

A Joint Analysis of Beam and Atmospheric Neutrinos



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UNIVERSITY OF
OXFORD

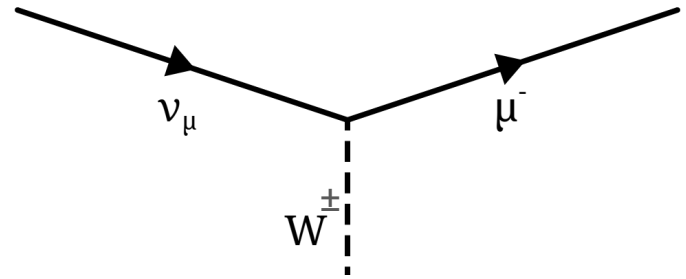


Neutrinos: What do we know?

	<p>mass $\approx 2.16 \text{ MeV}/c^2$</p> <p>charge $\frac{2}{3}$</p> <p>spin $\frac{1}{2}$</p> <p>u</p> <p>up</p>	<p>mass $\approx 1.273 \text{ GeV}/c^2$</p> <p>charge $\frac{2}{3}$</p> <p>spin $\frac{1}{2}$</p> <p>c</p> <p>charm</p>	<p>mass $\approx 172.57 \text{ GeV}/c^2$</p> <p>charge $\frac{2}{3}$</p> <p>spin $\frac{1}{2}$</p> <p>t</p> <p>top</p>	<p>0</p> <p>0</p> <p>1</p> <p>g</p> <p>gluon</p>	<p>mass $\approx 125.2 \text{ GeV}/c^2$</p> <p>0</p> <p>0</p> <p>0</p> <p>H</p> <p>higgs</p>
QUARKS	<p>mass $\approx 4.7 \text{ MeV}/c^2$</p> <p>charge $-\frac{1}{3}$</p> <p>spin $\frac{1}{2}$</p> <p>d</p> <p>down</p>	<p>mass $\approx 93.5 \text{ MeV}/c^2$</p> <p>charge $-\frac{1}{3}$</p> <p>spin $\frac{1}{2}$</p> <p>s</p> <p>strange</p>	<p>mass $\approx 4.183 \text{ GeV}/c^2$</p> <p>charge $-\frac{1}{3}$</p> <p>spin $\frac{1}{2}$</p> <p>b</p> <p>bottom</p>	<p>0</p> <p>0</p> <p>0</p> <p>1</p> <p>γ</p> <p>photon</p>	SCALAR BOSONS
	<p>mass $\approx 0.511 \text{ MeV}/c^2$</p> <p>charge -1</p> <p>spin $\frac{1}{2}$</p> <p>e</p> <p>electron</p>	<p>mass $\approx 105.66 \text{ MeV}/c^2$</p> <p>charge -1</p> <p>spin $\frac{1}{2}$</p> <p>μ</p> <p>muon</p>	<p>mass $\approx 1.77693 \text{ GeV}/c^2$</p> <p>charge -1</p> <p>spin $\frac{1}{2}$</p> <p>τ</p> <p>tau</p>	<p>mass $\approx 91.188 \text{ GeV}/c^2$</p> <p>0</p> <p>0</p> <p>1</p> <p>Z</p> <p>Z boson</p>	
LEPTONS	<p>mass $< 0.8 \text{ eV}/c^2$</p> <p>charge 0</p> <p>spin $\frac{1}{2}$</p> <p>ν_e</p> <p>electron neutrino</p>	<p>mass $< 0.17 \text{ MeV}/c^2$</p> <p>charge 0</p> <p>spin $\frac{1}{2}$</p> <p>ν_μ</p> <p>muon neutrino</p>	<p>mass $< 18.2 \text{ MeV}/c^2$</p> <p>charge 0</p> <p>spin $\frac{1}{2}$</p> <p>ν_τ</p> <p>tau neutrino</p>	<p>mass $\approx 80.3692 \text{ GeV}/c^2$</p> <p>$\pm 1$</p> <p>1</p> <p>W</p> <p>W boson</p>	GAUGE BOSONS VECTOR BOSONS

Neutrinos:

- Are fundamental particle in the Standard Model
 - Massless?
- Interact through the weak force
- “Pair” with charged leptons



- And they oscillate...

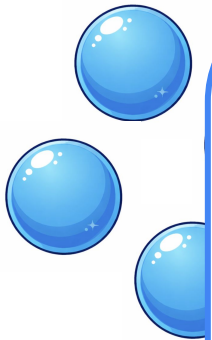
First observed in the '90s by the Super-Kamiokande and SNO experiments:



Observation showed a deficit of muon neutrinos as a function of distance they travelled:
→ Muon neutrinos changed flavour as they travel through space

Neutrino Oscillation

First observed in the '90s by the Super-Kamiokande and SNO experiments:

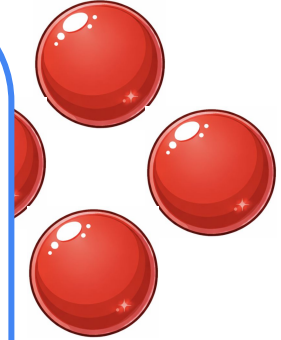
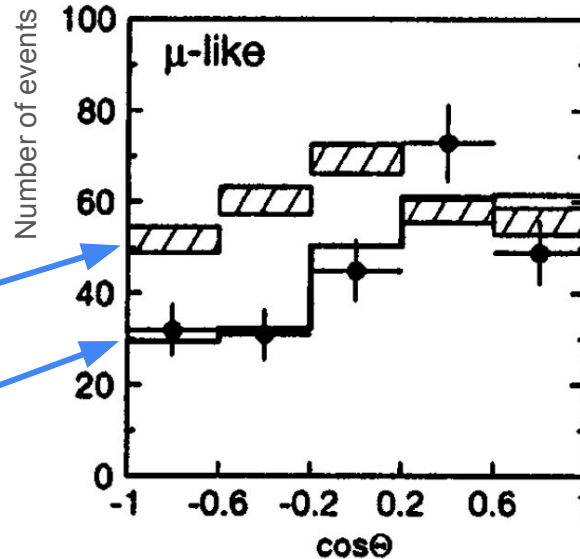


Observation
→ Muon

Deficit in events for
neutrinos which travelled
through the Earth

No oscillation expectation

Oscillated expectation



Travelled:

Neutrino Oscillation

First observed in the '90s by the Super-Kamiokande and SNO experiments:



In a simplified approach:

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(L, E) = \overbrace{\sin^2(2\theta)}^{\text{Amplitude}} \underbrace{\sin^2\left(\frac{\Delta m^2 L}{4E}\right)}_{\text{Frequency depends on distance travelled and neutrino energy}}$$

$$\Delta m^2 = m_{\alpha}^2 - m_{\beta}^2$$

Requires the neutrino to have non-zero mass

Frequency depends on distance travelled and neutrino energy

Three Flavour Neutrino Oscillation

Three flavour eigenstates (ν_e, ν_μ, ν_τ) and 3 mass eigenstates (ν_1, ν_2, ν_3):

Beam-based 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

$$\theta_{23} \sim 48^\circ$$
$$|\Delta m_{32}^2| \sim 2.45 \times 10^{-3} \text{eV}^2$$

Reactors

$$\theta_{13} \sim 8.6^\circ$$
$$\delta_{CP} \text{ unknown}$$

Solar and Reactors

$$\theta_{12} \sim 33^\circ$$
$$\Delta m_{21}^2 \sim 7.4 \times 10^{-5} \text{eV}^2$$

Long baseline accelerator experiments:

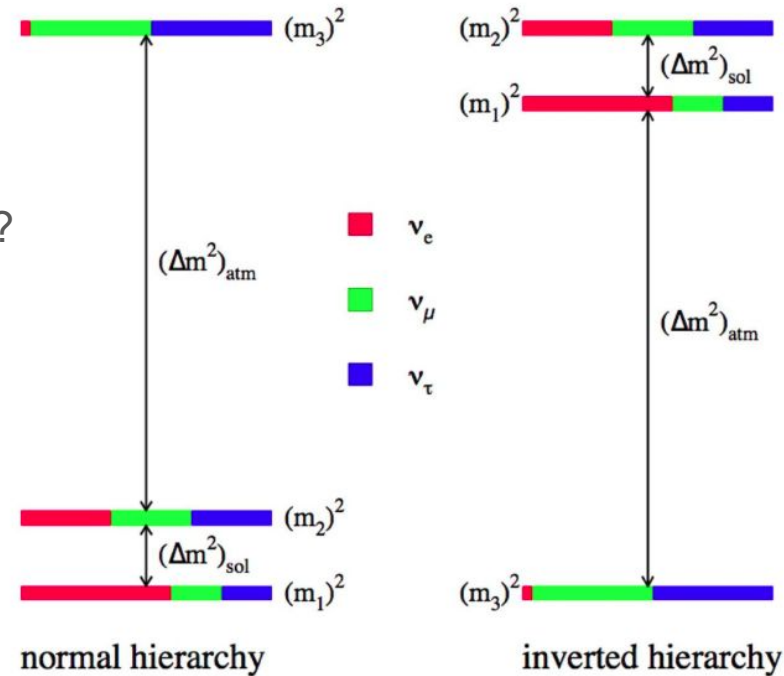
- Make the most precise measurements of $\theta_{23}, |\Delta m_{32}^2|$

Open Questions in Neutrino Oscillations

1. Is CP violated in the neutrino sector?: $P(\nu_\alpha \rightarrow \nu_\beta) = P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$?
2. What is the neutrino mass ordering?: $m_3 > m_2$?
 → Oscillations in vacuum only sensitive to $|\Delta m^2|$
 → Matter effects in the Sun provide: $m_2 > m_1$
 → Detected through matter effects in the Earth
3. Maximal mixing in atmospheric sector?: $\theta_{23} = 45^\circ$?
 → Lepton flavour symmetry?

Other questions:

- Are neutrinos their own antiparticles?
- Why do neutrinos weight so little?
- How many neutrinos are there?



