1Rμ	3.4%	3.2%
ν-mode 1Re	5.2%	4.9%
ν-mode 2Rμ	4.9%	3.9%
ν-mode 1Re1de	14.3%	6.3%
$\overline{\nu}$-mode 1Rμ	3.9%	5.0%
$\overline{\nu}$-mode 1Re	5.8%	6.7%



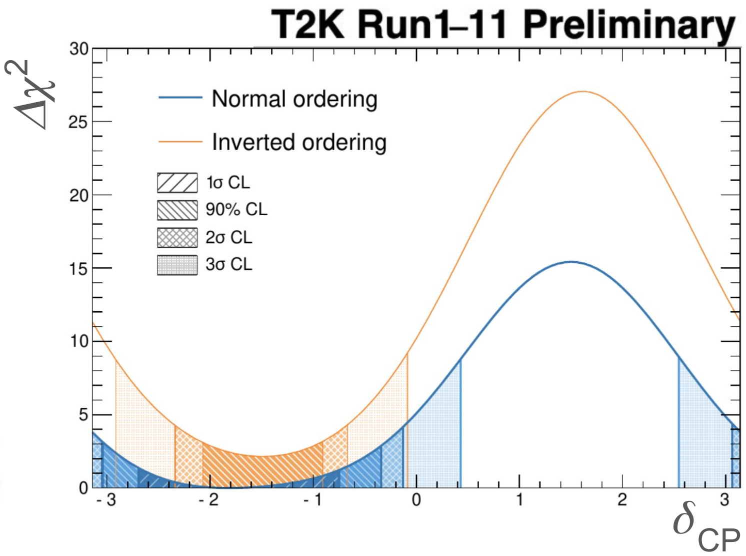
Oscillation Analysis Results



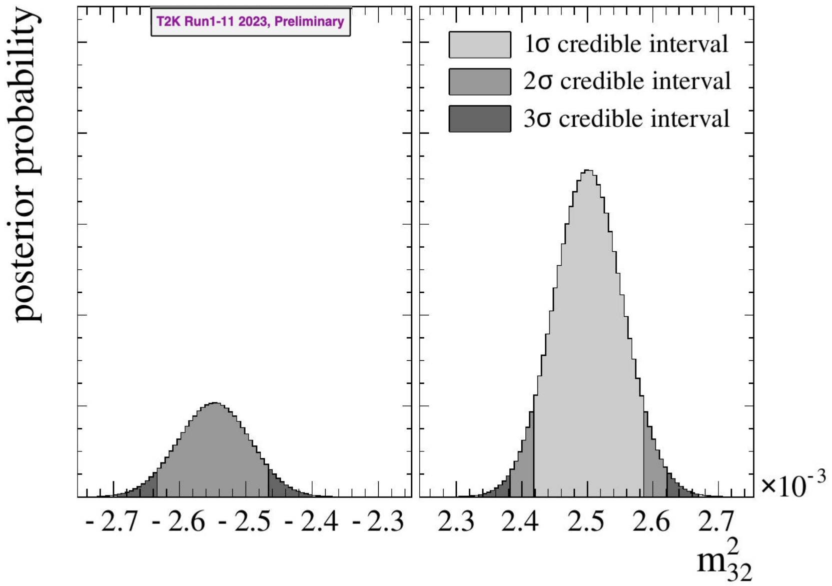
Maximal CP-violation region

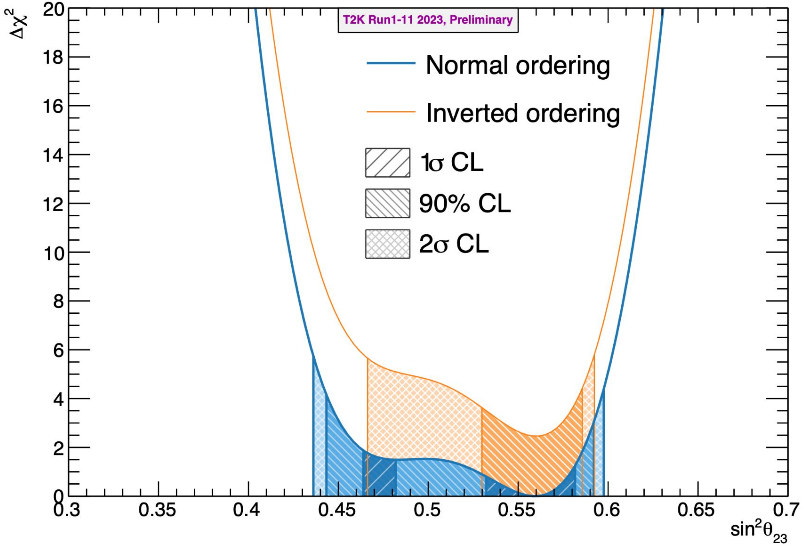
Best fit: $\delta_{CP} \approxeq -\pi/2$

CP conserving values within 2σ



Oscillation Analysis Results





	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IH ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00

