Neutrino Oscillation Analysis with Combined Data from Super-Kamiokande and T2K

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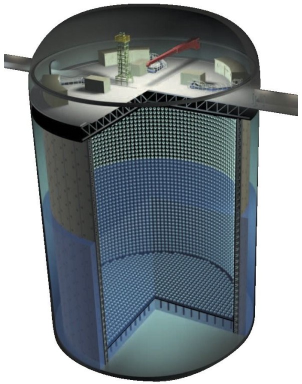
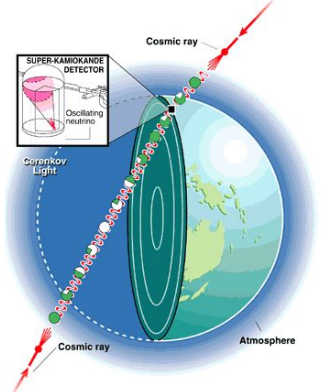
UNIVERSITY OF OXFORD

Experiments



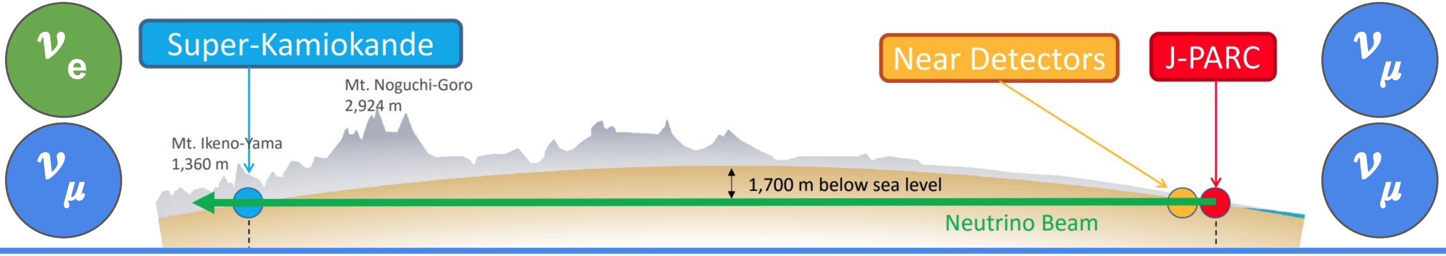


Super-Kamiokande (SK): 50 kton water Cherenkov detector:

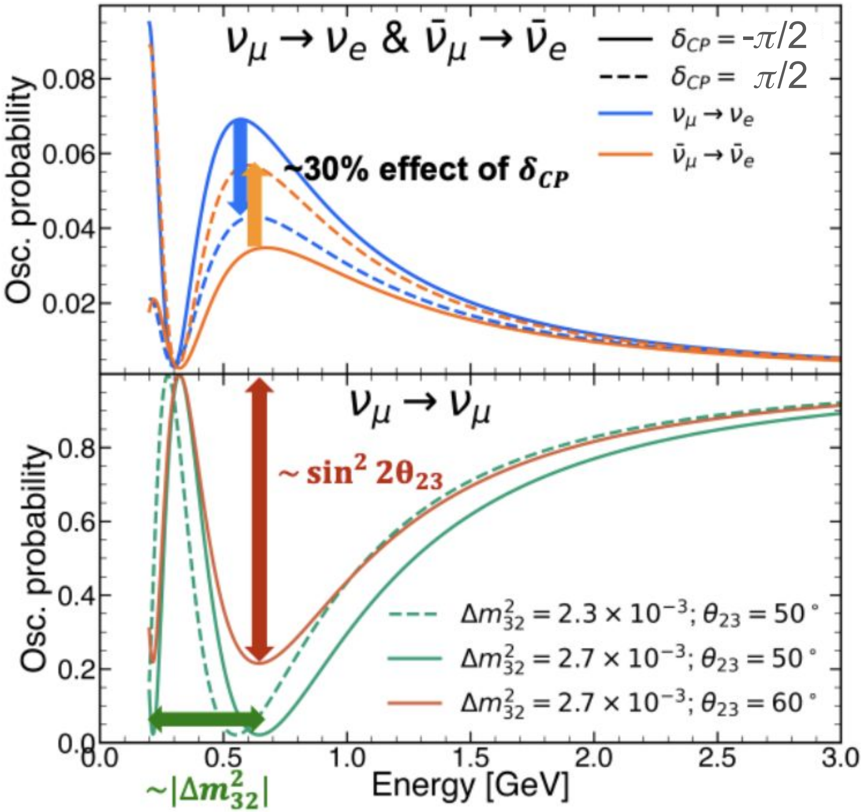
- Measure atmospheric neutrinos with large neutrino energy and baseline range
- Good separation of electrons and muons
- No event-by-event neutrino/antineutrino separation

Tokai-to-Kamioka (T2K): Long baseline (L=295km) beam oscillation experiment:

- Primary $\nu_\mu/\bar{\nu}_\mu$ beam peaked at $E_\nu = 0.6$ GeV/c
- Near detectors used to constrain flux and cross-section uncertainties
- Far detector oscillated measurement uses SK



Oscillations in T2K



Oscillation probability for T2K:

- Baseline, L = 295km
- Flux peak at 0.6GeV

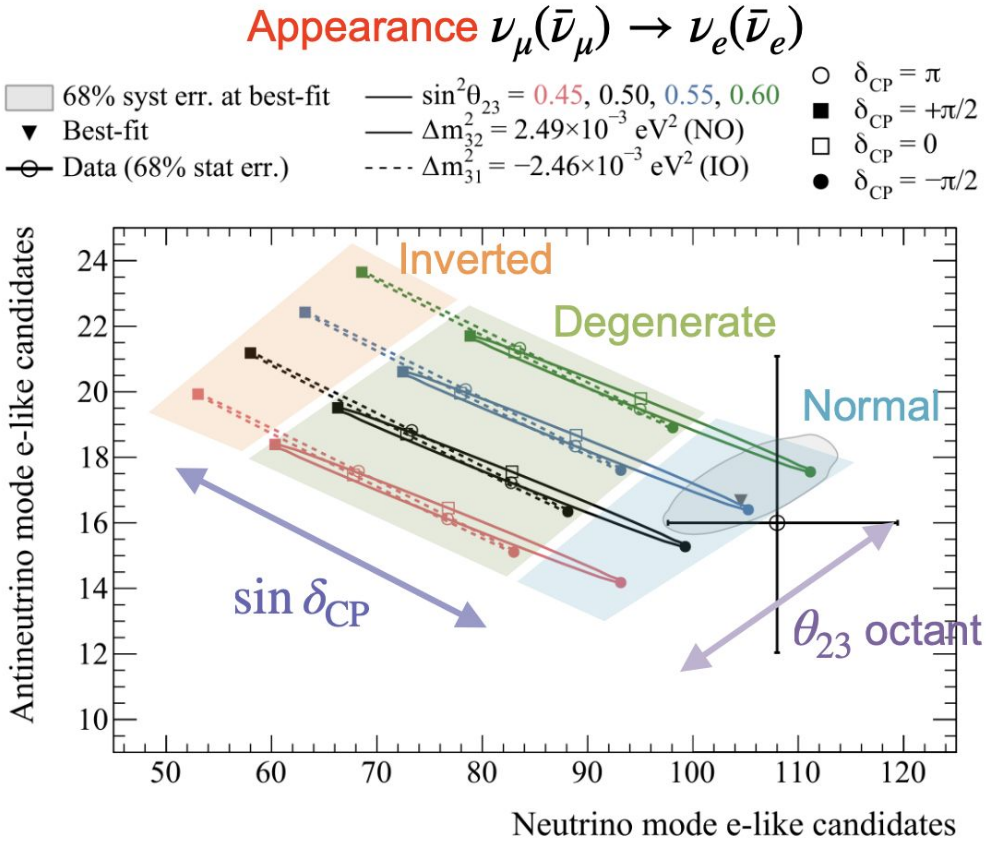
Disappearance probability ($\nu_\mu \to \nu_\mu$):

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

δ_{CP} modifies neutrino/antineutrino appearance ($\nu_\mu \to \nu_e$) probability:

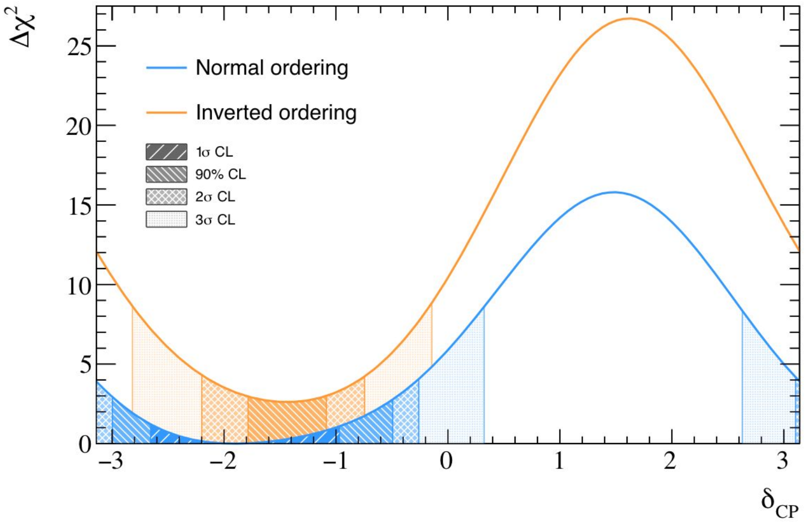
- Circular modulation over 2π period
- Asymmetric effect

Oscillations in T2K



Large degenerate region in mass hierarchy (MH) and δ_{CP}:

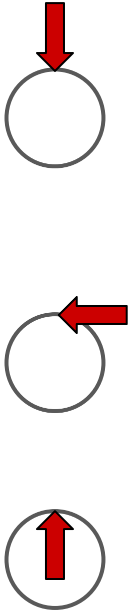
- T2K-only data prefers ~maximal CP violation