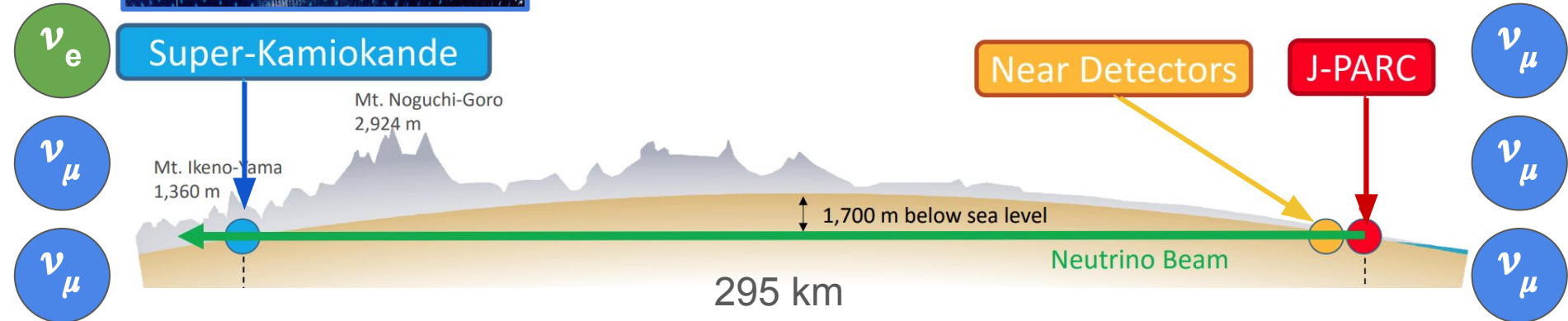
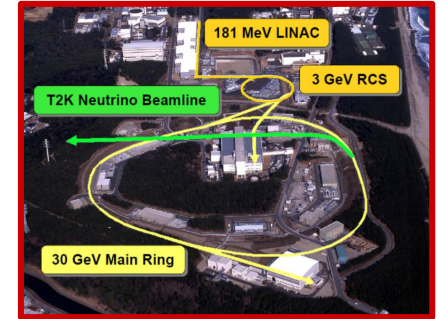
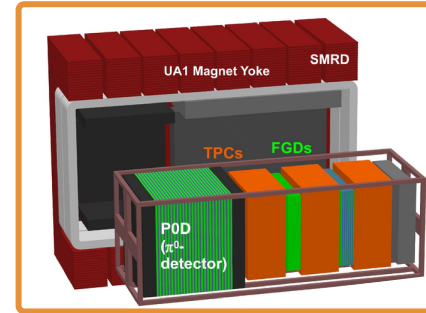
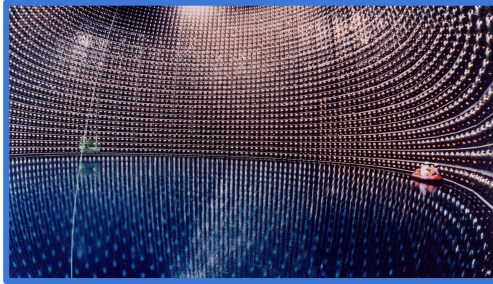
The Tokai-To-Kamiokande (T2K) Experiment

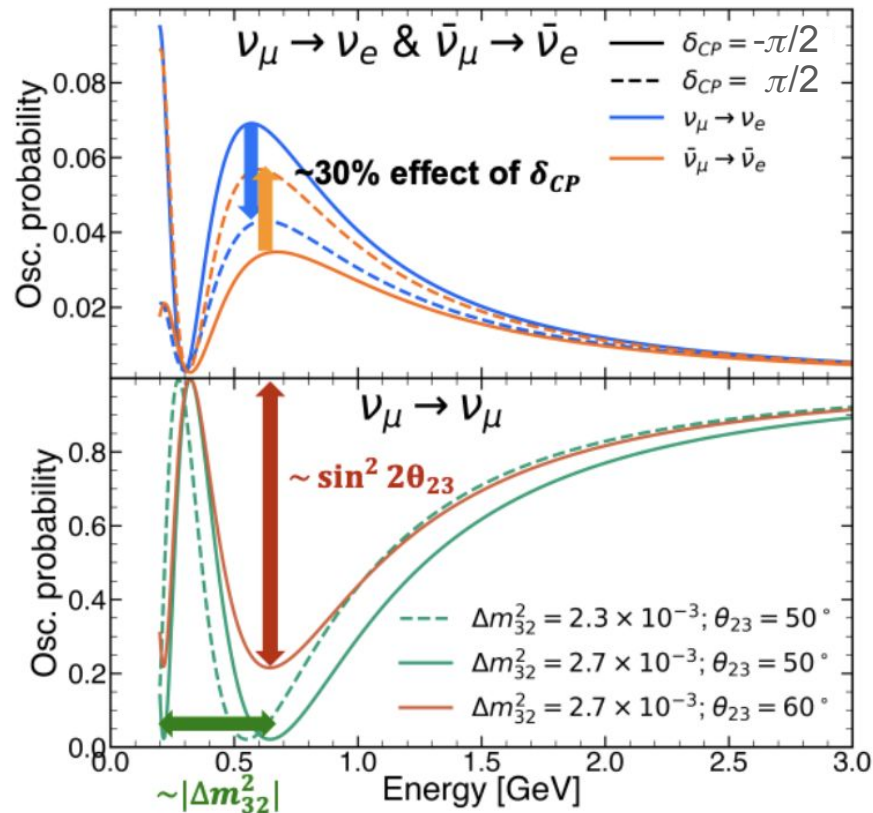
And how to look for neutrino oscillation...

Experimental Setup

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

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





Oscillation probability for T2K:

- Baseline, $L = 295\text{km}$

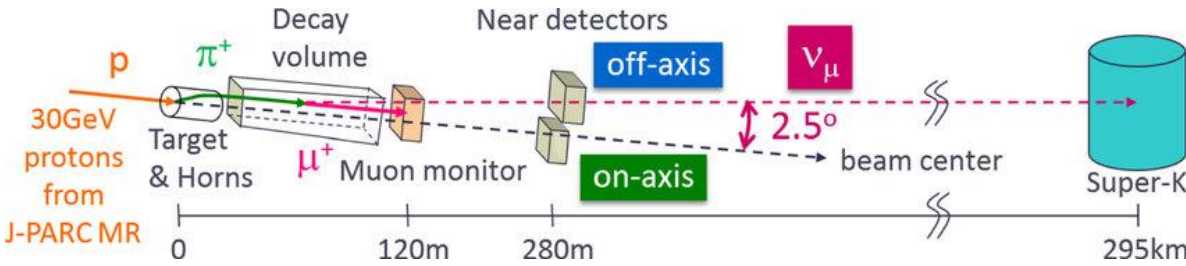
δ_{CP} modifies **neutrino/antineutrino** appearance probability ($\nu_\mu \rightarrow \nu_e$):

- Circular modulation over 2π period
- Asymmetric effect

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

- $\sin^2 2\theta_{23}$ modulates **amplitude**
- **Frequency** of oscillation $\sim |\Delta m_{23}^2|$

Neutrino Beam



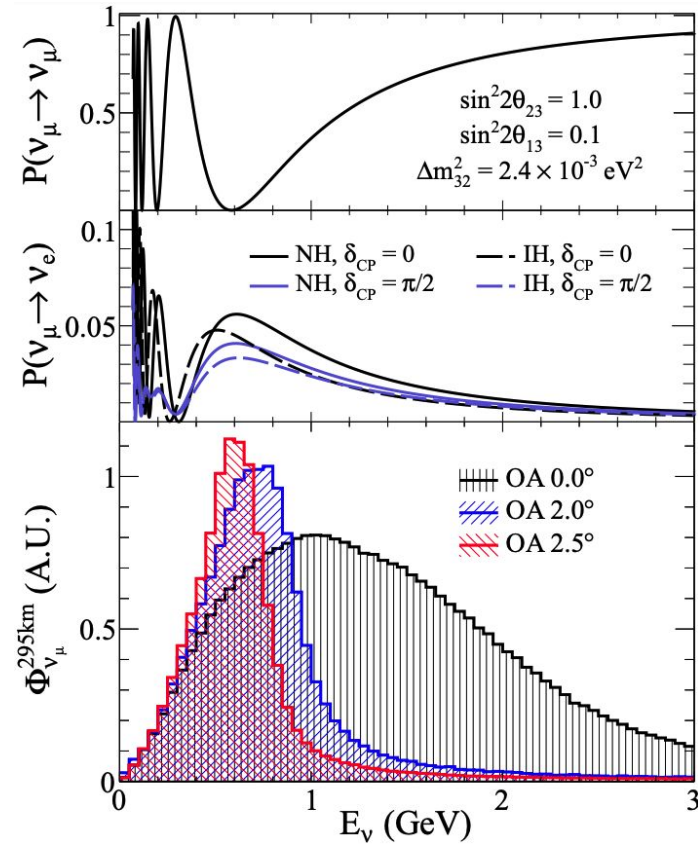
30 GeV proton beam extracted onto graphite target:

- p+C interactions produce hadron beam (π^\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

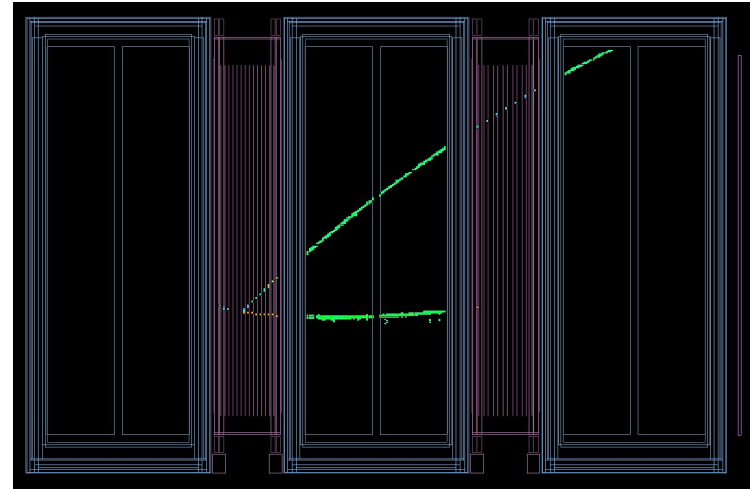
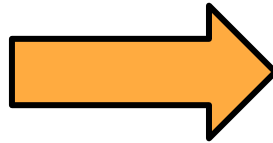
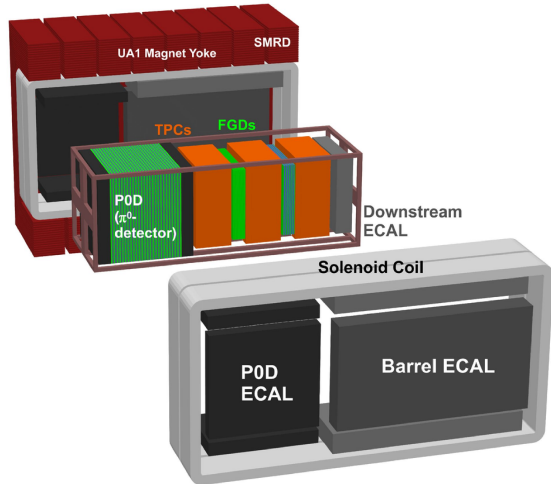
Off axis technique produces narrow-band beam



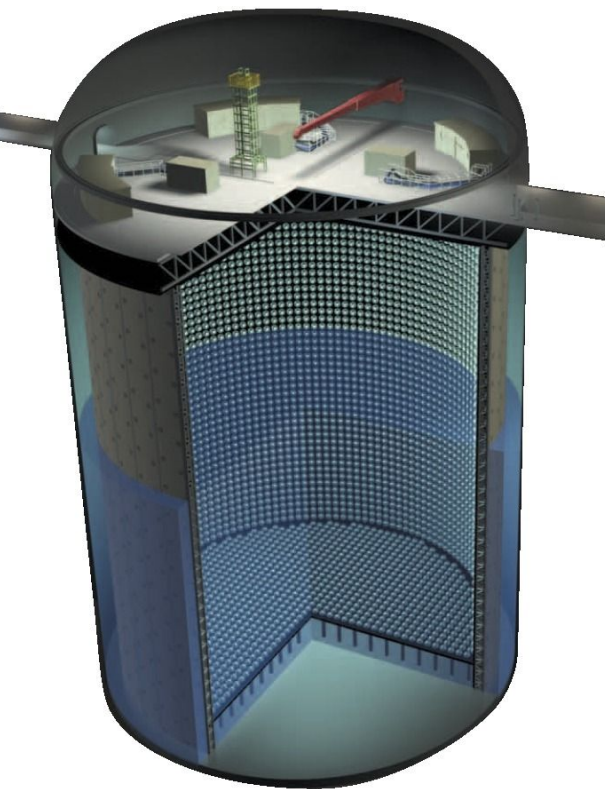
Near Detector (ND280)