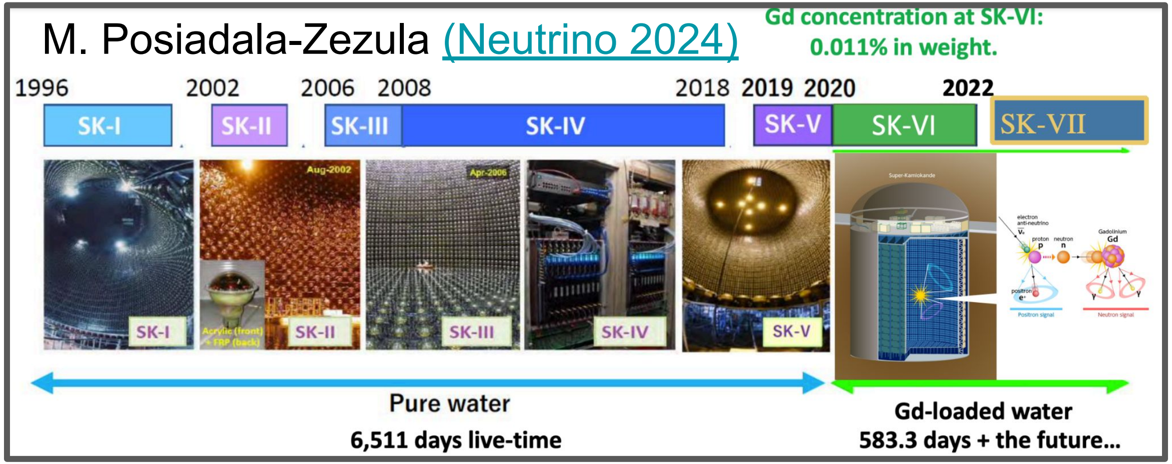
Bayes Factor B(NO/IO) = 3.3
Bayes Factor B(θ_{23}>0.5/θ_{23}<0.5) = 2.6

Weak preference for normal ordering and upper octant

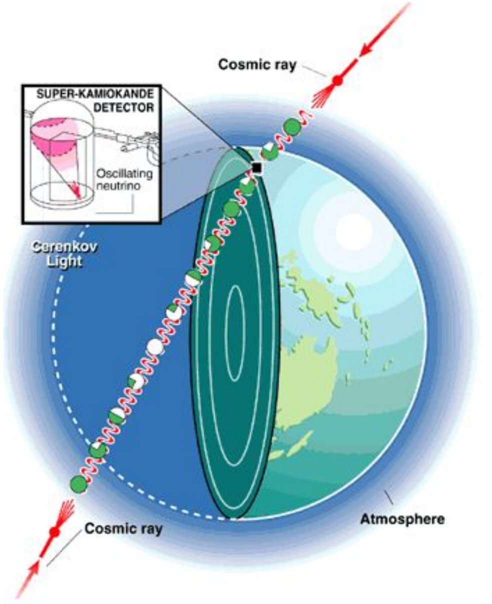
Joint Analyses

Two joint analyses released in 2023:

- T2K (beam) + NOvA (beam) → See the next talk for details
- T2K (beam) + SK (atmospherics) → **Arxiv 2405.12488**
    - T2K data (5 samples) POT: 3.6×10^{21} - Eur. Phys. J. C 83, 782
    - SK-IV data (18 samples) 3244 days - PTEP 2019 5, 054F01



M. Posiadala-Zezula (Neutrino 2024)

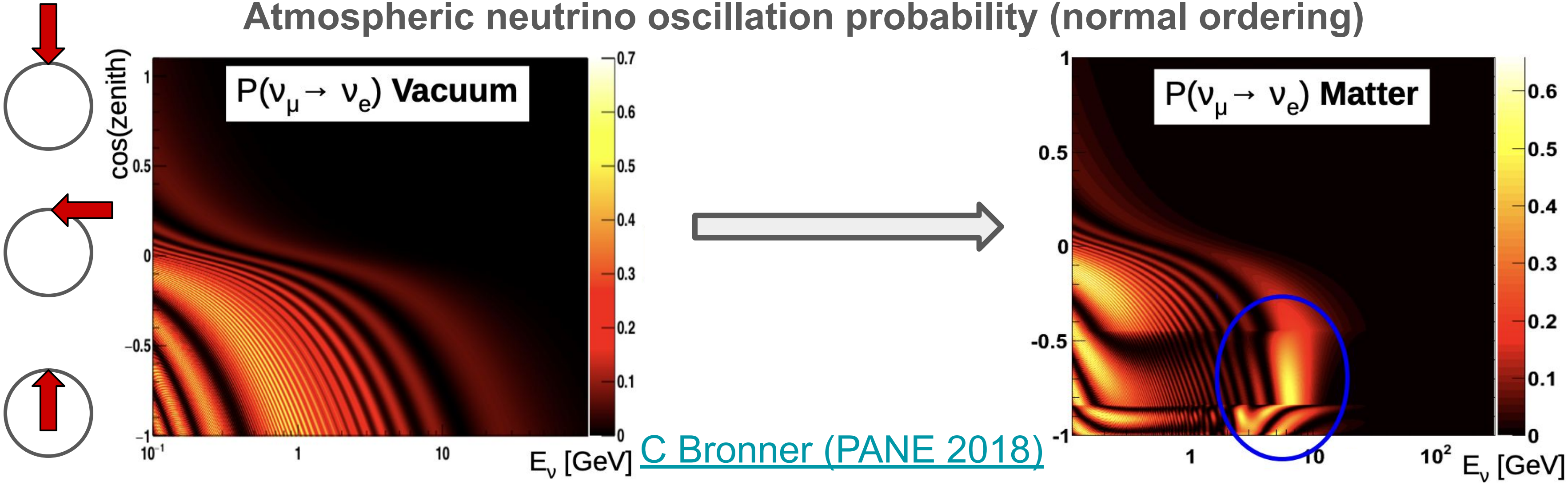


Atmospheric Oscillations in SK

SK has discriminating power of mass ordering due to resonant-induced matter effects between 2 and 10 GeV in upgoing-neutrinos [cos(zenith) < 0]:

- Enhancement of ν in NO; enhancement of $\overline{\nu}$ in IO
- Amplitude of effect depends on $\sin^2\theta_{23} \rightarrow$ sensitive to θ_{23} octant
- Effect not degenerate with δ_{CP}

Atmospheric neutrino oscillation probability (normal ordering)