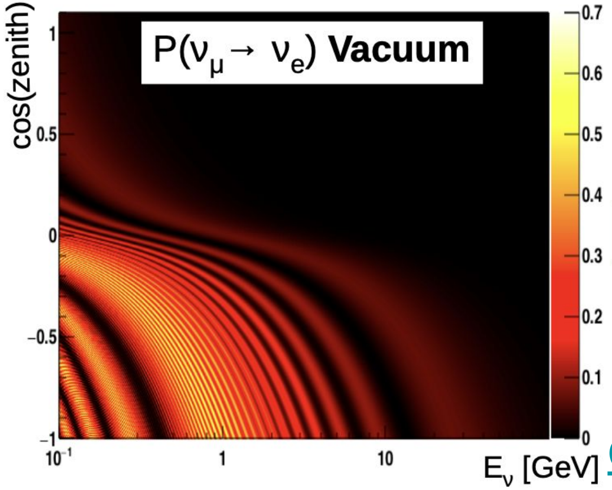
Atmospheric Oscillations in SK

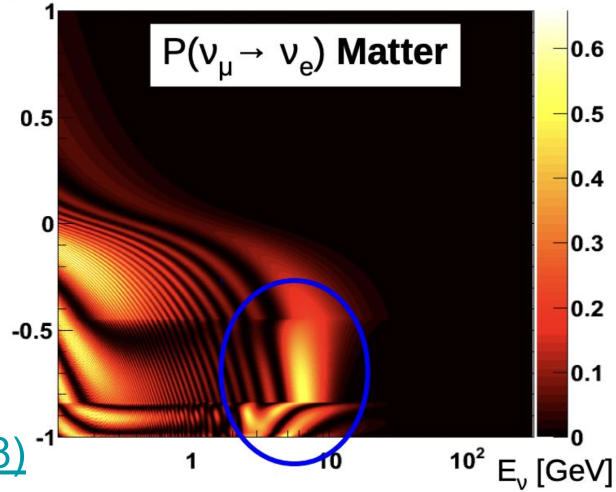
SK has discriminating power of mass ordering due to resonant-induced matter effects between 2 and 10 GeV in upgoing-neutrinos [cos(zenith) < 0]:

- 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



Atmospheric neutrino oscillation probability (normal ordering)



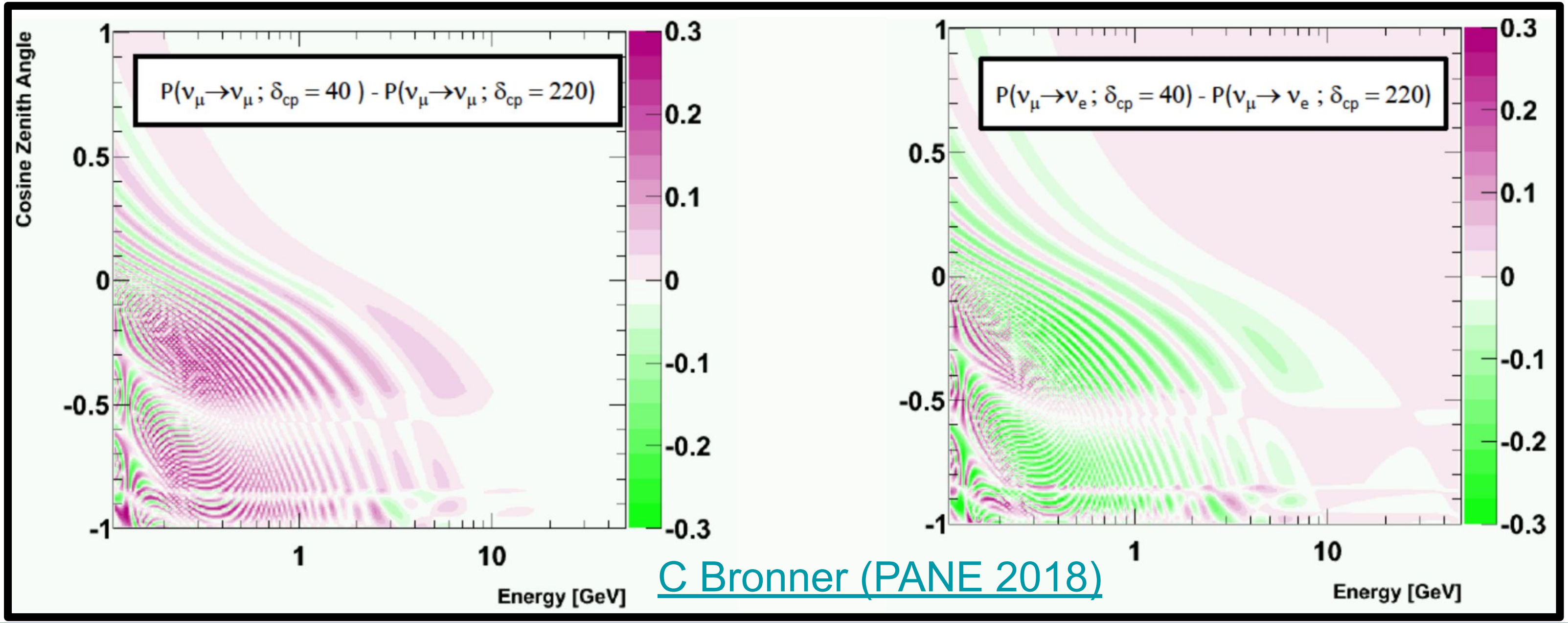


C Bronner (PANE 2018)

Atmospheric Oscillations in SK

SK has limited sensitivity to δ_{CP} through the normalisation of sub-GeV e-like events:

- Overall normalisation due to detector energy and angular resolution
- More ν_e events at δ_{CP} ~ 220°, fewer at δ_{CP} ~ 40°



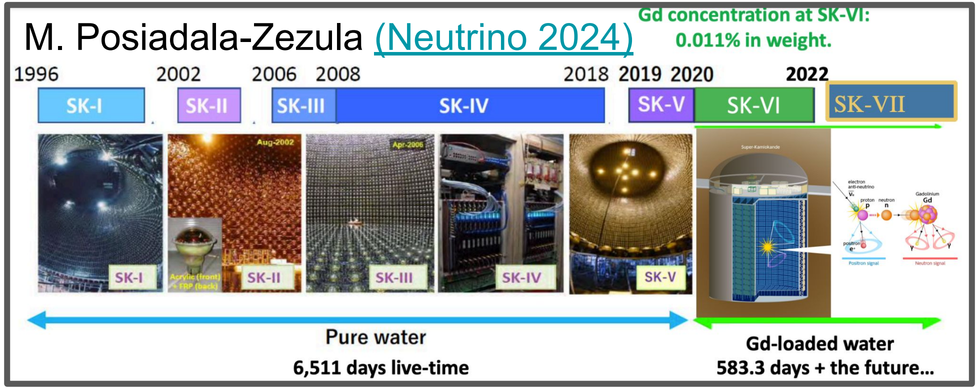
C Bronner (PANE 2018)

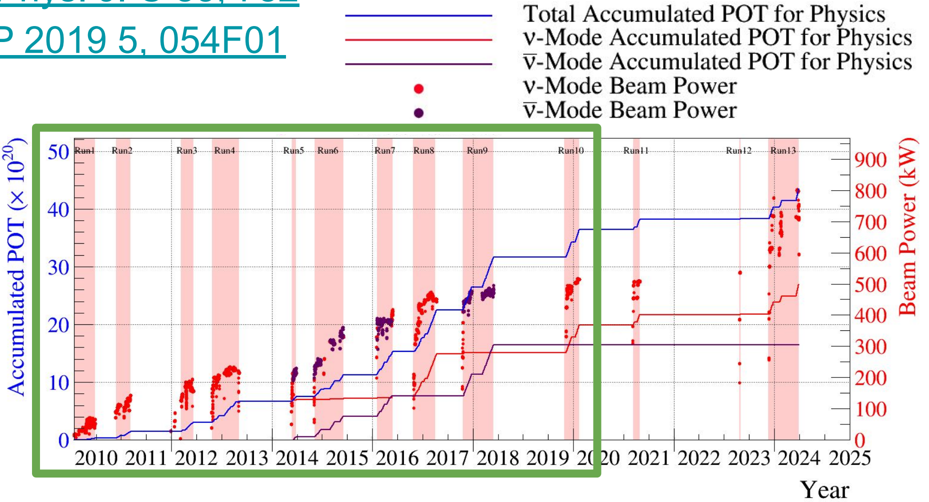
Joint Analyses

Two joint analyses released in 2023:

- T2K (beam) + NOvA (beam) → See the previous talks
- 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)