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 (SF GD, high-angle TPCs, time of flight): **Not** used within analyses shown



Far Detector - Super Kamiokande (SK)

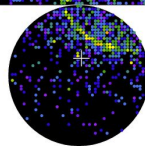
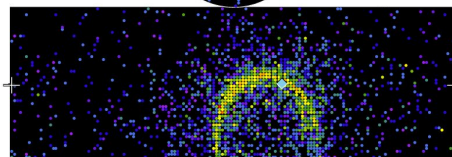
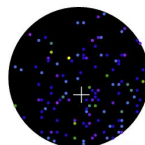


Large underground 50 kton water Cherenkov detector:

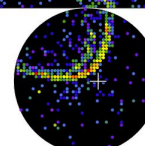
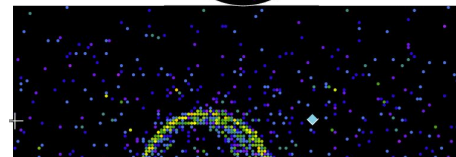
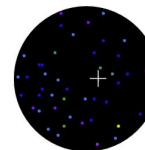
- ~11k 20" PMTs in the inner detector
- ~2k 8" PMTs in the outer detector, used as veto

Electron/muon separation using ring shape

Electron:



Muon:



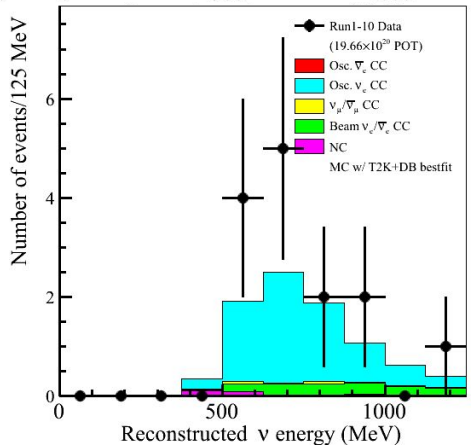
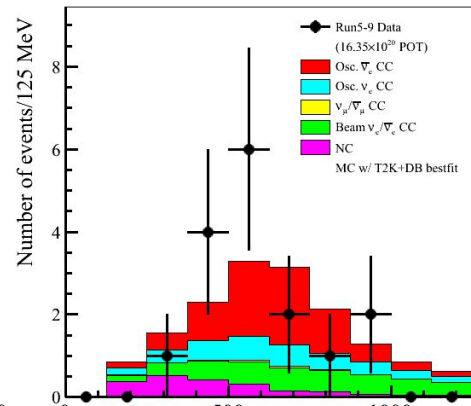
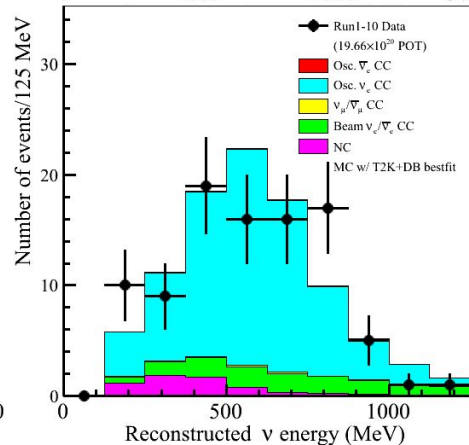
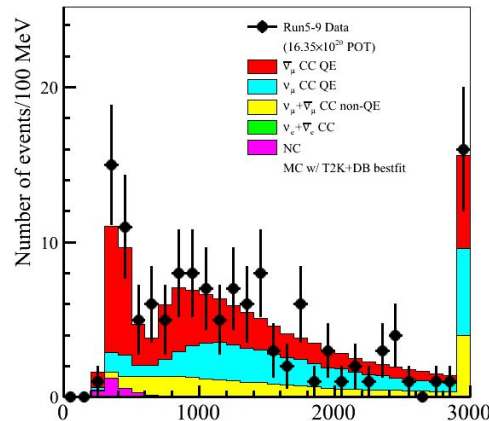
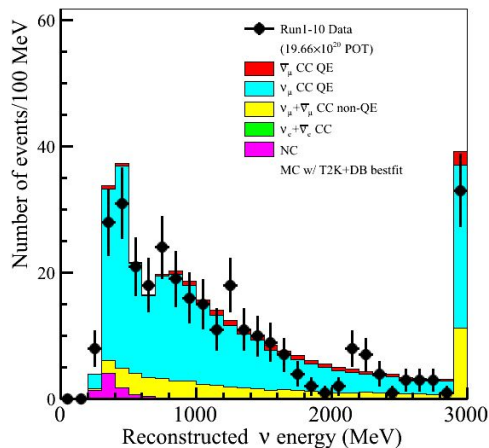
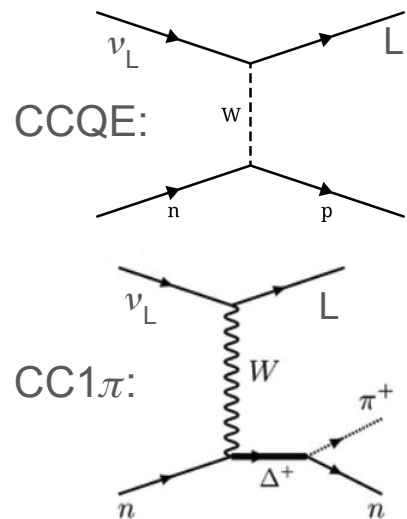
Unable to directly separate neutrino/antineutrino

- Rely on beam configuration

T2K Event Selection

Five selections at SK based on

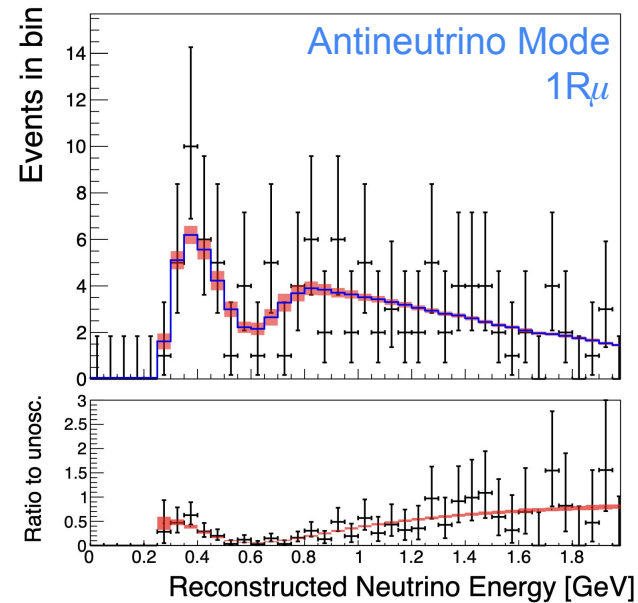
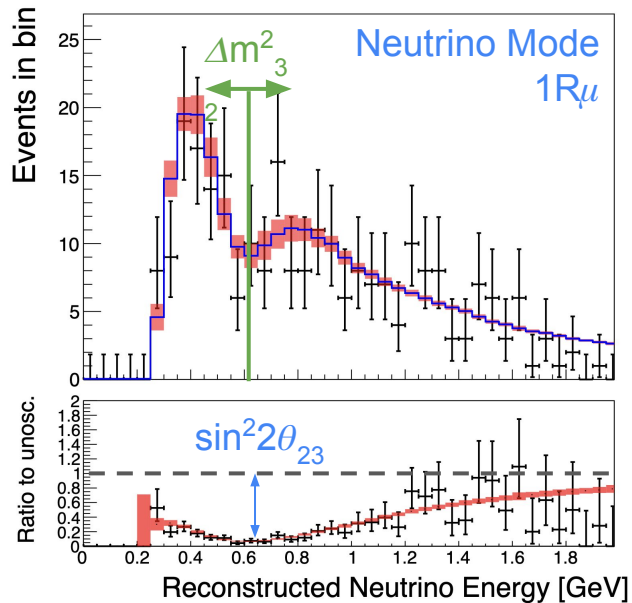
- Horn configuration
- Number of Cherenkov Rings
- Electron-like or Muon-like
- Presence of decay-electrons
→ Indicates pion production



Muon Neutrino Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \underbrace{\left[\cos^4(\theta_{13}) \sin^2(2\theta_{23}) \right]}_{\text{Leading term}} - \underbrace{\left[\sin^2(2\theta_{13}) \sin^2(\theta_{23}) \right]}_{\text{Secondary term}} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

Main sensitivity to atmospheric parameters is provided by the muon-like samples:



Muon Neutrino Disappearance



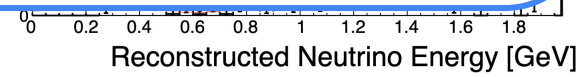
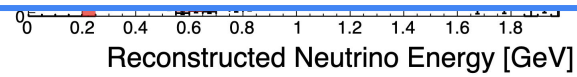
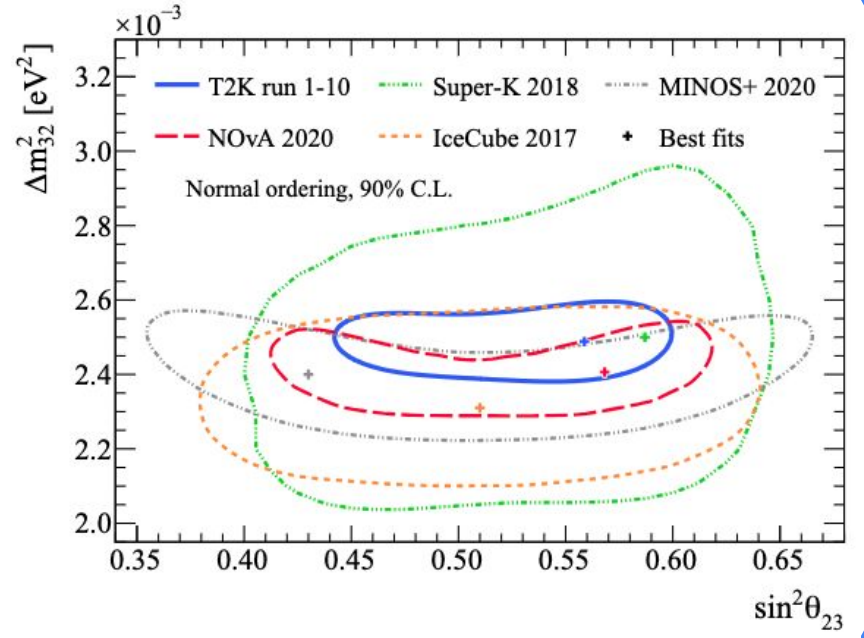
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4c_{12}^2 c_{13}^2 s_{23}^2 \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right) - 8c_{12}^2 c_{13} s_{23}^2 s_{12}^2 \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E} \right) \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right) - 4c_{12}^2 s_{12}^2 s_{23}^2 \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E} \right) \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right) - 4c_{12}^2 c_{13}^2 s_{23}^2 s_{12}^2 \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E} \right) \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