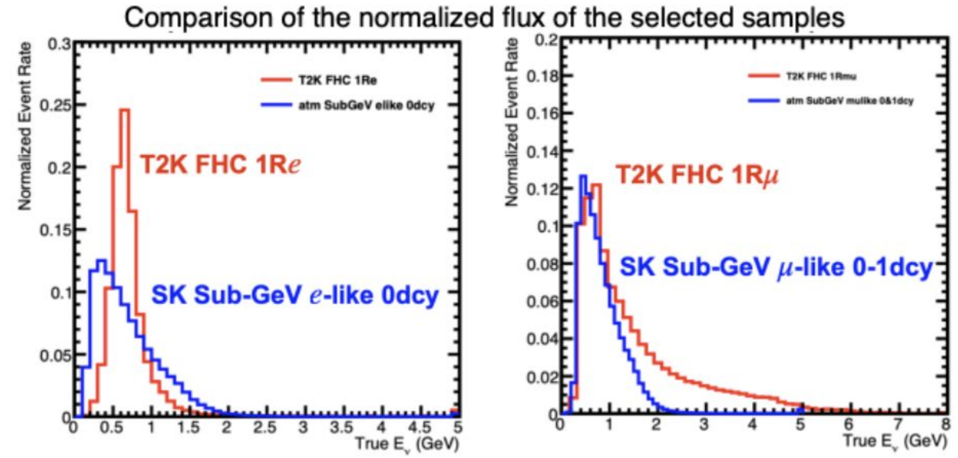
C Bronner (PANE 2018)

Motivation of T2K+SK Joint Analysis

Combining experiments should provide us with:

- Better sensitivity to oscillation parameters and mass ordering due to increased stats
- SK helps **break degeneracy** between δ_{CP} and **mass ordering** in T2K
- T2K can constrain $\sin^2\theta_{23}$ better → improve sensitivity to **mass ordering** in SK

Both experiments have **overlapping energy spectrum**:



Correlated systematics

T2K near detector can be used to constrain cross-section uncertainties for low-energy atmospheric samples

Systematics

Developed unified interaction model for T2K beam and SK low-energy samples

- High energy: Mostly based on SK model

Same detector simulation and reconstruction software used in both experiments:

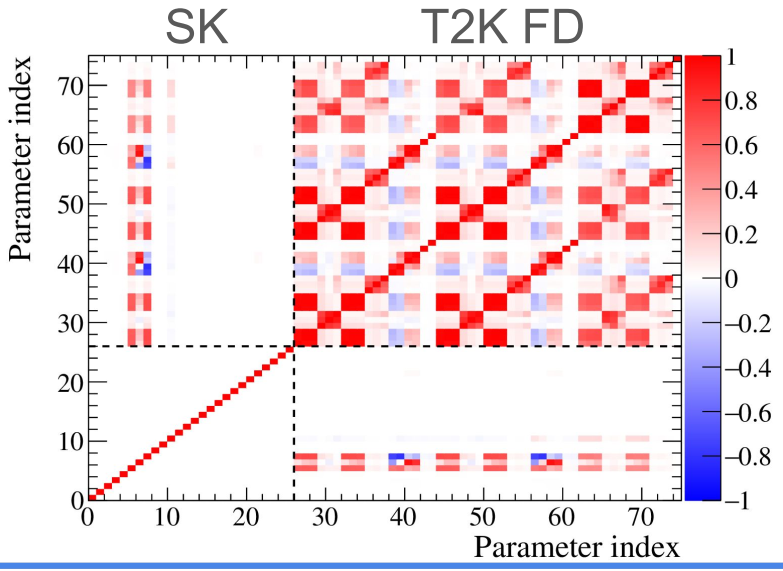
- Correlated detector systematics included within joint analysis

Interaction model:

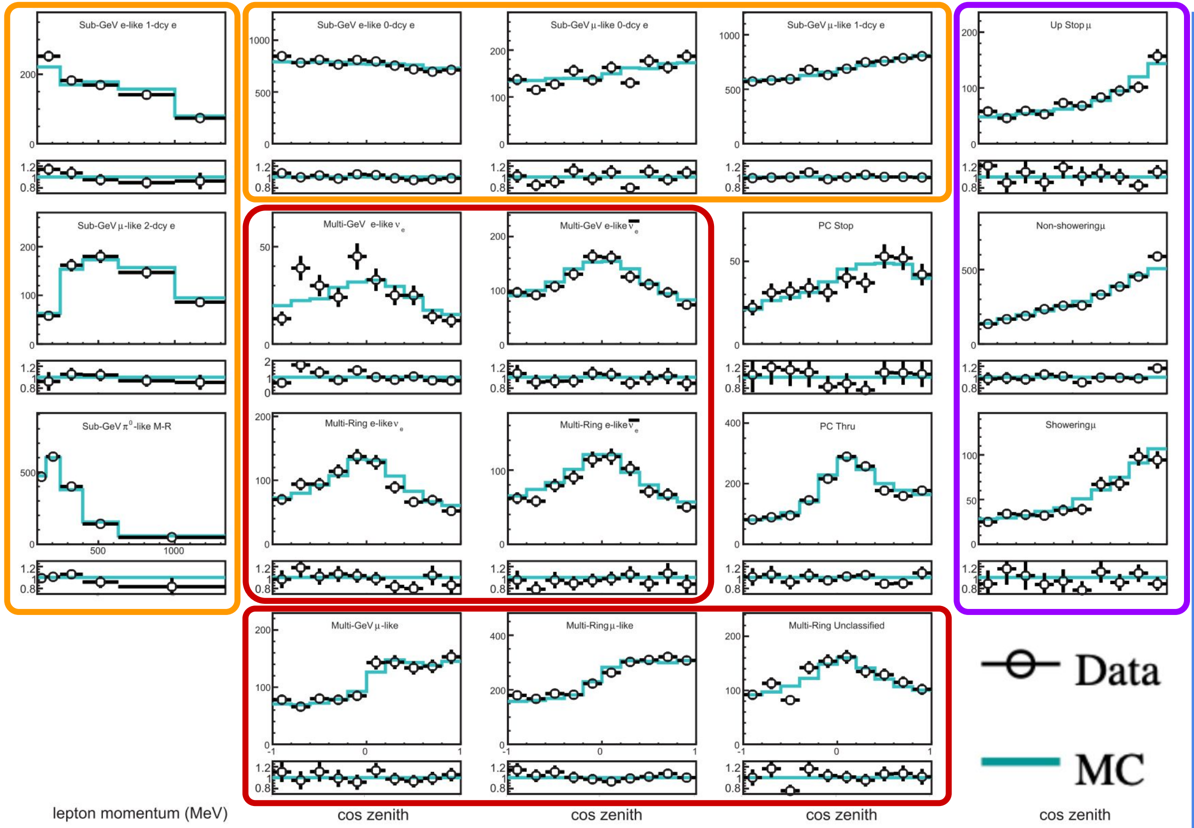
Interaction Model Summary

	"Low-energy" samples SK FC sub-GeV and T2K	**"High-energy" samples** SK FC multi-GeV, PC, Upmu
Charged Current Quasi-Elastic (CCQE)	T2K model with ND280 constraint, correlated in low-E/highE (except for high-Q^2 parameters)	
	high-Q^2 params w/ND280	high-Q^2 params w/o ND
	+ extra ν_e/ν_μ xsec diff. error	
Two particles two holes (CC2p2h)	T2K model w/ND280	SK model (100% error) + T2K-style shape error
Resonant Interactions	T2K model w/ND280 + new p_π shape uncertainty + extra NC1π^0 uncertainties	SK model for 3 dials also in T2K model, use more recent, larger T2K priors
Deep inelastic	T2K model w/ND280	SK model
Tau neutrino interactions	SK model (25% normalization error) correlated in low-E/highE	
Final State Interactions	T2K model w/ND280	T2K model w/o ND280 (mostly same as SK model)
Secondary Interactions	T2K model, correlated in low-E/high-E not applied to SK Upmu samples	

Detector model:



SK Atmospheric Samples



PTEP 2019 5, 054F01

18 SK atmospheric samples with 3244.4 days of data taking:

Multi-GeV samples:

- Sensitive to mass ordering and θ_{23} octant

Sub-GeV samples:

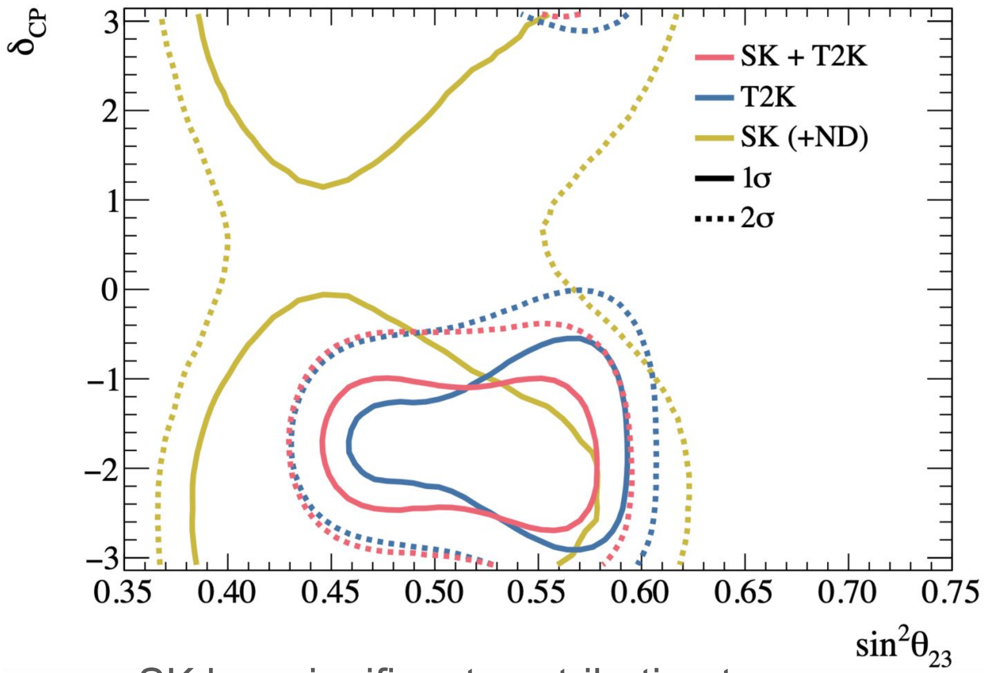
- Electron CCQE-like sample normalisation sensitive to δ_{CP}

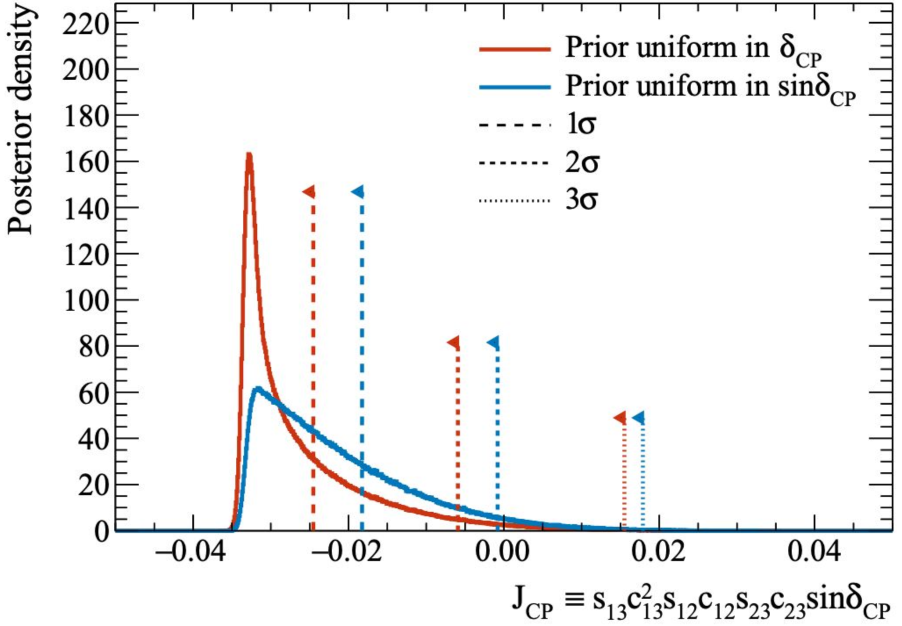
Upward going muons:

- Sensitive to $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$ due to ν_μ disappearance

T2K+SK Oscillation Analysis Results

Conclusion: between **1.9σ** and **2.0σ** exclusion of CP symmetry





SK has significant contribution to preference of octant

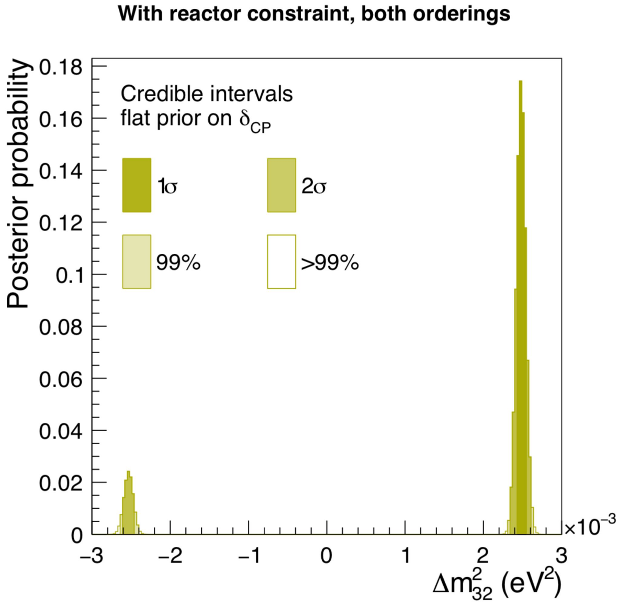
Exclusion of CP-conserving values of $J_{CP}=0$ is **2.2σ** (**1.9σ**) for flat δ_{CP} ($\sin\delta_{CP}$) prior

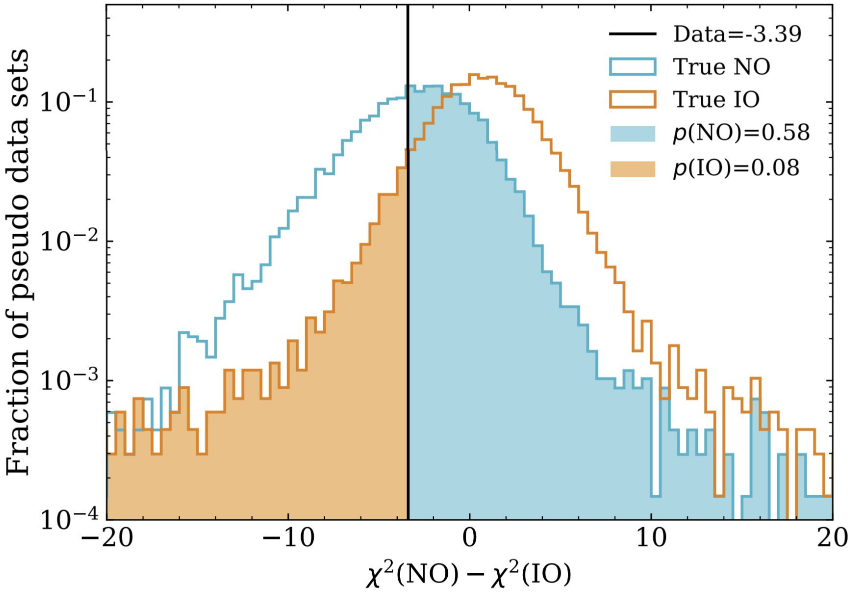
T2K+SK Oscillation Analysis Results

[Reminder: Recent T2K analysis B(NO/IO) = 3.3]

Slight preference for normal ordering:

- Bayes factor **B(NO/IO) = 8.98**
- Normal ordering preferred, with **p-value** for IO = **0.08**
  - Corresponds to 1.64σ deviation assuming equal prior probabilities





Future Plans for T2K

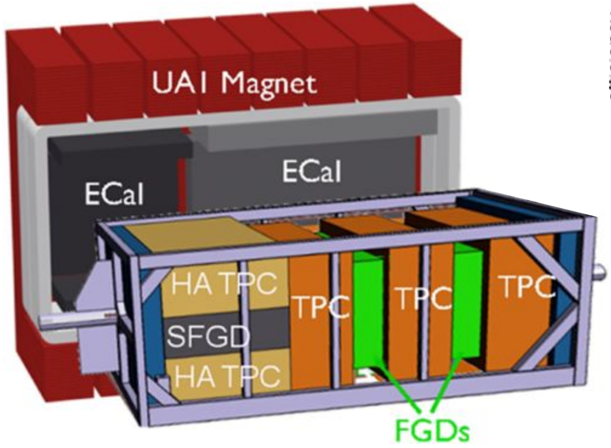
(See L. Magaletti's talk)