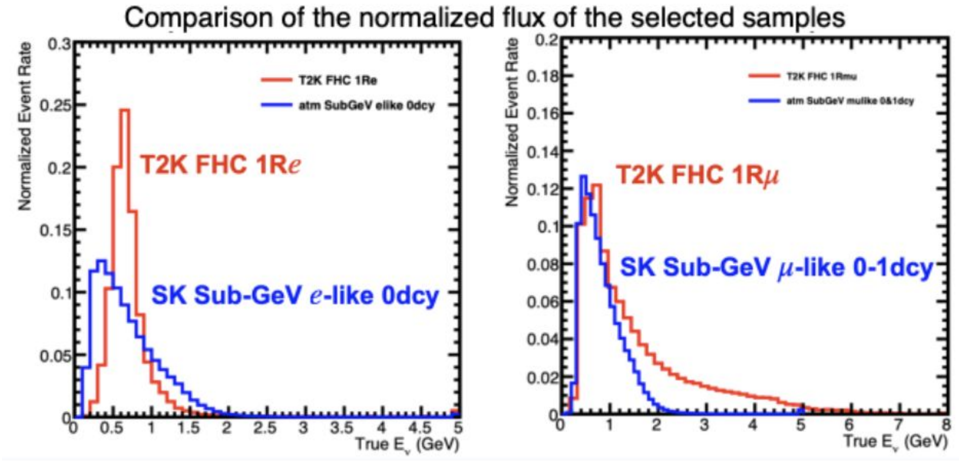


Motivation of T2K+SK Joint Analysis

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

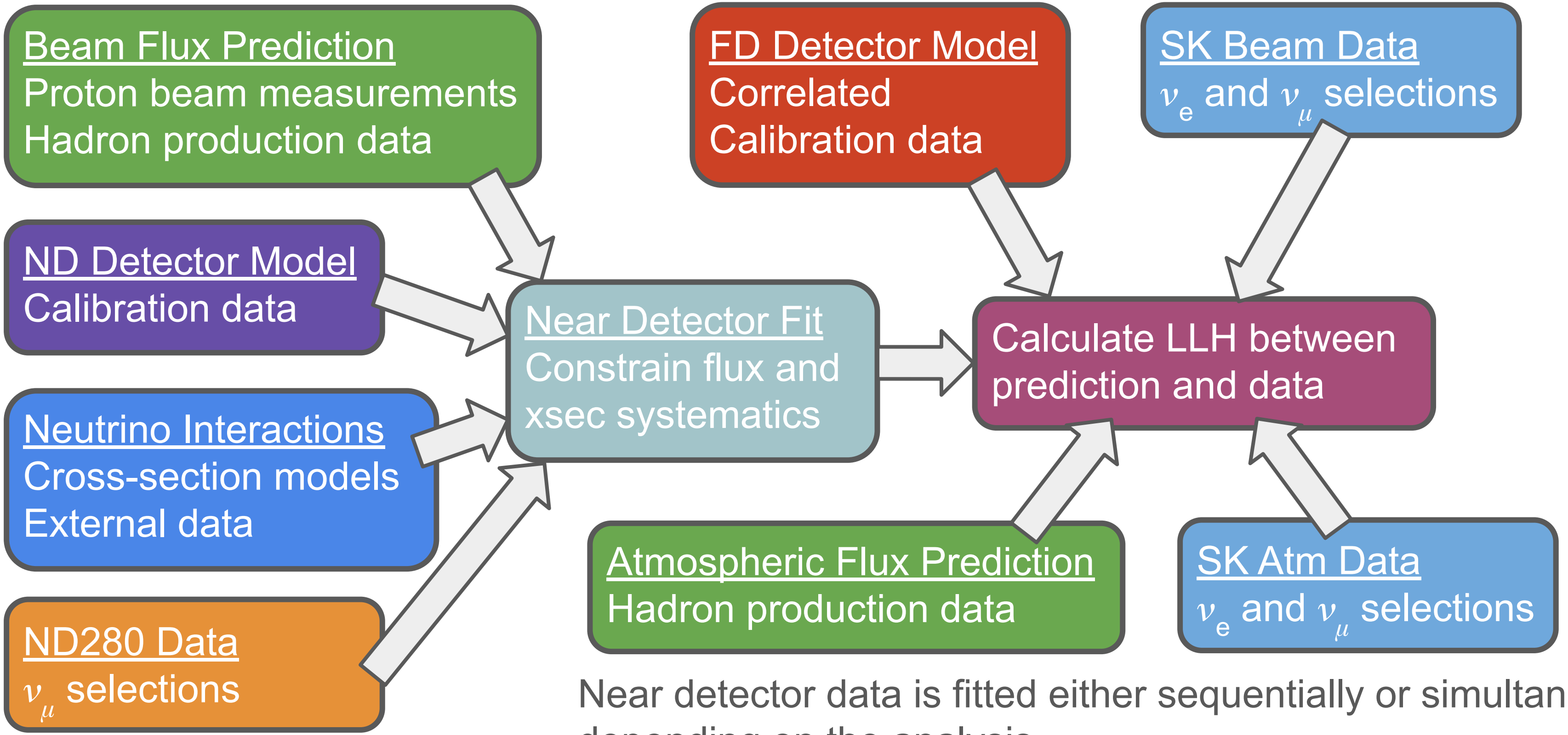
Both experiments have **overlapping energy spectrum**:



<u>Correlated systematics</u>

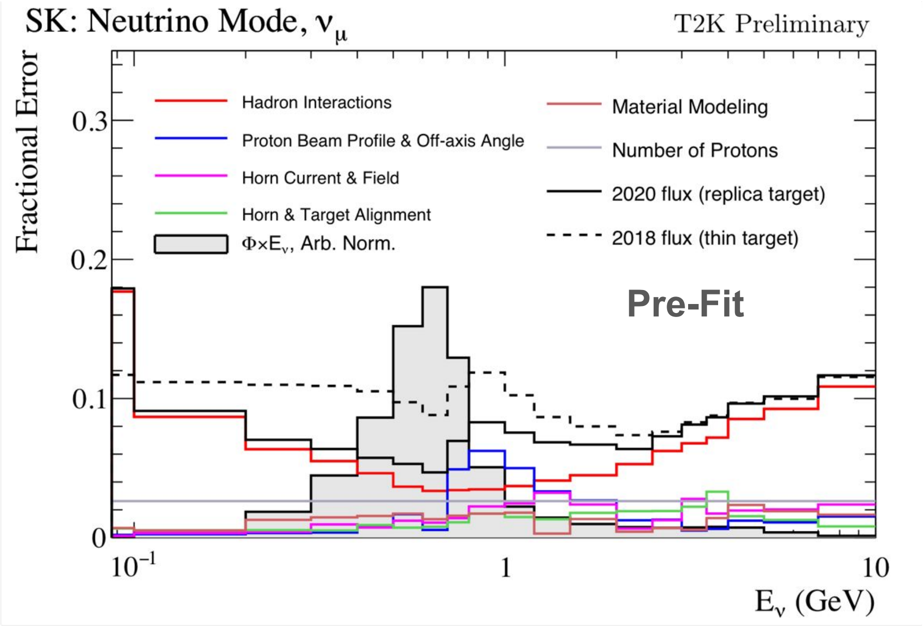
T2K near detector can be used to constrain cross-section uncertainties for low-energy atmospheric samples

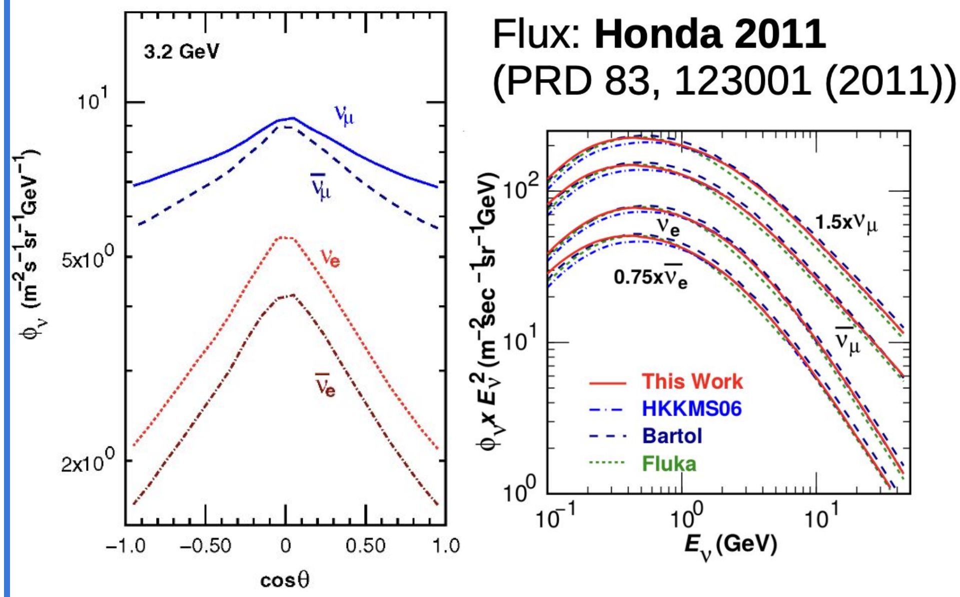
Analysis Methodology in Joint Analysis



Near detector data is fitted either sequentially or simultaneously, depending on the analysis

Neutrino Flux Modelling





Flux uncertainty ~6% at peak of spectrum:

- External hadron production data (e.g NA61)

No correlations included in flux modeling

Use downgoing neutrino (un-oscillated) flux to control the flux uncertainties

- Large overlap in the neutrino energy range

Cross Section Modelling

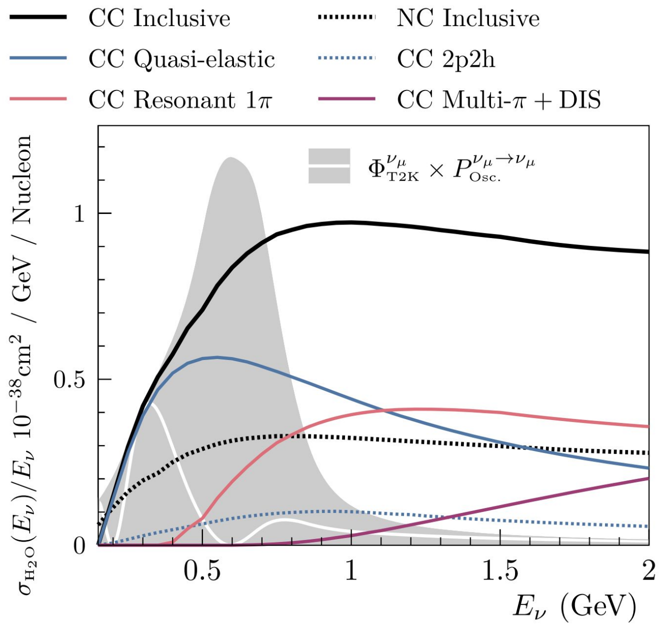
Interaction model:

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	

Correlated in beam and low energy atmospherics: NEUT

- High energy uses SK model



Low energy interactions dominated by CCQE:

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

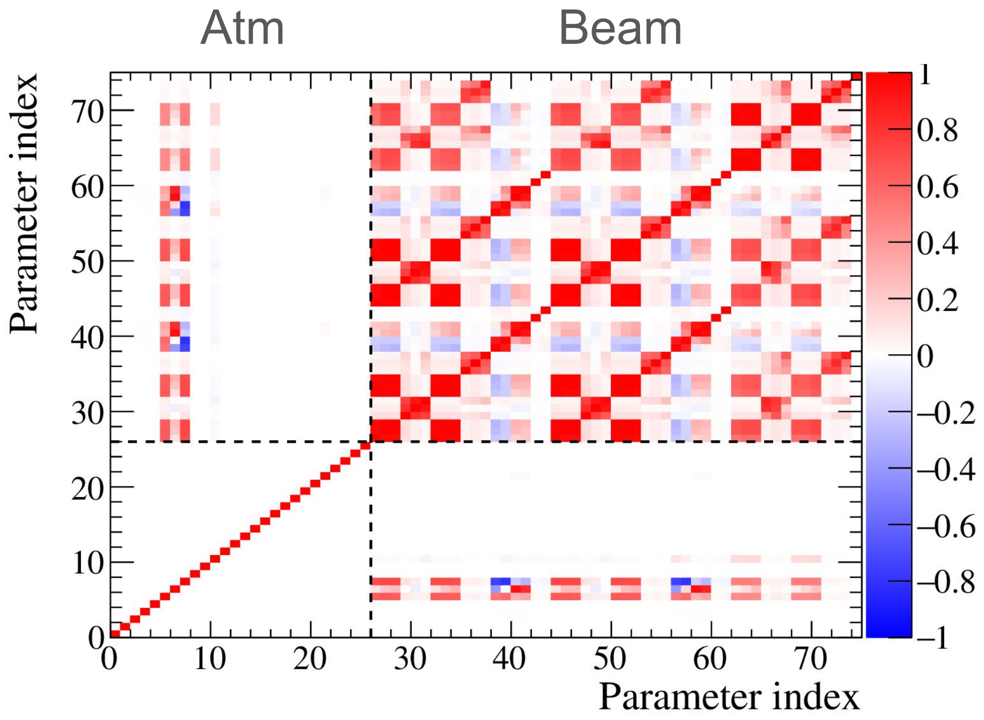
Correlated Detector Modelling

Correlated detector model developed in joint analysis:

- Larger range in energy in SK
- Larger number of multi-ring events
- Better constraint of the uncertainties

Based on SK model, with additional beam uncertainties added for T2K part

Detector model:

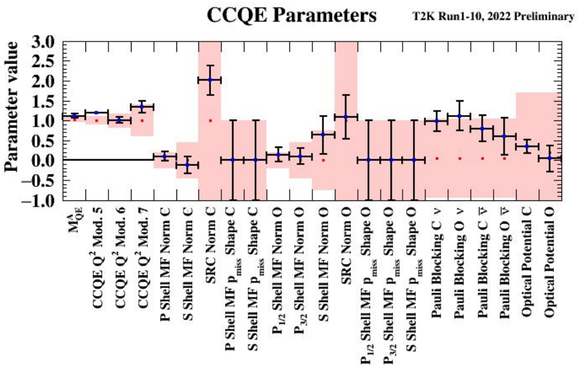


ND280 Fit

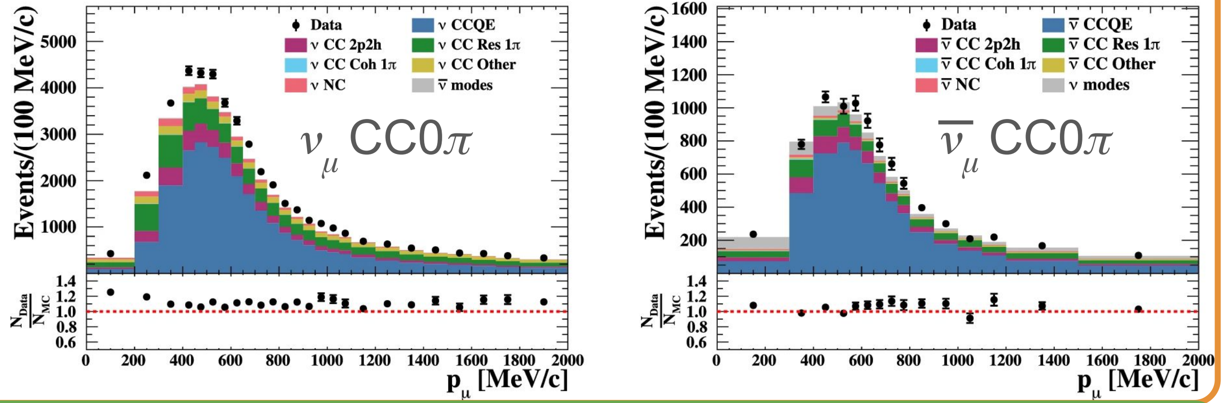
18 Samples based on:

- Horn current
- Target (CH/H_2O)
- Number of pions and protons

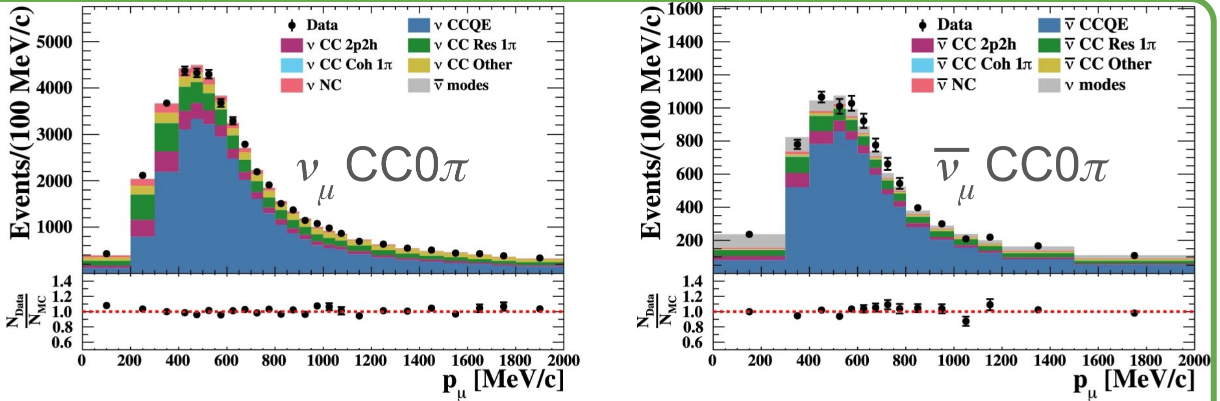
Tune and reduce flux and cross-section uncertainty:



Before Fit



After Fit



T2K Beam Selections

5 samples, split by:

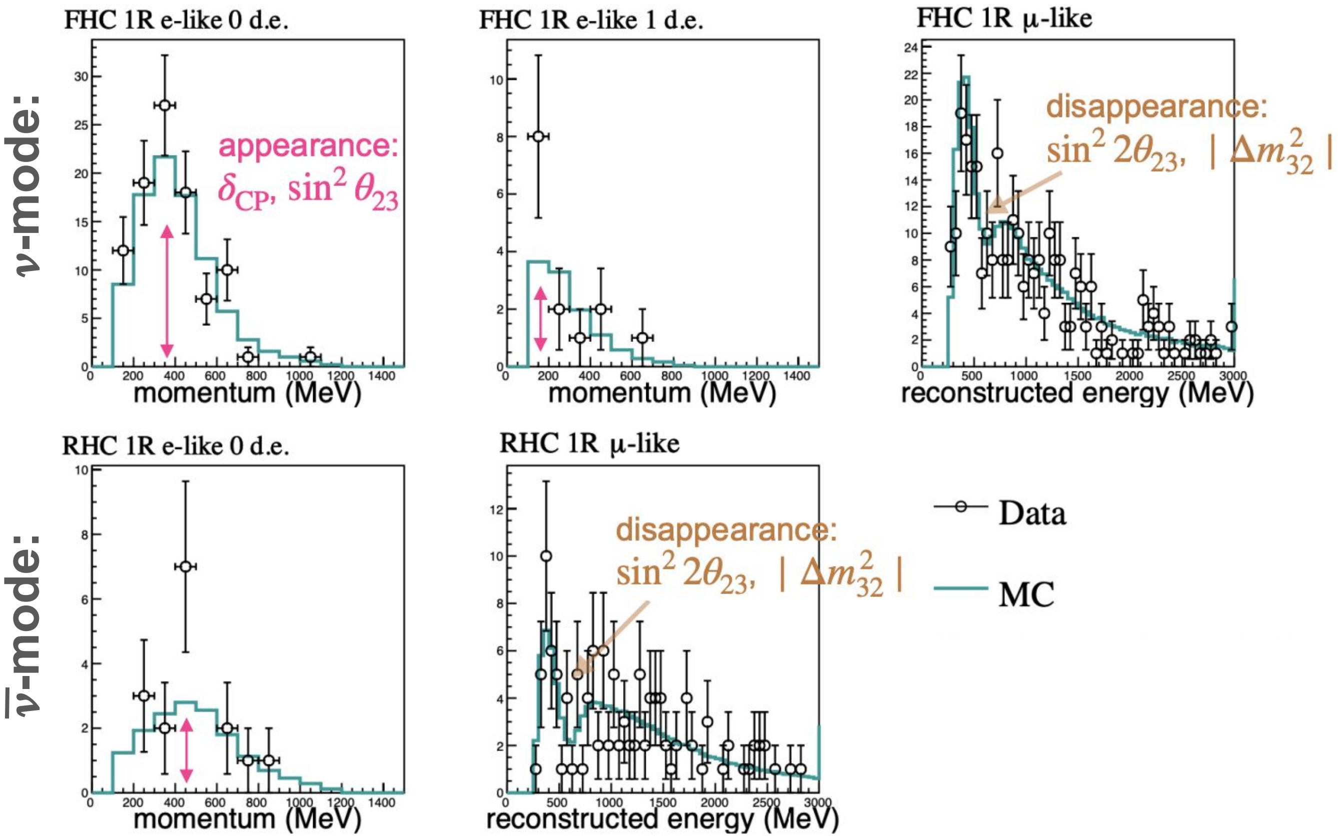
- Beam configuration
- Electron/Muon PID
- Number of decay electrons