Main se

World leading constraints:

Compatible with maximal mixing:

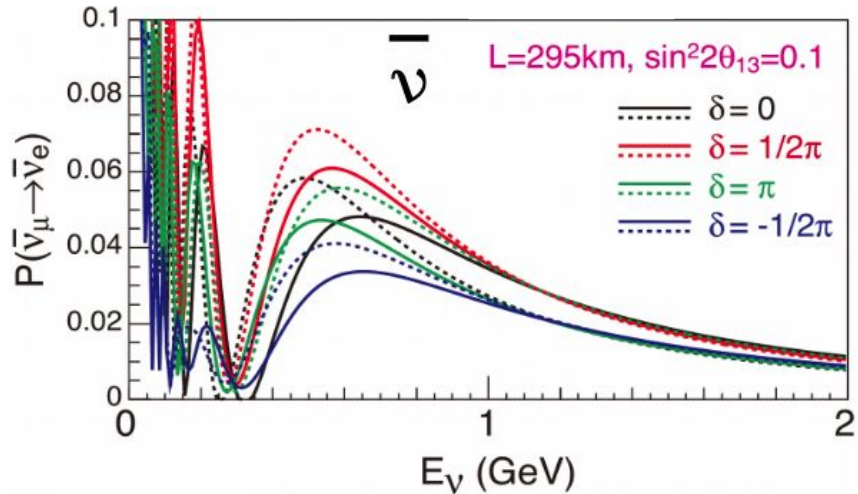
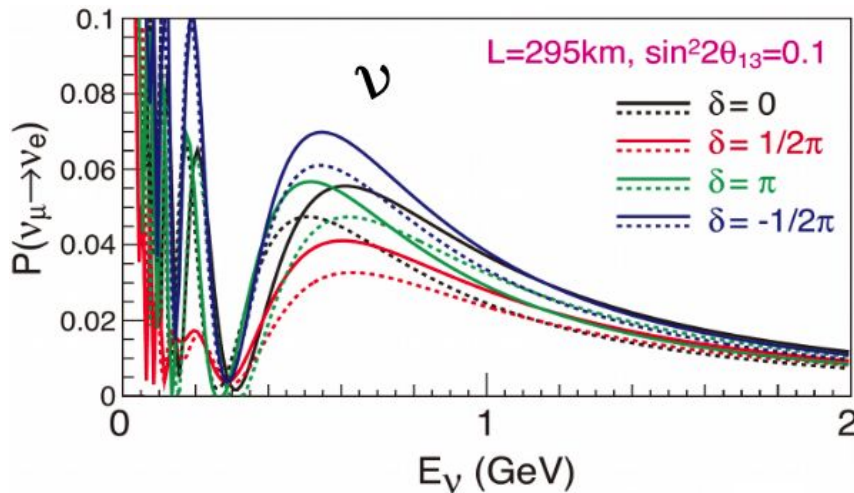
$$0.49 < \sin^2 \theta_{23} < 0.58$$



Electron Neutrino Appearance

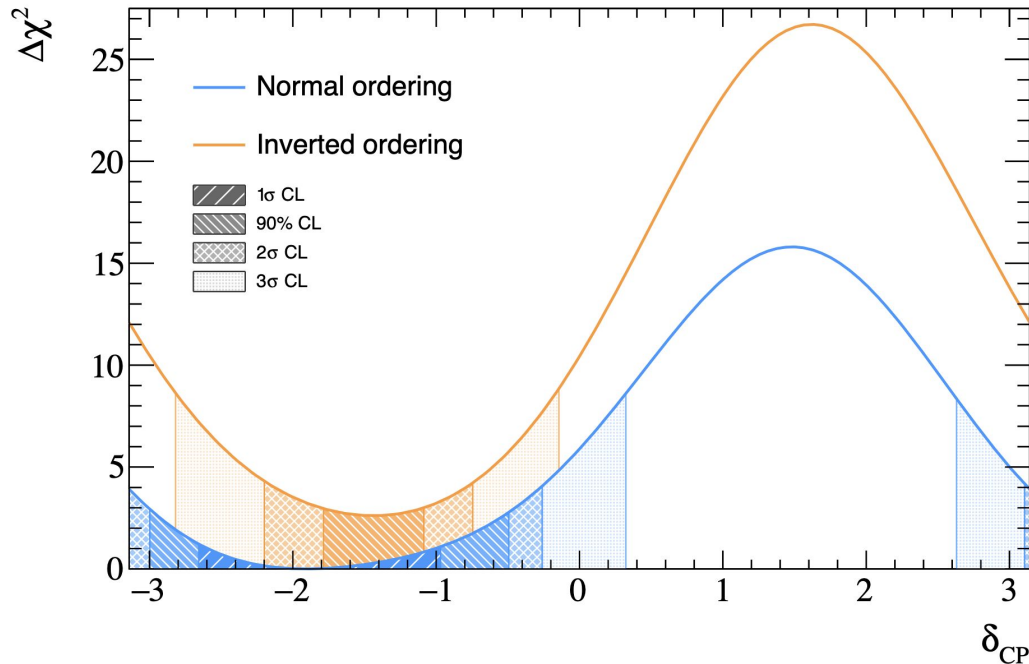
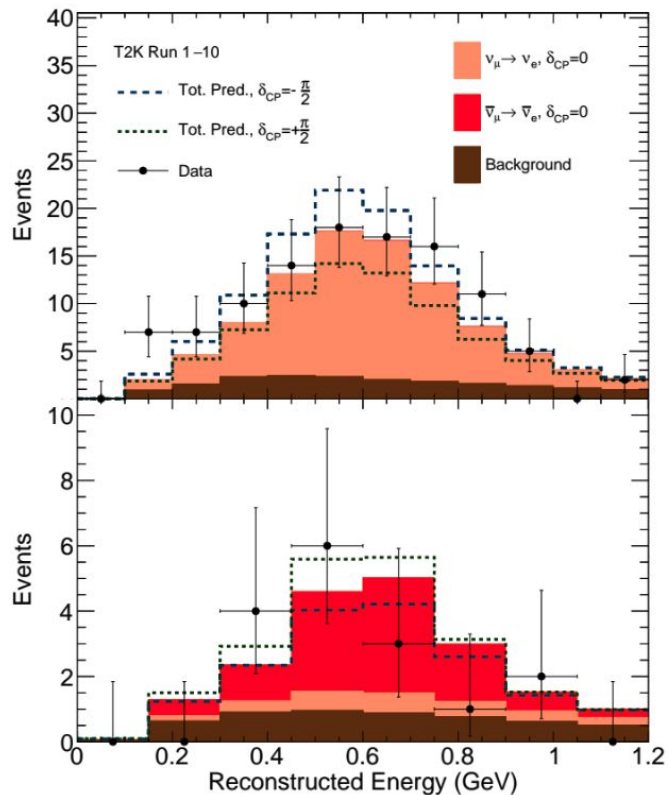
$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & \boxed{4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}} \rightarrow \text{Leading term: } \theta_{13} \text{ dependence} \\
 & + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta - s_{12} s_{13} s_{23}) \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\
 & \pm 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} + \dots
 \end{aligned}$$

CP violation effect: \rightarrow Opposite effect for neutrinos and antineutrinos:



Mass ordering: Same effect as δ_{CP} \rightarrow Smaller due to “low” matter density of beam

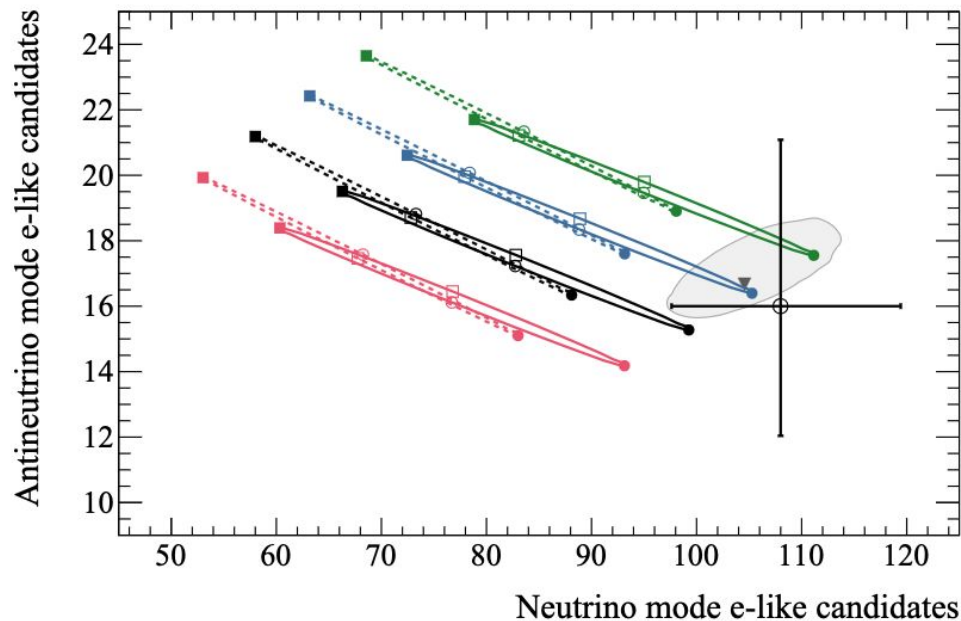
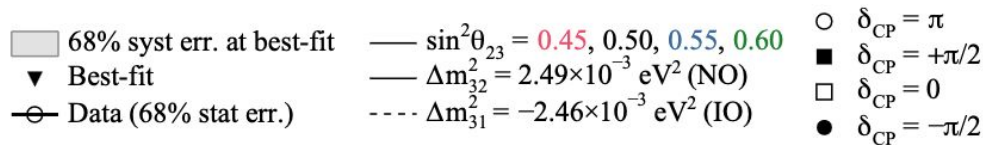
Electron Neutrino Appearance



CP conservation excluded at 90% confidence level:

- Normal ordering very mildly preferred

Joint Fit with Atmospheric Neutrinos?



Looking towards next generation experiment:

- How can we maximise the sensitivity?