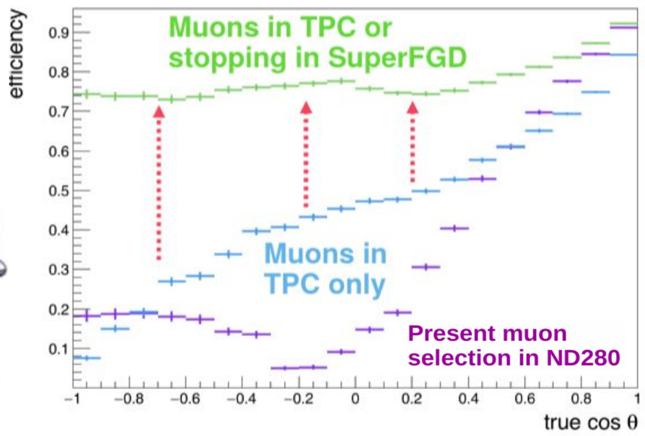
Upgraded near detector:

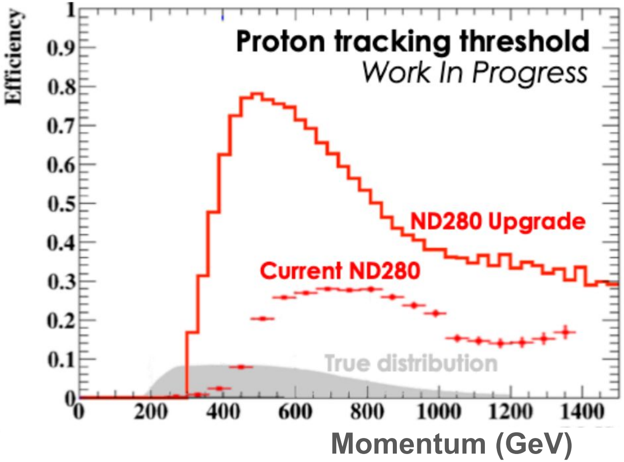
- High-angle TPCs
- Time of flight detectors
- New scintillator target (SFGD)

Improved efficiency for:

- Selecting muons of any angle
- Low momentum protons
- Neutron reconstruction



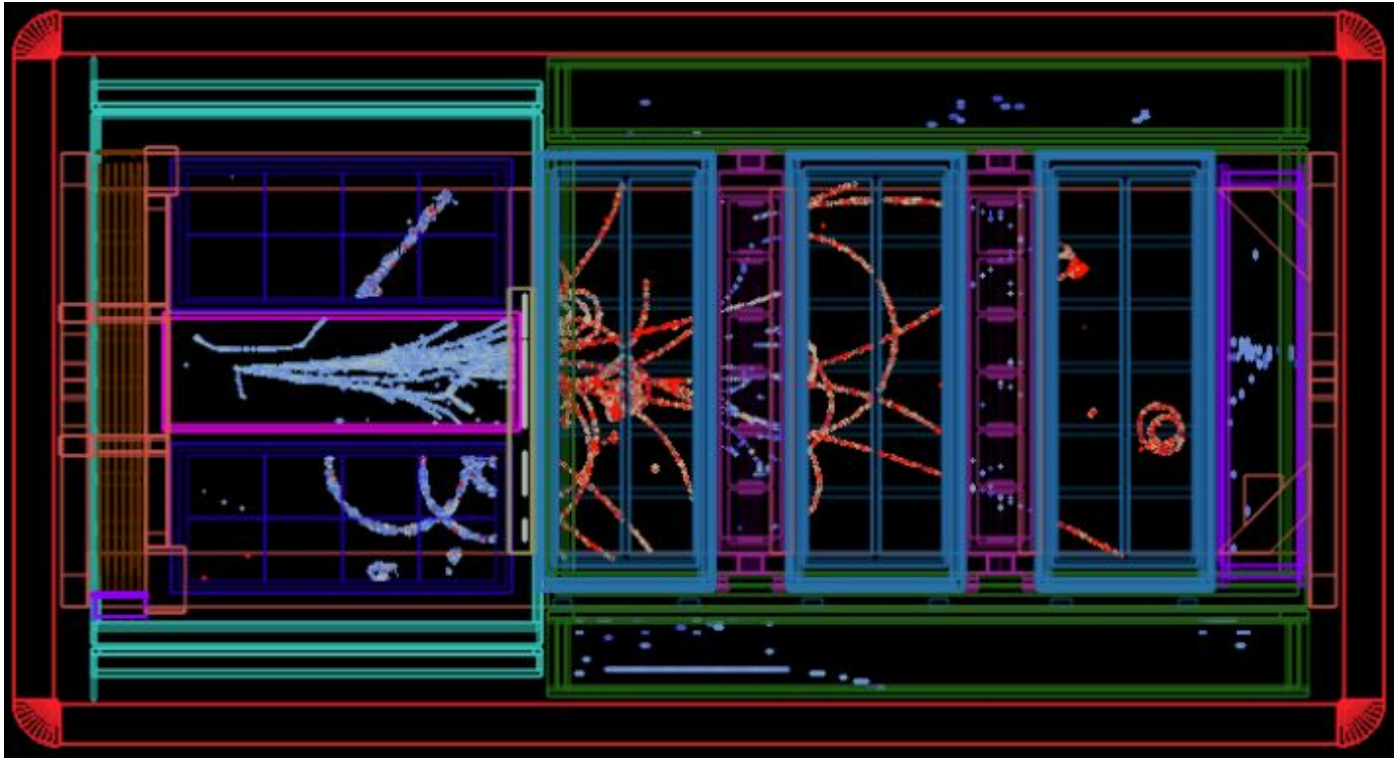




Future Plans for T2K

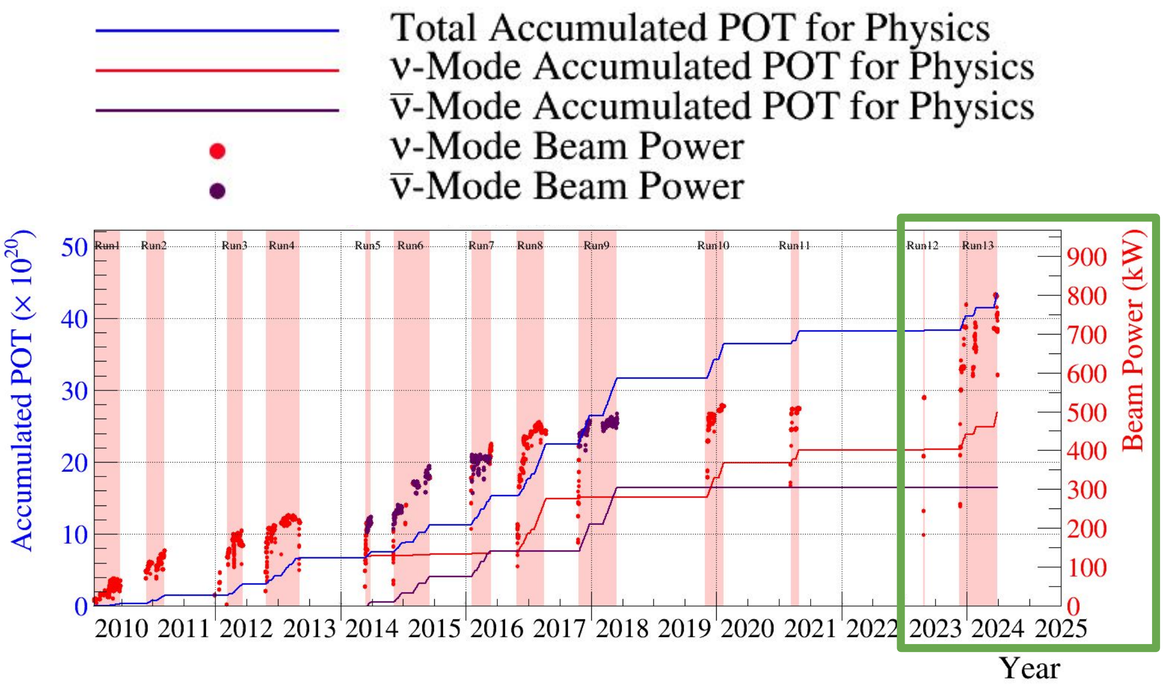
Upgrade installed: June 2024

(See L. Magaletti's talk)



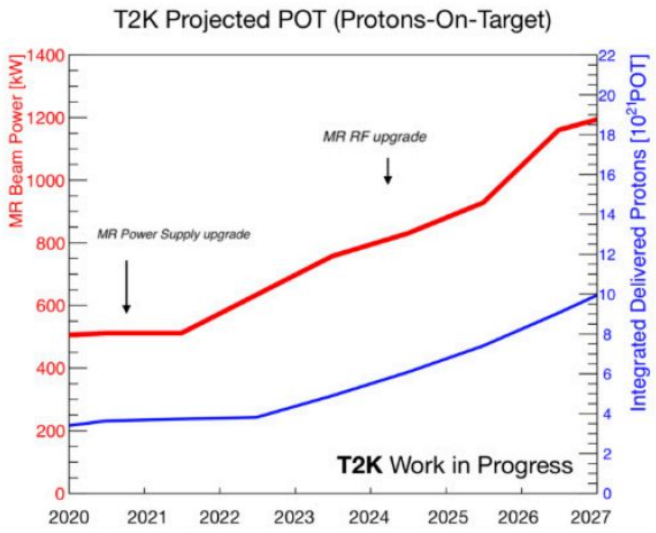
Future Plans for T2K

New **data** already taken - Aim 10×10^{21} POT



Higher beam power upgrades:

- 800 kW already achieved



Conclusion

T2K is a long baseline experiment aiming to make precise measurements of θ_{23} and Δm^2_{32}, and looking to distinguish the **mass ordering** and **CP violation**

New **T2K** oscillation analysis presented which includes: +10% data in neutrino mode, and improved detector systematics:

- Improvement in precision of measurement consistent with previous analysis
- **CP symmetry** excluded at 90% CL
- Mild preference for normal ordering

Joint analyses with SK released: (See next talk for T2K+NOvA results)

- The CP-conserving value of the Jarlskog invariant is excluded with a significance varying between 1.9σ and 2.0σ depending on the analysis considered

Stay tuned for future results with high beam power and detector upgrades!

Backup Slides

Oscillation Probability

C. Giganti (Neutrino 2024)

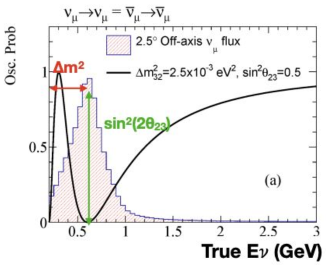
Physics case

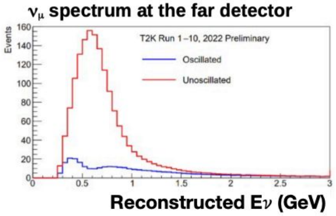
ν_μ and $\bar{\nu}_\mu$ disappearance

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

Same oscillation probability for ν and $\bar{\nu}$

Sensitive to $|\Delta m^2_{32}|$ and to $\sin^2(2\theta_{23})$ → no sensitivity to mass ordering and δ_{CP}





ν_e and $\bar{\nu}_e$ appearance

$$P(\overset{(-)}{\nu_\mu} \to \overset{(-)}{\nu_e}) \simeq \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}]$$

$$(\mp)\alpha\frac{J_0 \sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}]$$

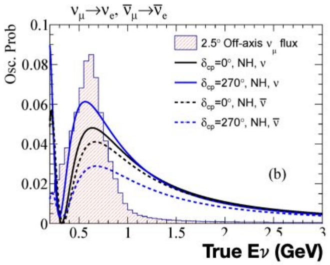
$$+\alpha\frac{J_0\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