3.6×10^{21} Protons on Target

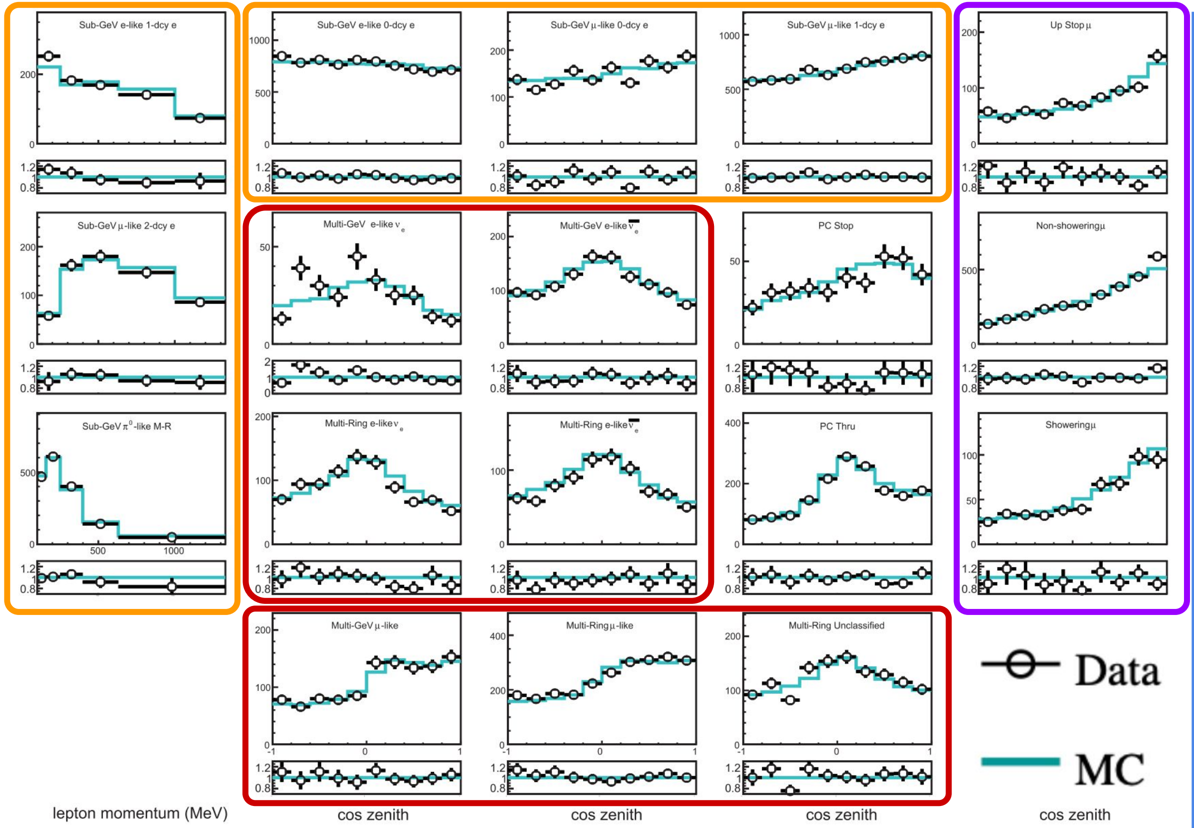
- 55%:45% split in ν:$\overline{\nu}$

Consistency shows good agreement between SK and T2K samples:

- Agreement between systematic parameters favored by the two datasets, p-val = 0.24



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

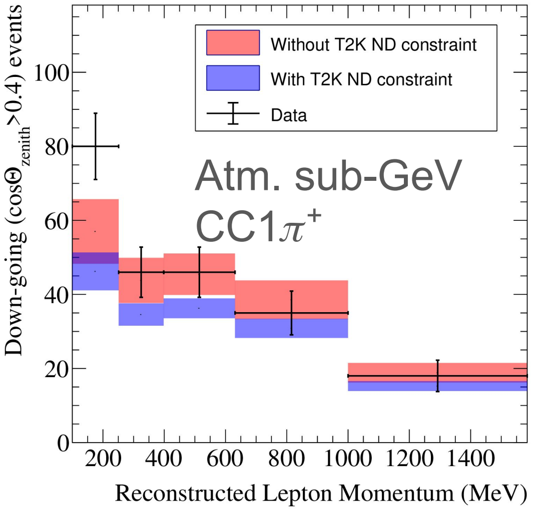
Oscillation Parameter Measurements

Robustness Studies

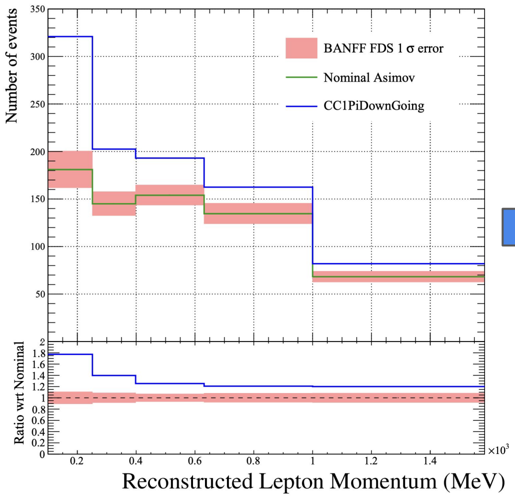
Predict potential biases from out-of-model effects
- Test 14 alternative models or data-driven effects to estimate the bias
- Biases on Δm^2_{32} are included via Gaussian smearing

Example: Excess in down-going (un-oscillated) atmospheric data after applying ND constraints

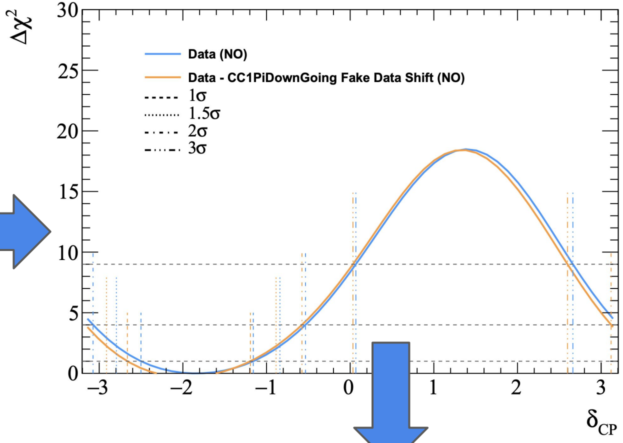
Effect:



Construct fake data with excess:



Evaluate effect using difference between nominal and fake data fit

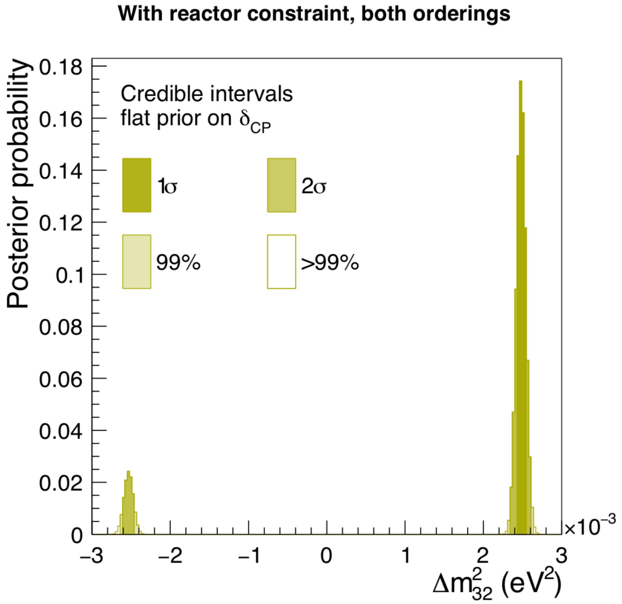


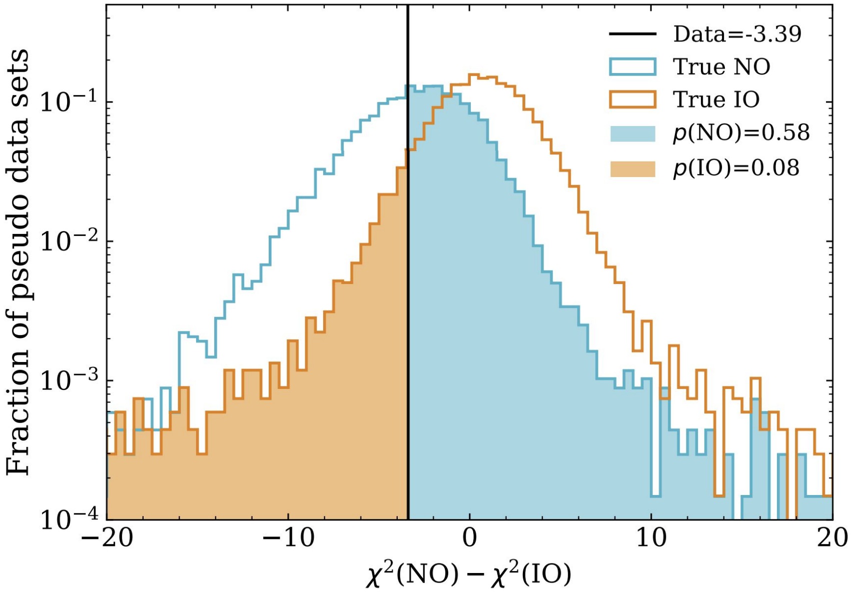
Apply difference to data results

T2K+SK Oscillation Analysis Results

Slight preference for normal ordering:

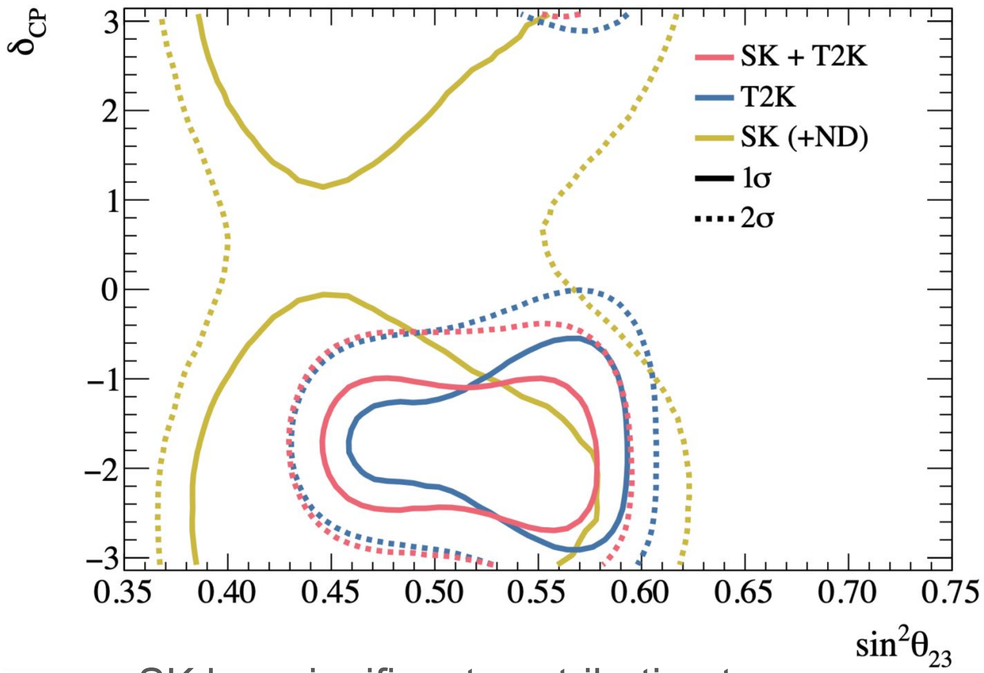
- Bayes factor **B(NO/IO) = 8.98**
- Normal ordering preferred, with **p-value** for IO = **0.08**
  - Corresponds to 1.2σ deviation using one-sided test



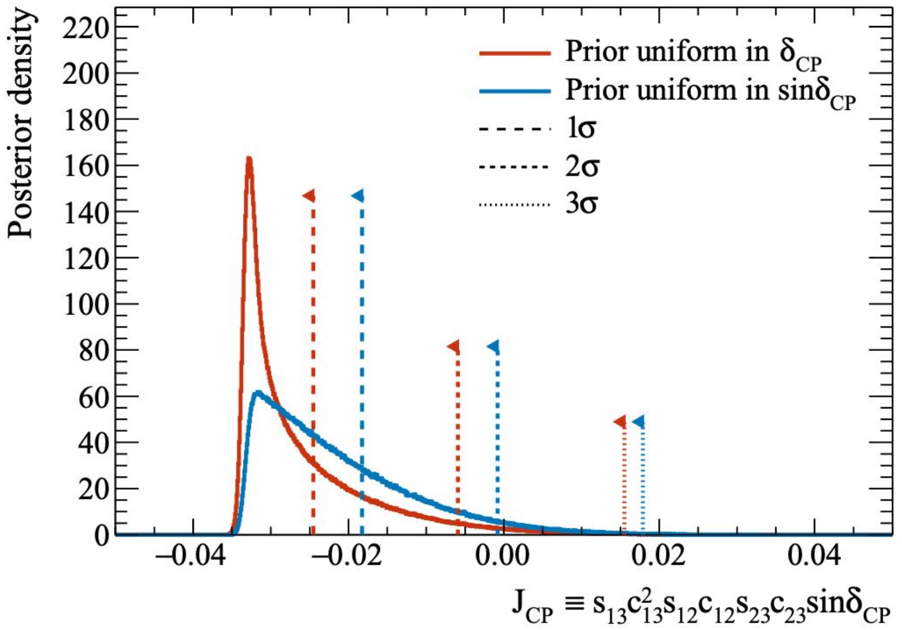


T2K+SK Oscillation Analysis Results

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

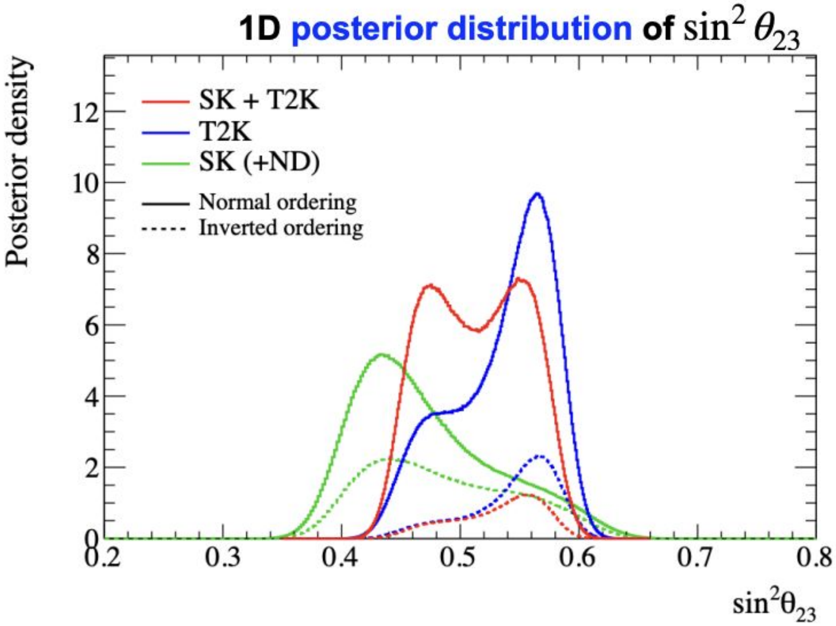


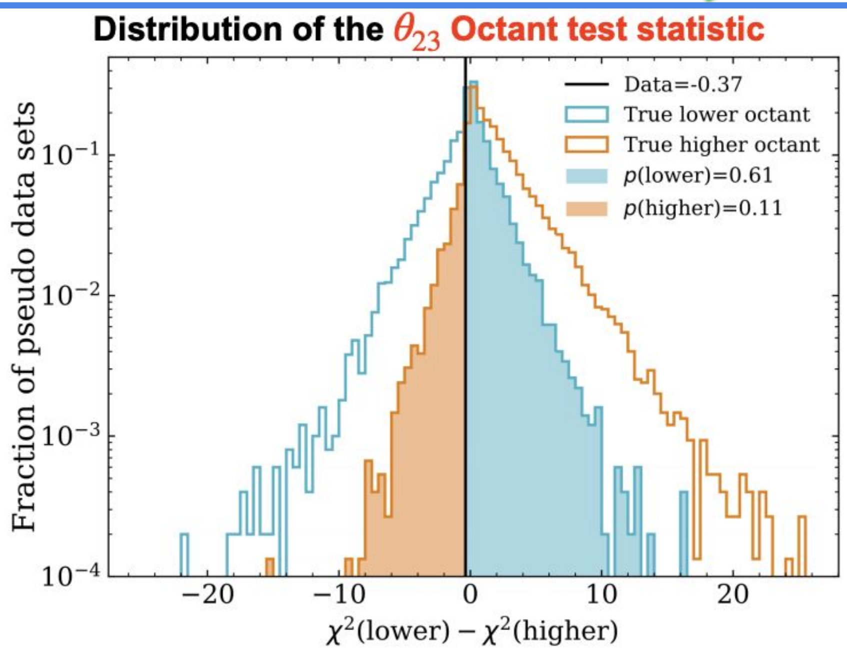
SK has significant contribution to preference of octant



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





Different octant preference by each experiment:

- Combined analysis: Bayesian posterior probability prefers UO (0.64)
- Corresponds to ~0.9σ fluctuation of LO

P-value (CLs) for UO from Frequentist analysis is 0.11 (0.28)

- **Conclusion**: no obvious preference for octant

Conclusion

First joint oscillation analysis of T2K beam + SK atmospheric neutrinos has been performed:

Both Bayesian and Frequentist results provided, with additional robustness studies:

- Limited rejection of inverse hierarchy at **90% CL**
- Charge-Parity conservation rejected between **1.9σ** and **2.0σ** exclusion
- No preference on the θ_{23} octant

Potential for future updates:

- SKIV (3244.4 days) $\rightarrow$ SKI to SKV (6511.3 days)
- T2K Run 1-10 $\rightarrow$ Run 1-11 (10% increase in ν-mode data)
- Updates to flux and interaction models

Results from the analysis presented in **Arxiv 2405.12488**

Backup Slides

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
$\theta_{23} \sim 45^\circ$
$|\Delta m^2_{32}| \sim 2.5\times10^{-3}\,eV^2$

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

Solar and Reactors
$\theta_{12} \sim 35^\circ$
$\Delta m^2_{21} \sim 7.5\times10^{-5}\,eV^2$

Long baseline accelerator (LBL) experiments:

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

Oscillation Probability

C. Giganti (Neutrino 2024)

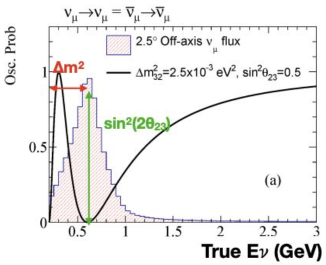
Physics case

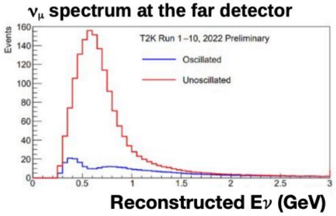
ν_μ and $\bar{\nu}_\mu$ disappearance

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

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

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

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

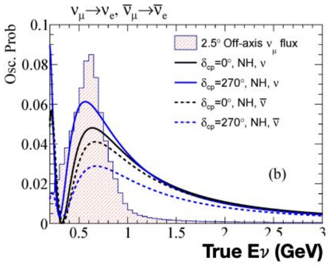
$$+\alpha\frac{J_0\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

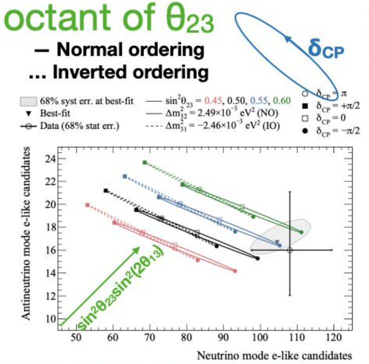
$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30$