Effect of varying δ_{CP} and mass hierarchy are very degenerate:

- Atmospheric neutrinos experience more “matter” as they travel to the detector

→ Joint analysis breaks the degeneracy:

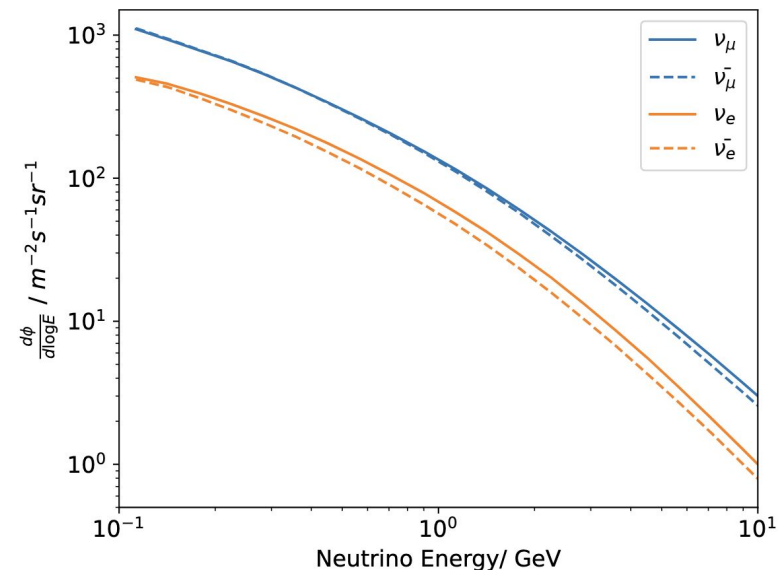
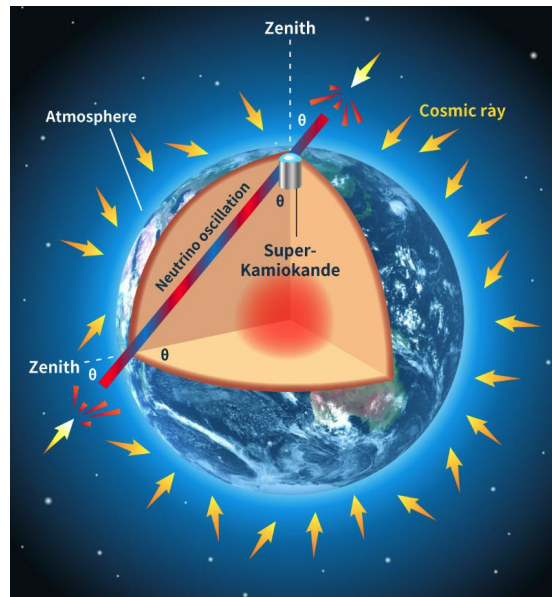
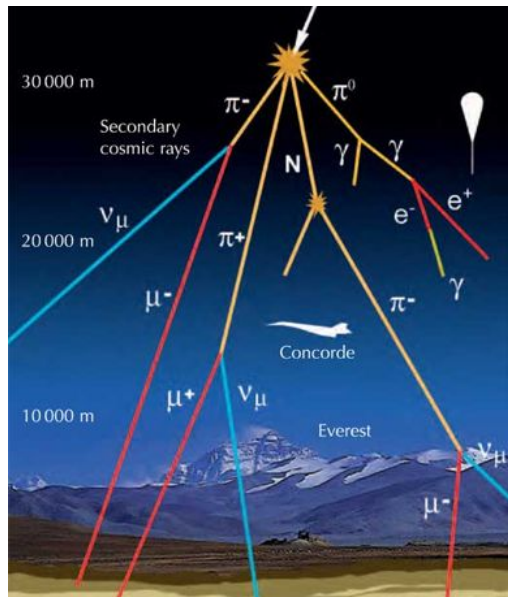
- Leads the way for joint analyses in HK



Atmospheric Neutrinos at SK

Understanding how they contribute to oscillation measurements

Atmospheric Neutrinos at SK



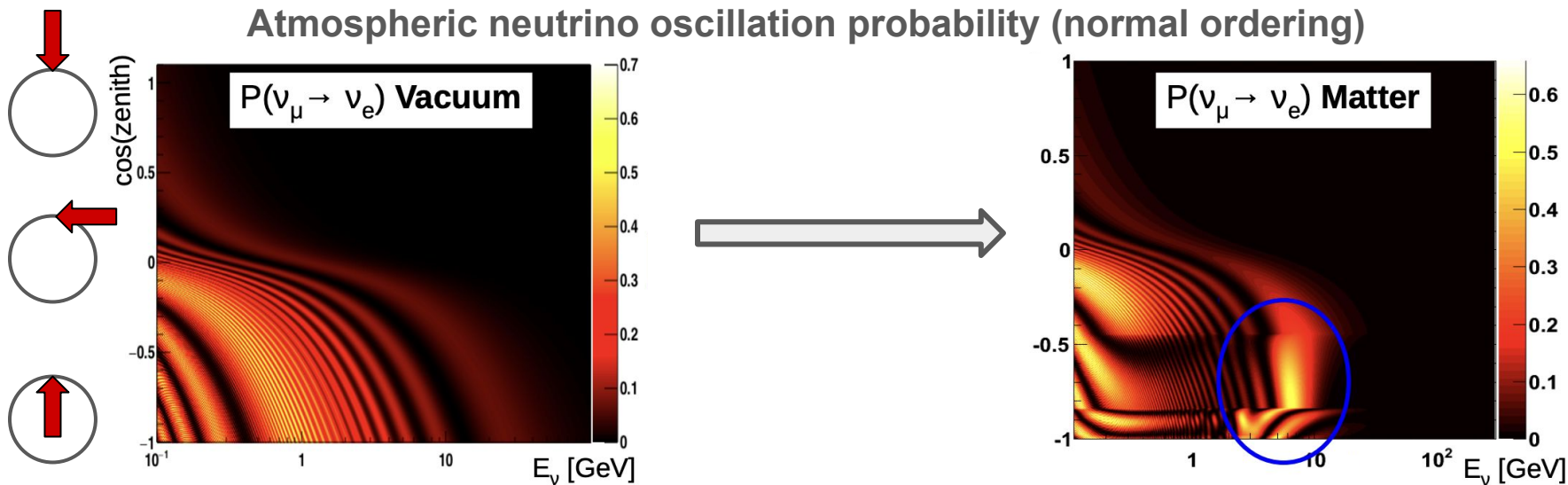
Neutrinos generated from interactions of high energy cosmic rays in the upper atmosphere:

- Distance they travel before hitting the detector depends on incoming direction $\rightarrow \theta_Z$
- Broad-band flux distribution: 10 MeV \rightarrow 10 TeV

Atmospheric Neutrino Oscillation Signature

Atmospheric neutrinos sensitive to mass ordering due to resonant-induced matter effects:

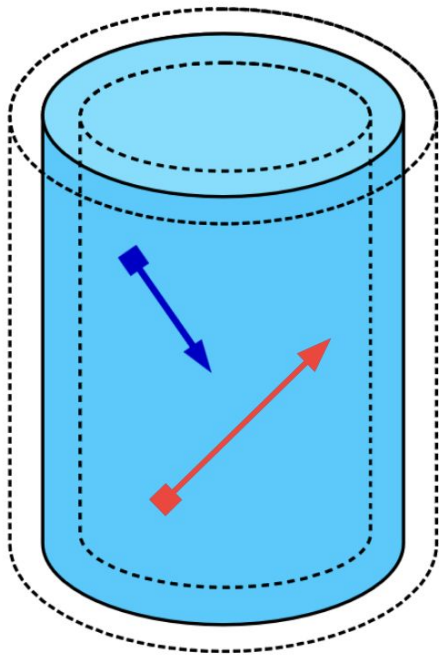
- Enhancement of ν in NO; enhancement of $\bar{\nu}$ in IO
- Amplitude of effect depends on $\sin^2\theta_{23} \rightarrow$ sensitive to θ_{23} octant
- Effect not degenerate with δ_{CP}



Understanding SK Samples

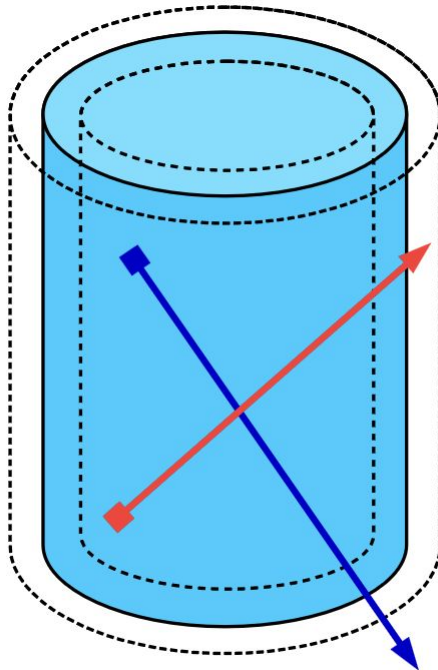
Fully contained:

1. Vertex in FV
2. End-point in ID



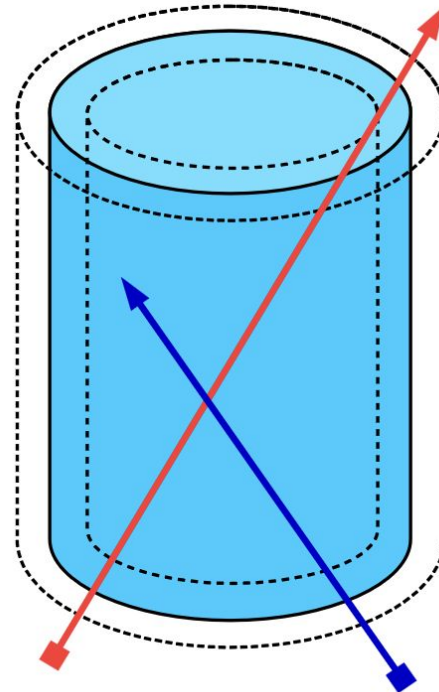
Partially contained:

1. Vertex in FV
2. End-point in OD



Upward Going:

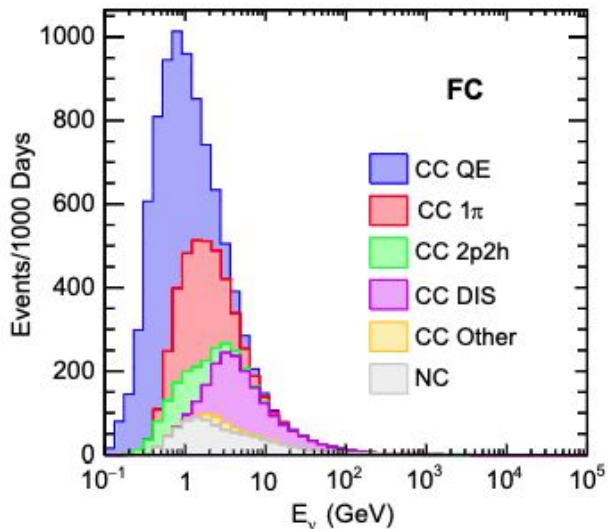
1. Vertex out of detector
2. $\cos(\theta_z) < 0$



Understanding SK Samples

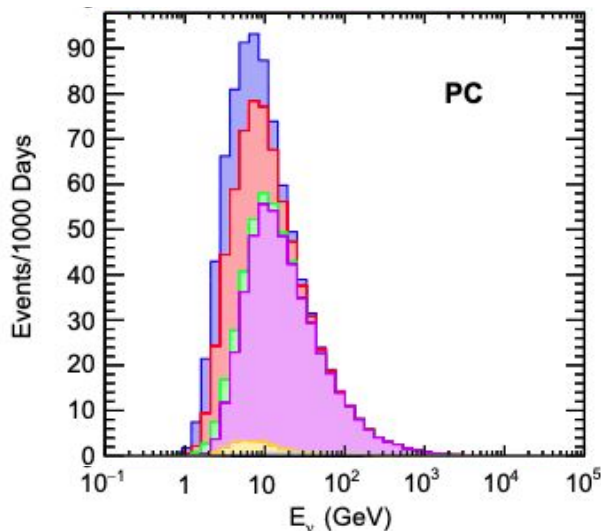
Fully contained:

1. Vertex in FV
2. End-point in ID



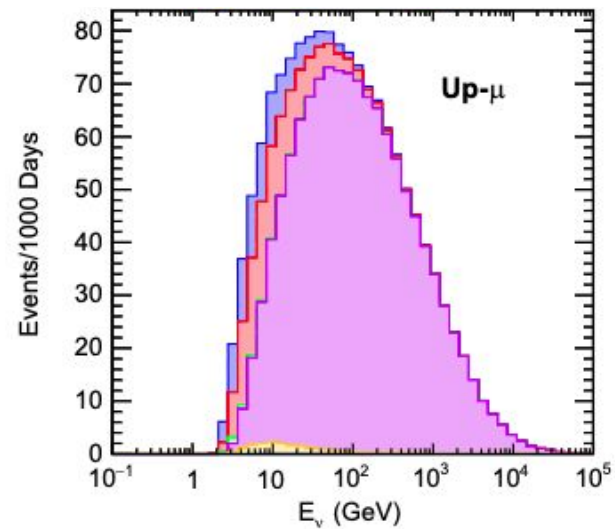
Partially contained:

1. Vertex in FV
2. End-point in OD



Upward Going:

1. Vertex out of detector
2. $\cos(\theta_z) < 0$

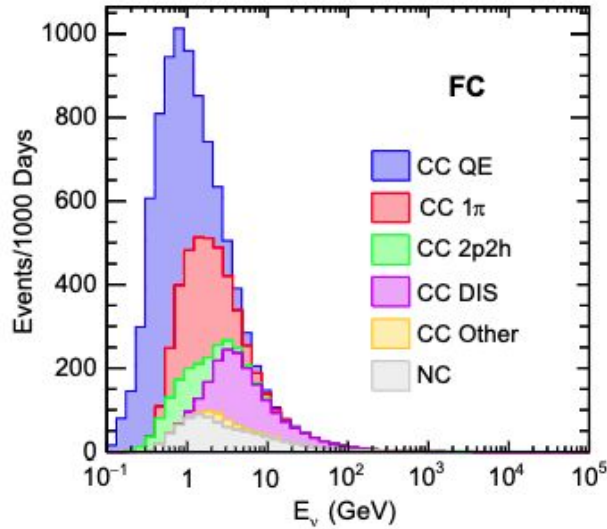


Neutrino Energy

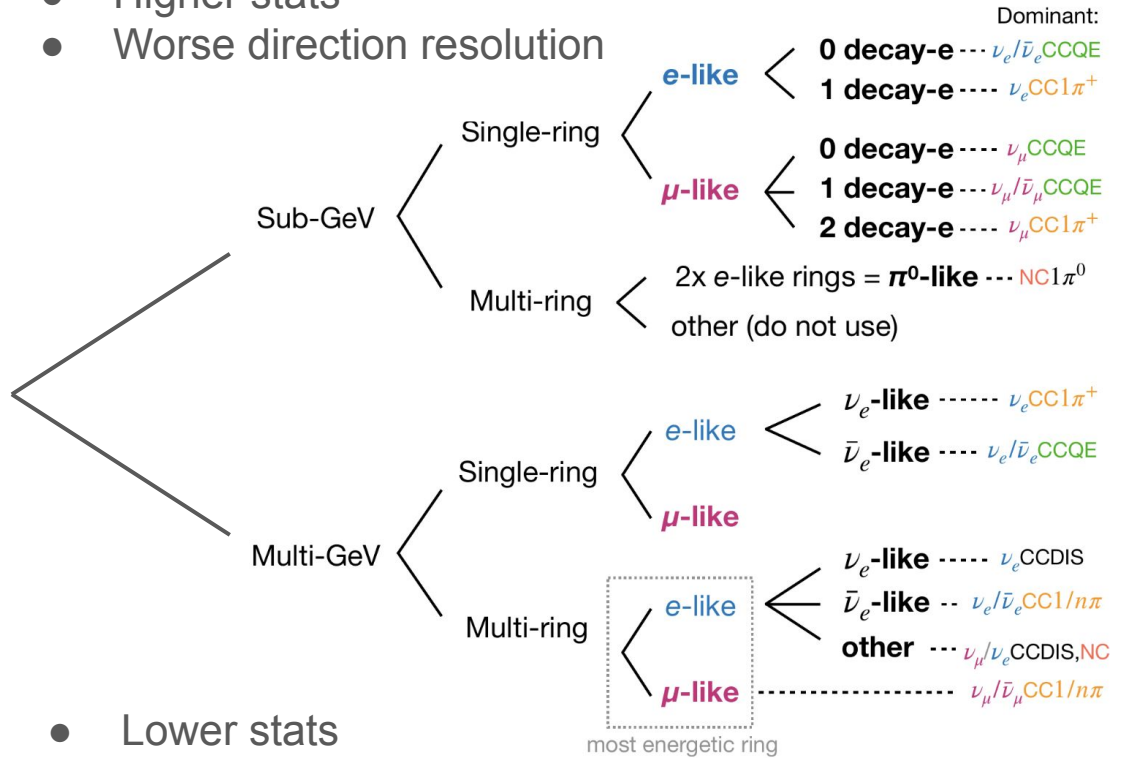
Fully Contained Event Selection

Fully contained:

1. Vertex in FV
2. End-point in ID

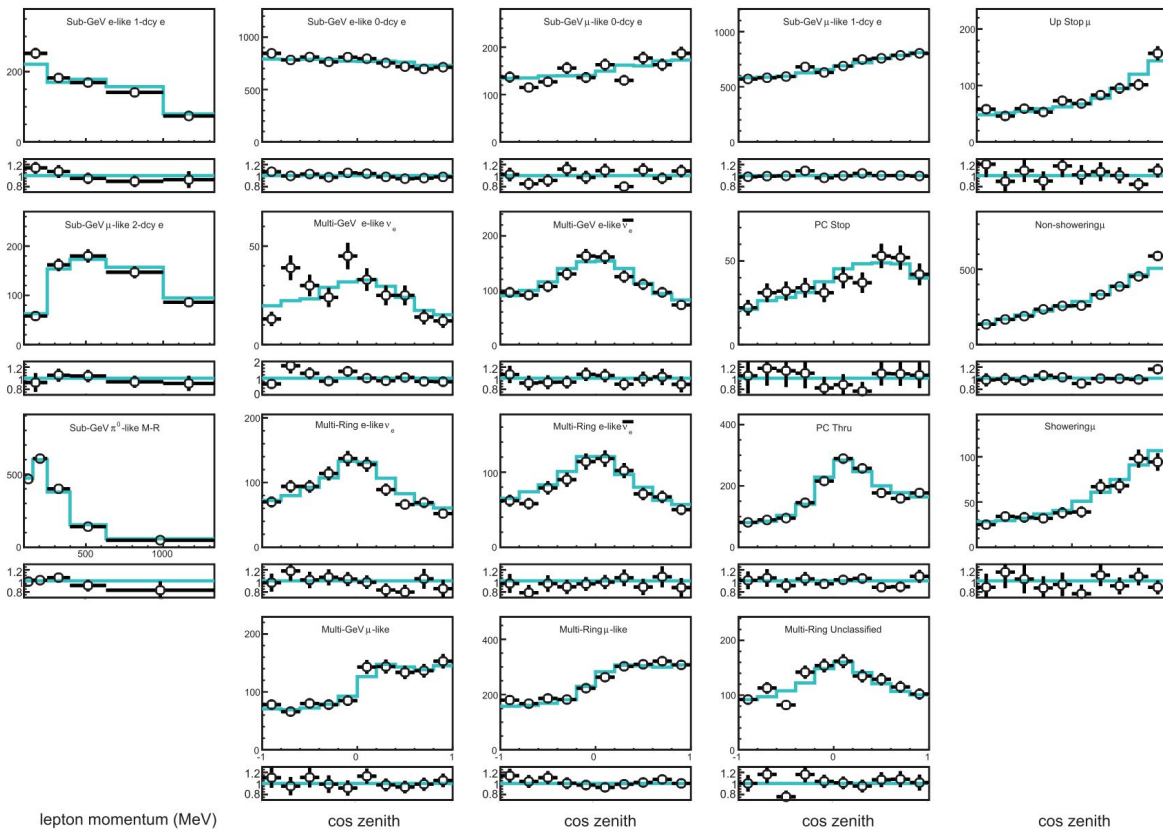


- Higher stats
- Worse direction resolution



- Lower stats
- Better direction resolution

SK Event Selection

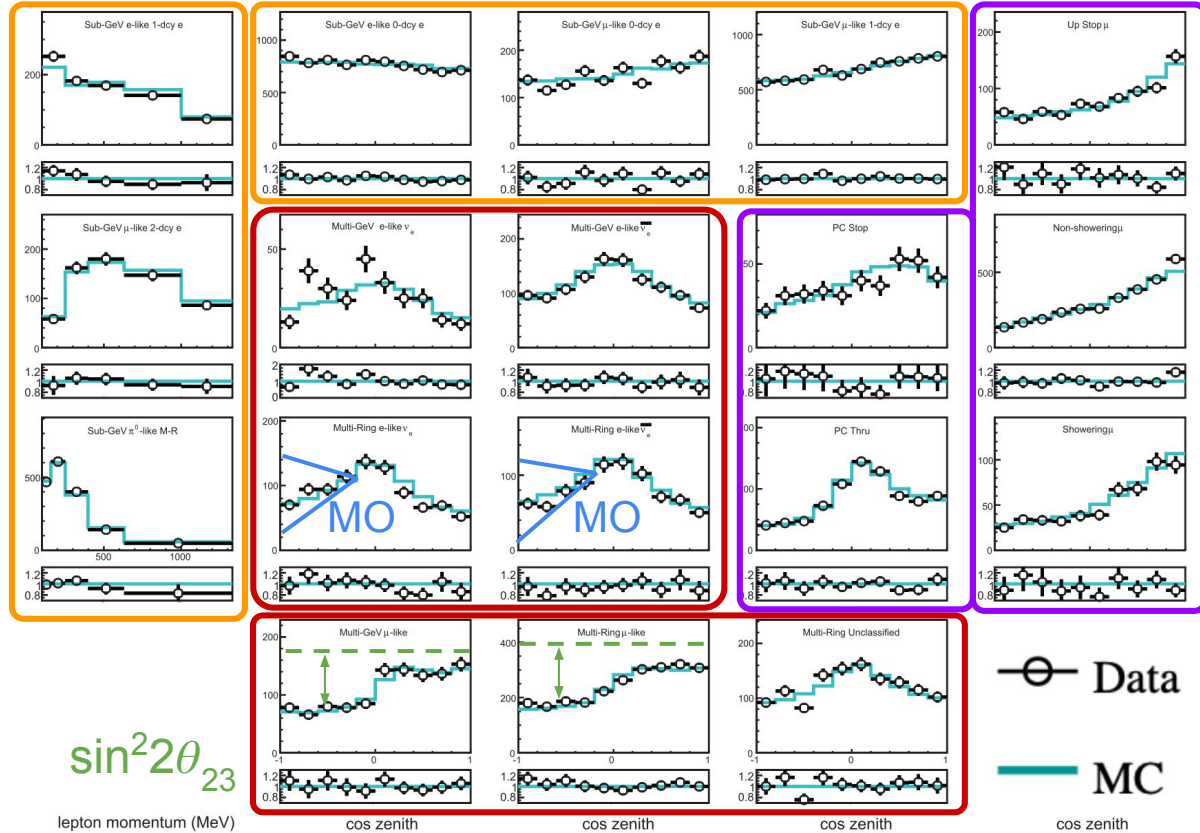


SK Event Selection

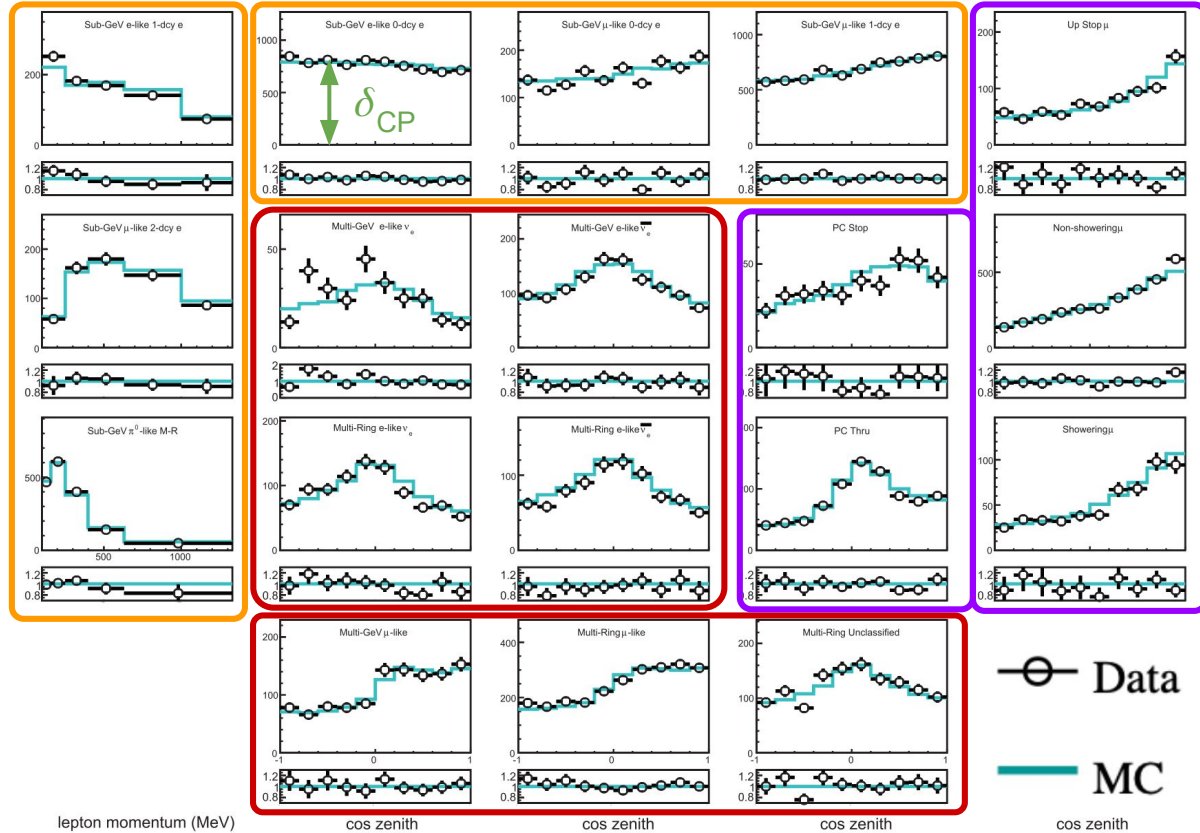


Multi-GeV samples:

- Sensitive to mass ordering and $\sin^2\theta_{23}$



SK Event Selection



Multi-GeV samples:

- Sensitive to mass ordering and $\sin^2\theta_{23}$

Sub-GeV samples:

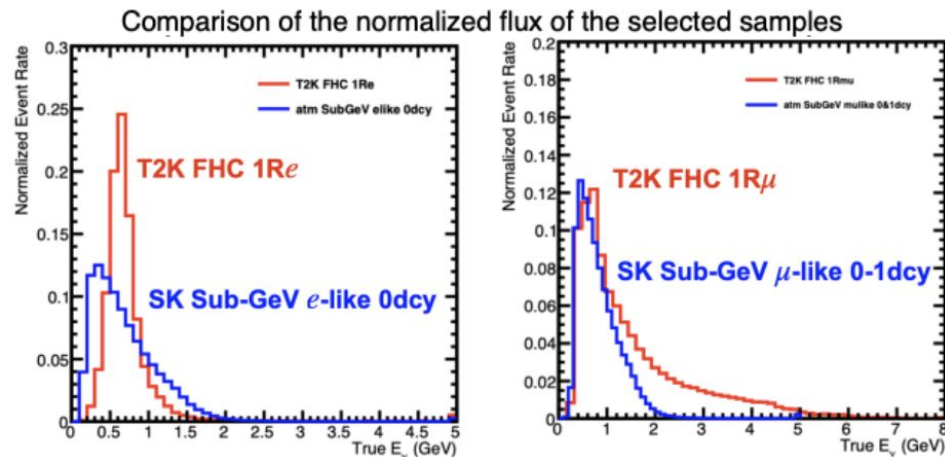
- Electron CCQE-like sample normalisation sensitive to δ_{CP}

Reminder of Motivation for 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 \rightarrow 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



Preparing the Joint Analysis

Understanding the samples and systematics

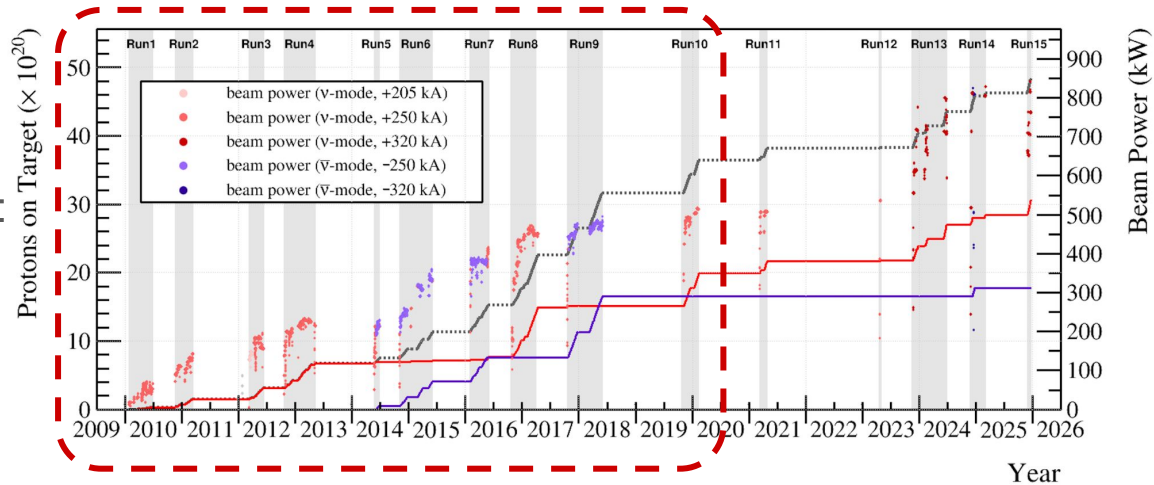
Datasets used

Utilising beam data from 2010-2019
(run 1-10)

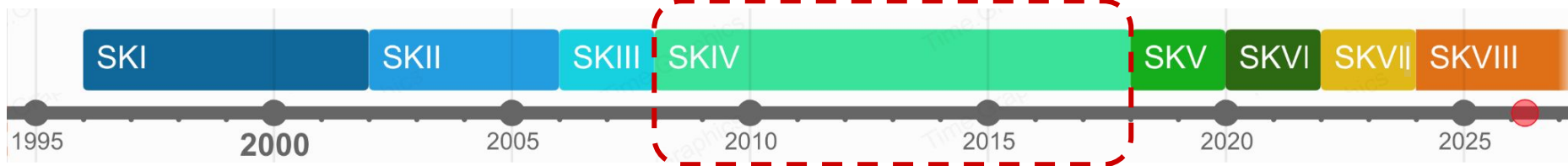
Measured in protons on target (POT):

- Neutrino mode: 19.7×10^{21}
- Antineutrino mode: 16.3×10^{21}

Using atmospheric data from same
time period



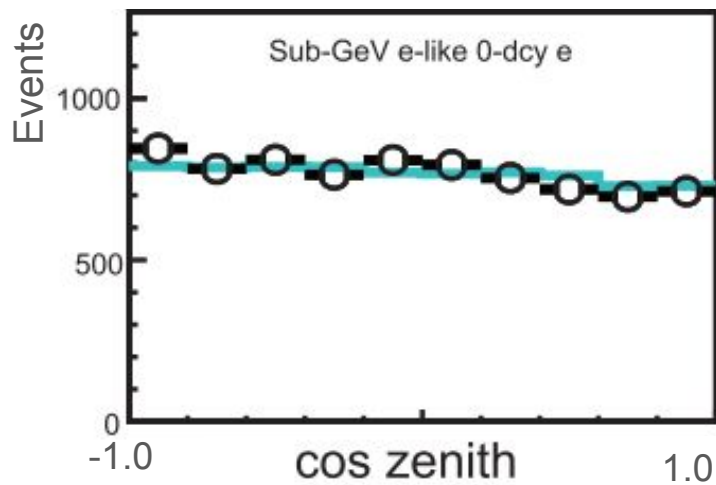
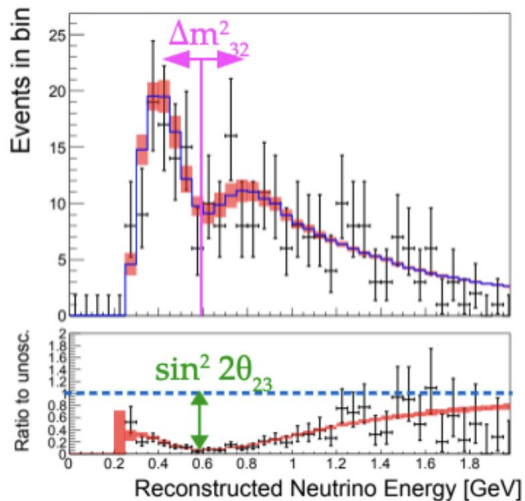
→ Atmospheric data taken from SKIV period: 3244.4 days of operation:



Systematic Uncertainties

Goal: Measure oscillation parameters → What do we actually measure in the detector:

$$\text{Number of events} = \text{Flux of neutrinos} \times \text{Probability of } \nu \text{ interacting} \times \text{Efficiency of detecting } \nu \times \text{Oscillation probability}$$



→ Need uncertainties associate with each term:
→ Correlated uncertainties?

Neutrino Flux Uncertainties

$$\text{Number of events} = \boxed{\text{Flux of neutrinos}} \times \text{Probability of } \nu \text{ interacting} \times \text{Efficiency of detecting } \nu \times \text{Oscillation probability}$$

T2K and Atmospheric flux overlap in $<1\text{GeV}$ region:

- Generated by same hadronic processes?