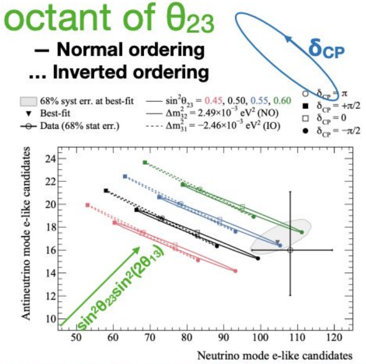
$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30$

$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$

$A = (\mp)2\sqrt{2}G_F n_e E/\Delta m^2_{31}$

Sensitivity to δ_{CP}, to the mass ordering and to the octant of θ_{23}

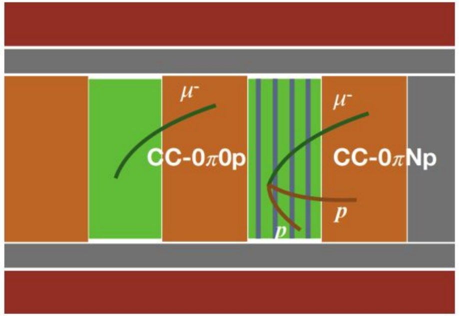




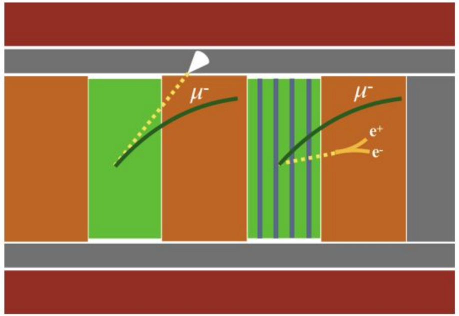
ND Selections

New samples in neutrino mode:

T. Doyle (NuFact 2023)

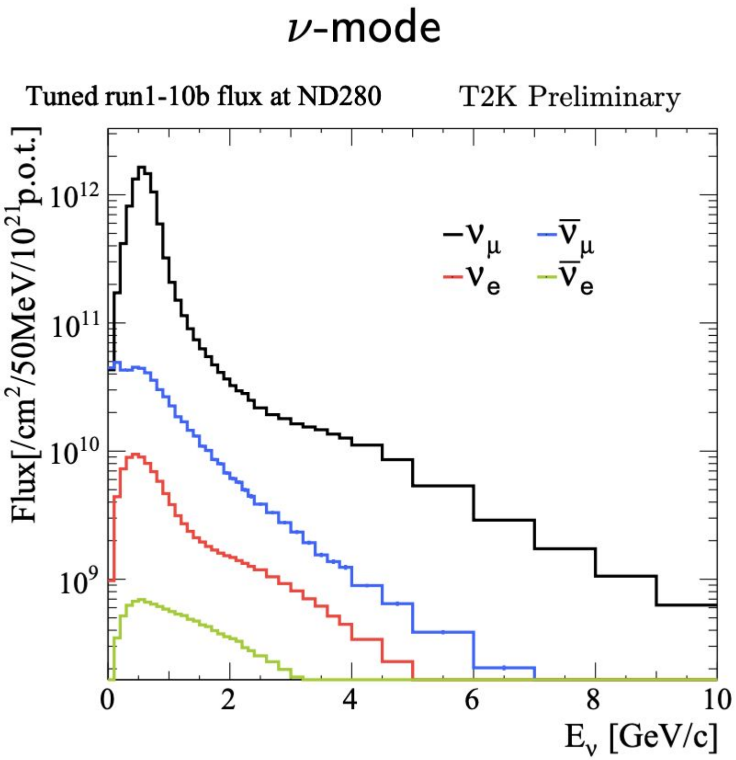


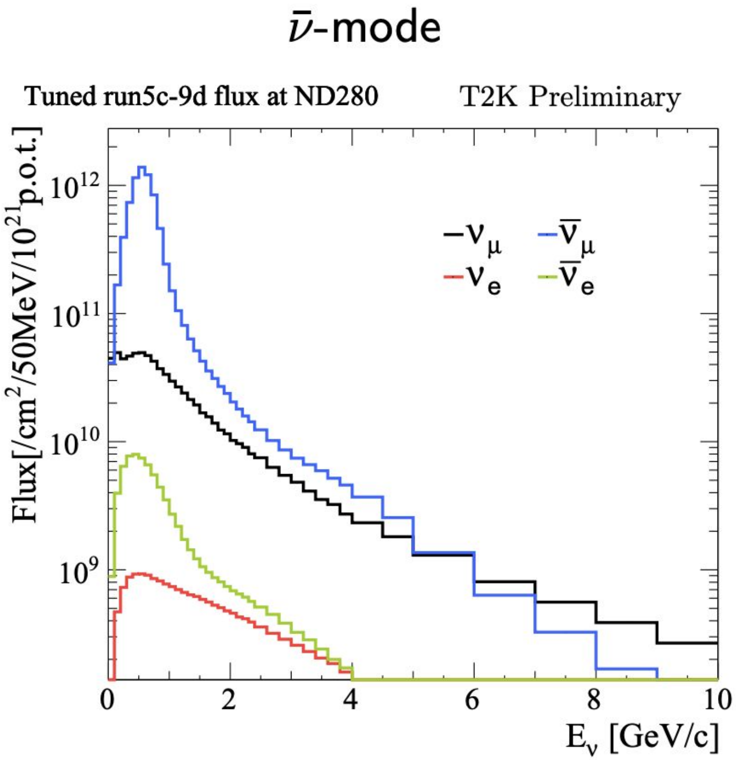
- Split CC0π sample based on presence or absence of **protons**
- Different sensitivity to nuclear effects:
  - → Separates (q_0, q_3) peaks in Valencia 2p2h model



- Isolate CCπ^0 interactions by looking for **photons** in the ECals and TPCs
- Contributions from DIS (30%), multi-pion production (20%) and resonant π^0 production (24%)
- Improves purities of other ND samples

Neutrino Flux





Neutrino Flux Uncertainties