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

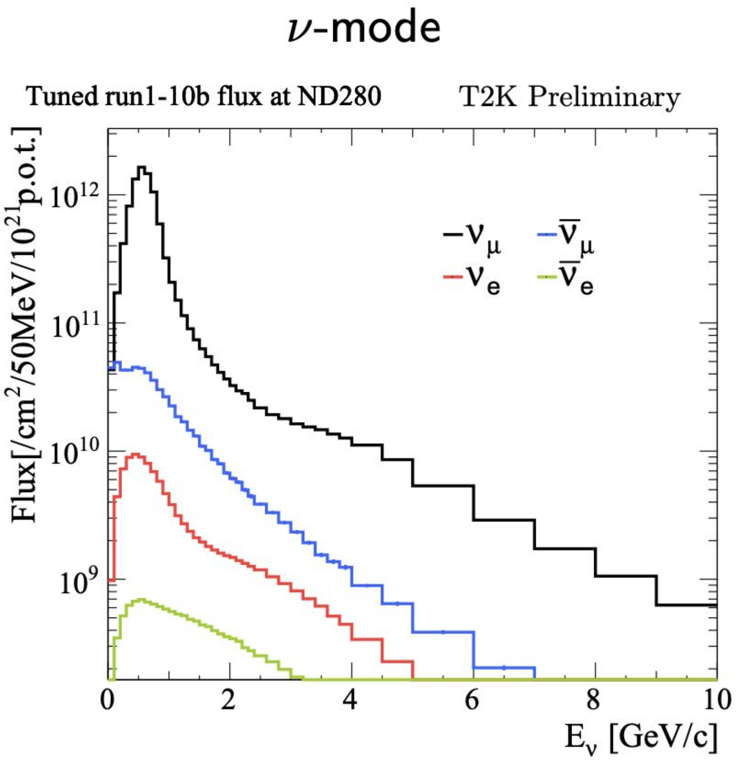
$A = (\mp)2\sqrt{2}G_F n_e E/\Delta m^2_{31}$

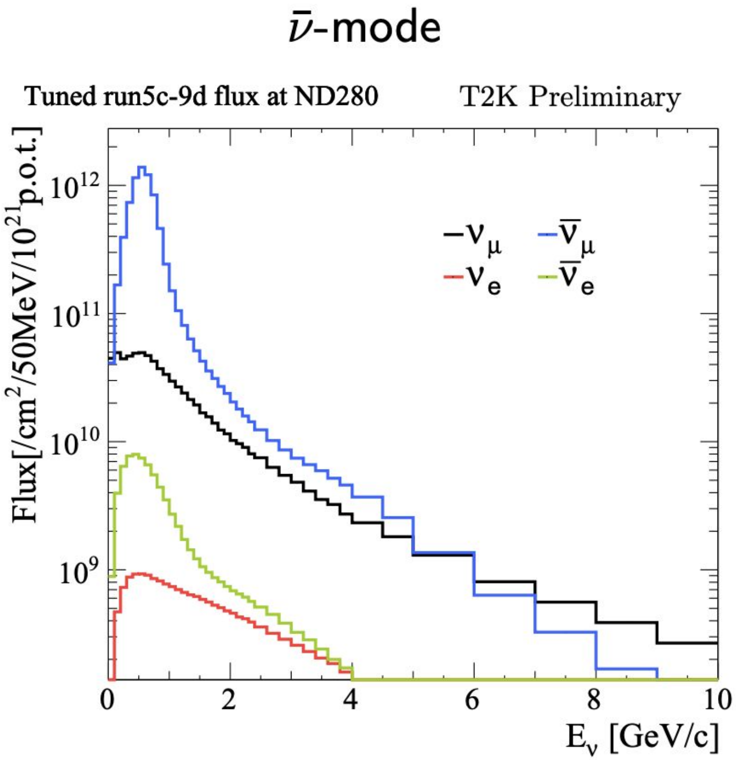
Sensitivity to δ_{CP}, to the mass ordering and to the octant of θ_{23}



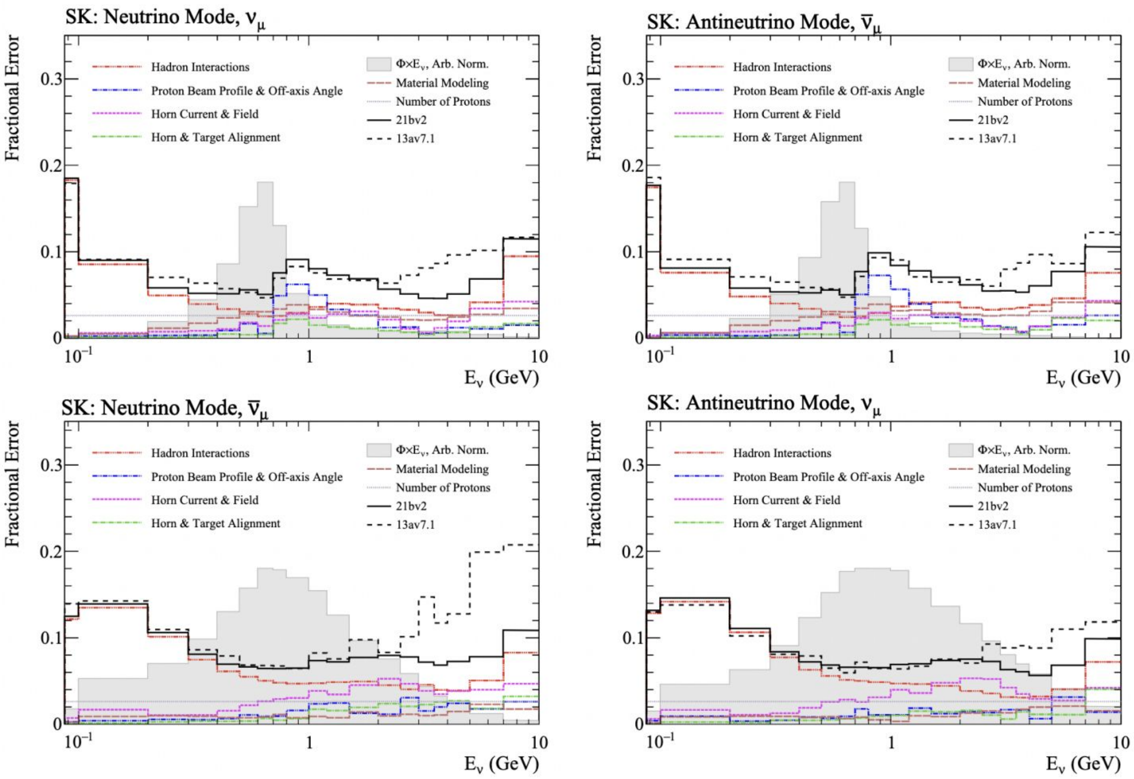


Neutrino Flux





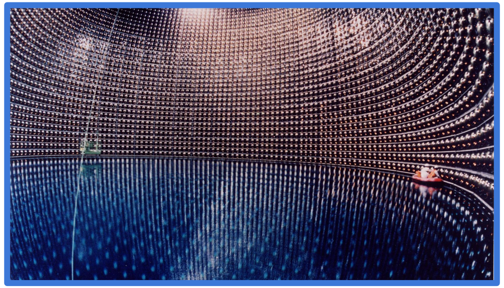
Neutrino Flux Uncertainties

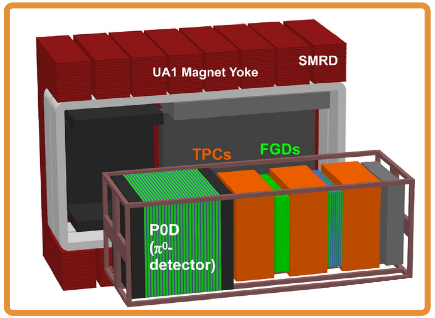


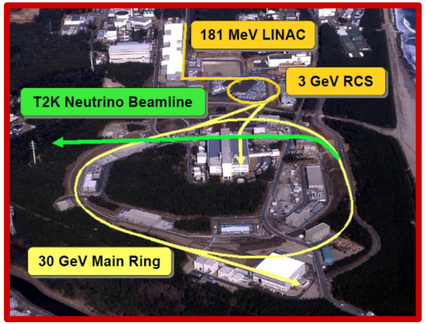
T2K Experiment

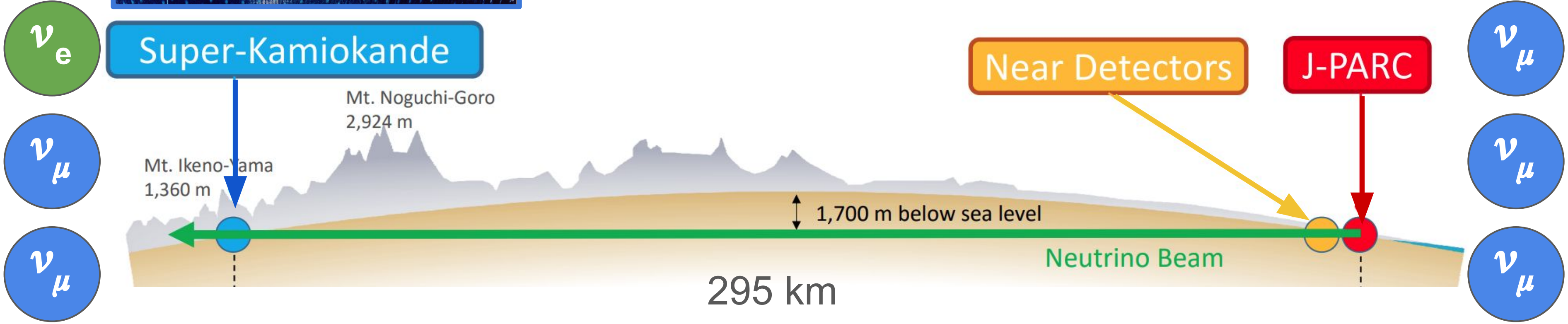
High intensity neutrino(antineutrino) beam produced at **J-PARC**:

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

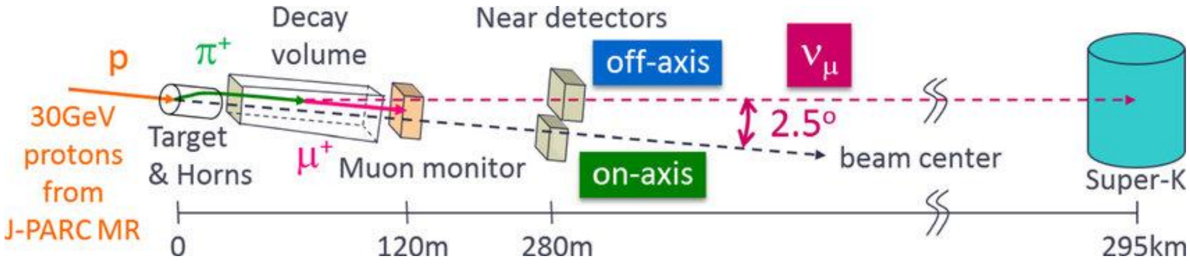








Beamline



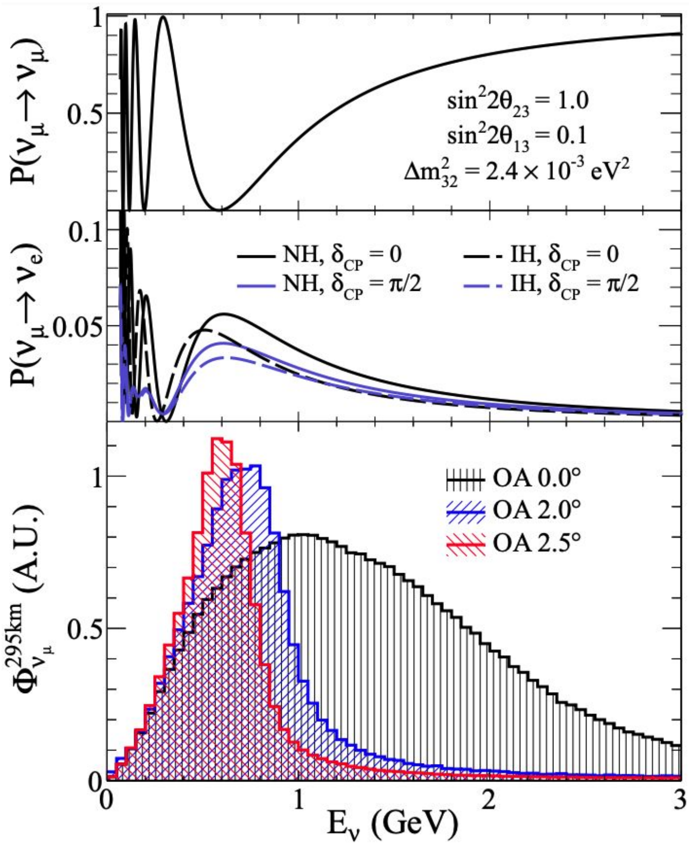
30 GeV proton beam extracted onto graphite target:

- 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

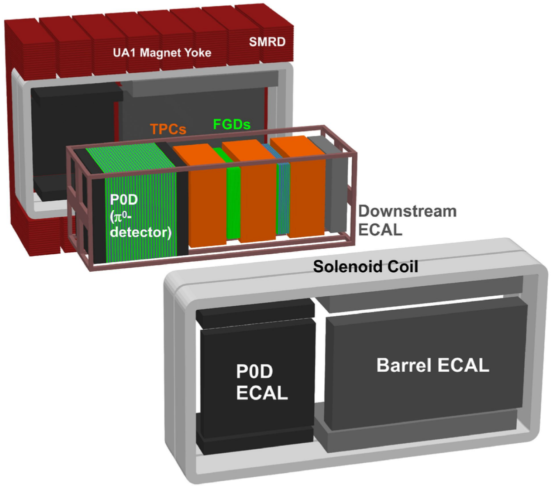
Off axis technique produces narrow-band beam

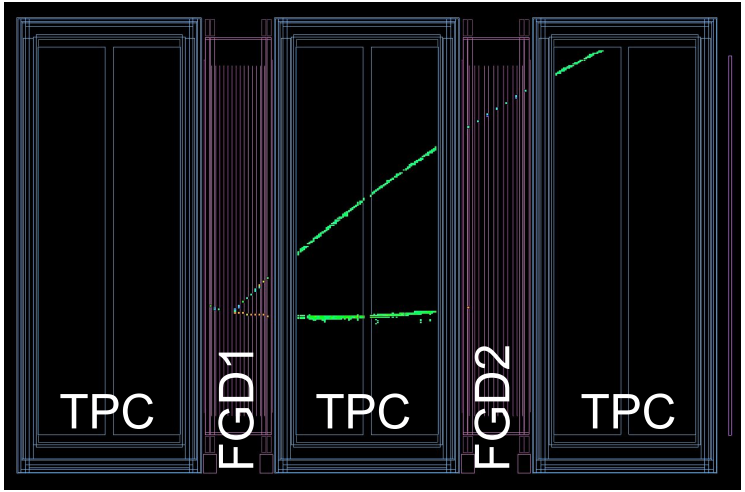


Near Detector (ND280)

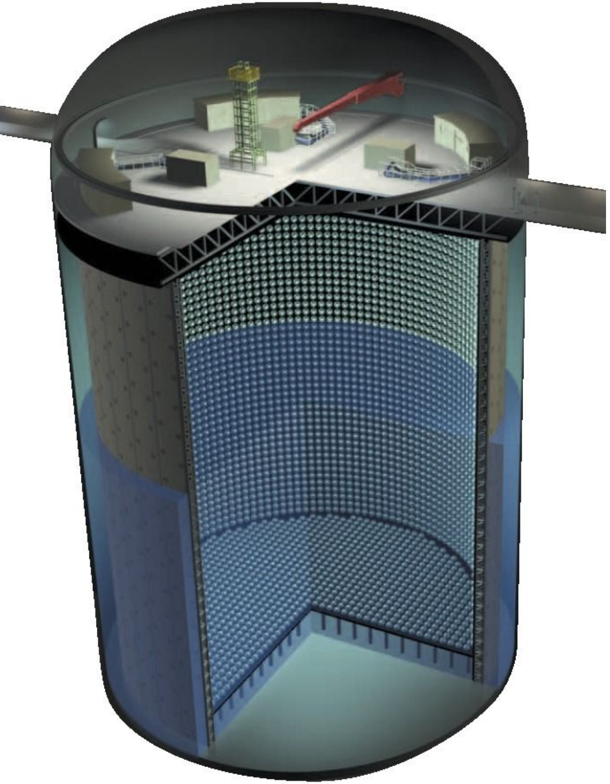
Measure beam spectrum and flavour composition pre-oscillation:

- 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): **Not** used within analyses shown





Super Kamiokande (SK)

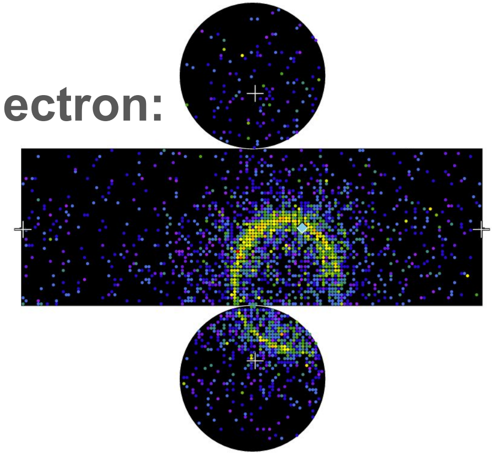


Large underground 50 kton water Cherenkov detector:

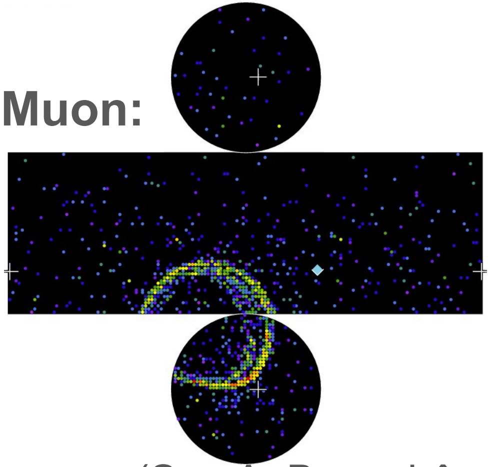
- ~11k 20” PMTs in the inner detector
- ~2k 8” PMTs in the outer detector, used as veto

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

Electron:



Muon:



(See A. Beauchêne’s talk)

Sample Breakdown

	CCQE	CC1pipm	CCcoh	CCMpi	CCDIS	NC1pi0	NC1pipm	NCcoh	NCoth	2p2h	NC1gam	CCMisc	NCMpi	NCDIS	CC1pi0
FHCCC1pi-2020	0.03	0.83	0.02	0.03	0.00	0.01	0.01	0.00	0.01	0.02	0.00	0.00	0.01	0.00	0.03
RHC1Re-2020	0.58	0.12	0.01	0.01	0.00	0.07	0.01	0.01	0.00	0.13	0.03	0.00	0.01	0.00	0.02
FHC1Re-2020	0.65	0.11	0.00	0.00	0.00	0.04	0.01	0.00	0.00	0.13	0.02	0.00	0.00	0.00	0.02
RHC1Rmu-2020	0.59	0.18	0.00	0.02	0.00	0.00	0.02	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.03
FHC1Rmu-2020	0.59	0.18	0.00	0.03	0.00	0.00	0.03	0.00	0.00	0.13	0.00	0.00	0.01	0.00	0.03
SubGeV-pi0like	0.05	0.02	0.00	0.00	0.00	0.68	0.06	0.06	0.03	0.01	0.00	0.00	0.07	0.00	0.01
SubGeV-mulike-2dcy	0.03	0.80	0.01	0.10	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.03
SubGeV-mulike-1dcy	0.70	0.13	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.02
SubGeV-mulike-0dcy	0.65	0.11	0.00	0.01	0.00	0.01	0.05	0.00	0.02	0.12	0.00	0.00	0.01	0.00	0.02
SubGeV-elike-1dcy	0.05	0.75	0.01	0.10	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.02	0.01	0.03
SubGeV-elike-0dcy	0.69	0.11	0.00	0.01	0.00	0.03	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.02