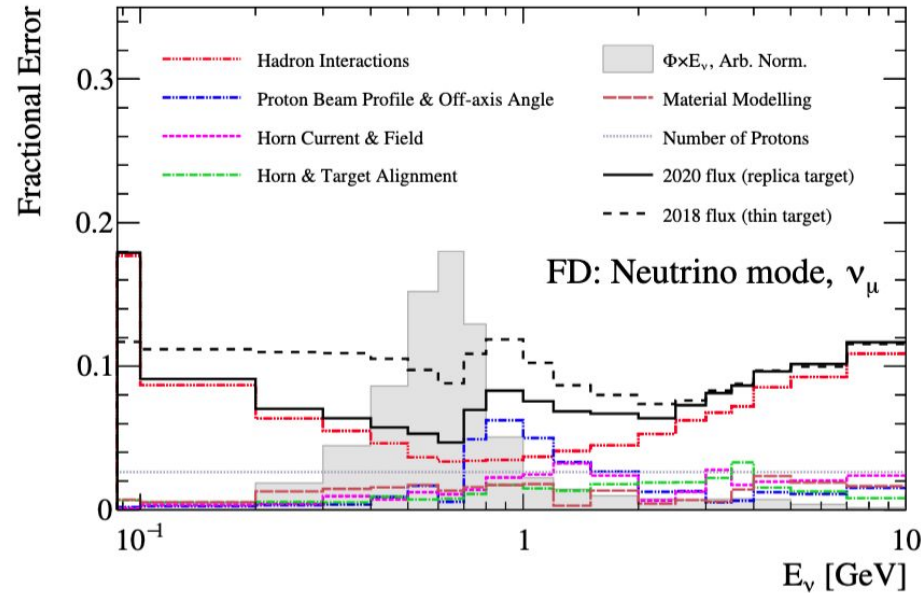
Beam neutrinos generated from interactions of pions in graphite target

→ Simulation tuned on NA61 hadron production (HP) data using a replica target

Atmosphere comprises of Nitrogen and Oxygen

→ Simulation tuned on different set of HP data

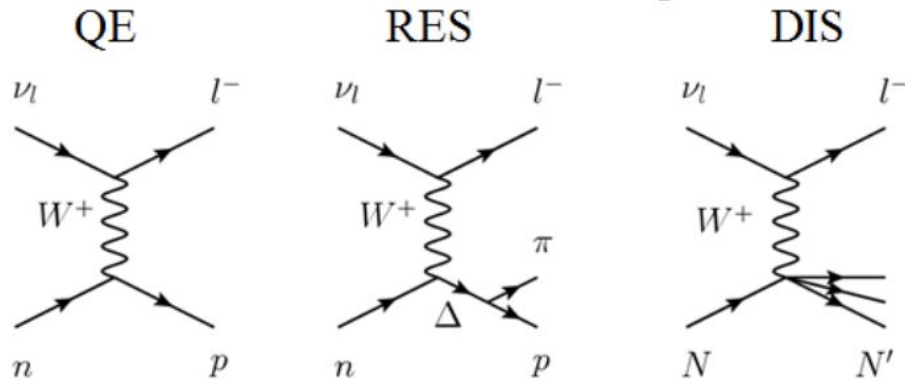
Flux uncertainties are not correlated in this first analysis → Future development



Neutrino Interaction Uncertainties

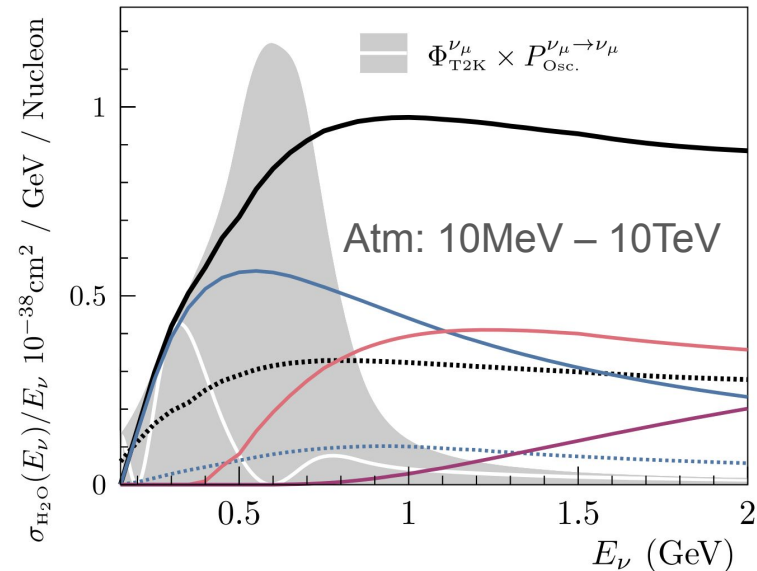
$$\text{Number of events} = \text{Flux of neutrinos} \times \boxed{\text{Probability of } \nu \text{ interacting}} \times \text{Efficiency of detecting } \nu \times \text{Oscillation probability}$$

Neutrino interaction with the nuclei depends on energy:



Ideally: correlated cross-section of all interaction types between beam and atmospheric samples

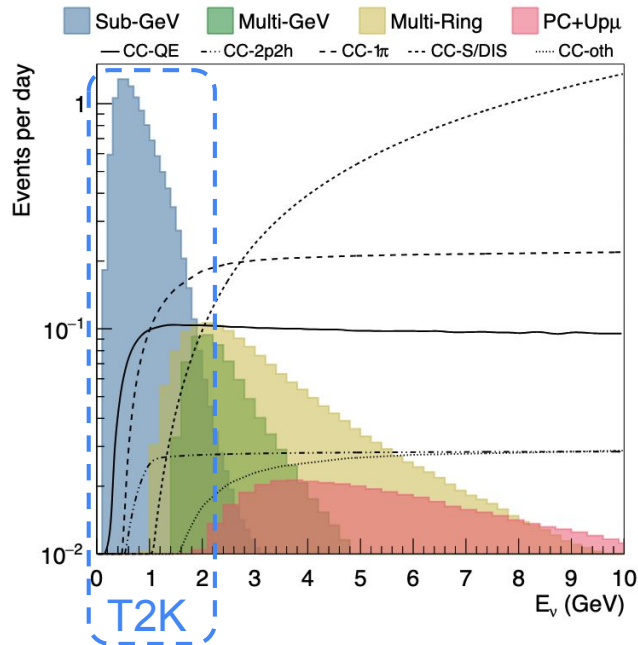
- CC Inclusive
- CC Quasi-elastic
- CC Resonant 1π
- ⋯ NC Inclusive
- ⋯ CC 2p2h
- CC Multi- π + DIS



Neutrino Interaction Uncertainties

$$\text{Number of events} = \text{Flux of neutrinos} \times \text{Probability of } \nu \text{ interacting} \times \text{Efficiency of detecting } \nu \times \text{Oscillation probability}$$

Reality: T2K cross-section model is built to be robust in the $< 1\text{-}2$ GeV region



Each experiment's interaction uncertainty model focus on what affects their analysis:

- SK high-energy samples include a lot of resonant and DIS events → Not important for T2K
- Direction known for beam → Not for atmospheric

Neutrino Interaction Uncertainties

$$\text{Number of events} = \text{Flux of neutrinos} \times \text{Probability of interacting} \times \text{Efficiency of detecting} \times \text{Oscillation probability}$$

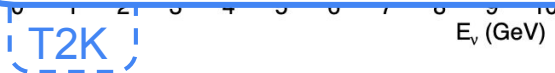
Solution:

Correlated uncertainties for T2K and Sub-GeV:

- Constrained by data from the near detector

Use SK high-energy model for multi-GeV samples

	“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 + extra ν_e/ν_μ xsec diff. error	high-Q ² params w/o ND
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 NC1 π^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	



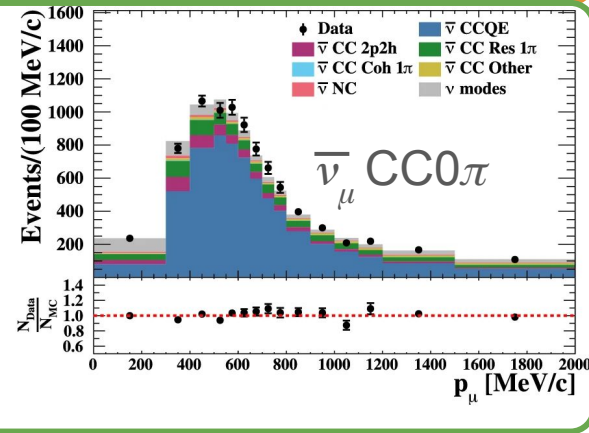
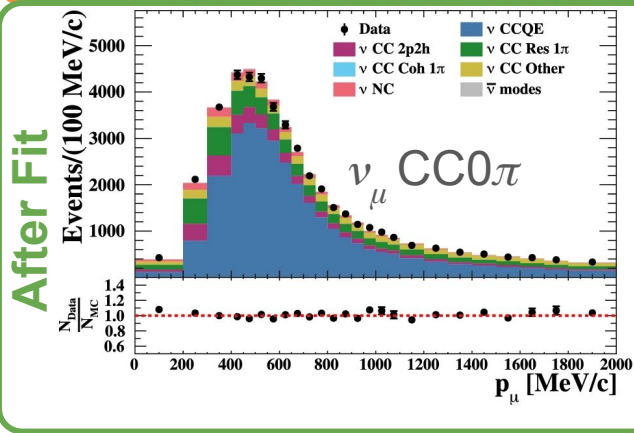
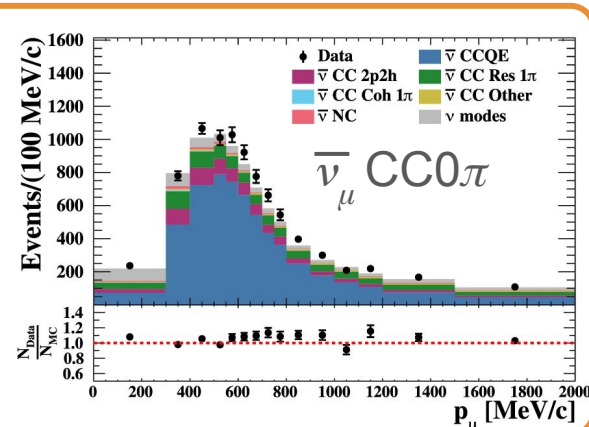
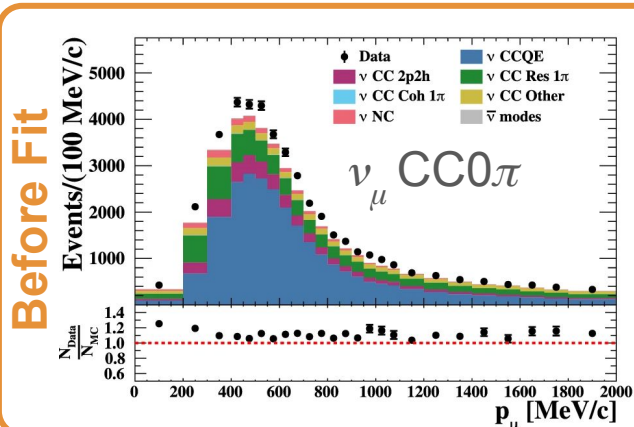
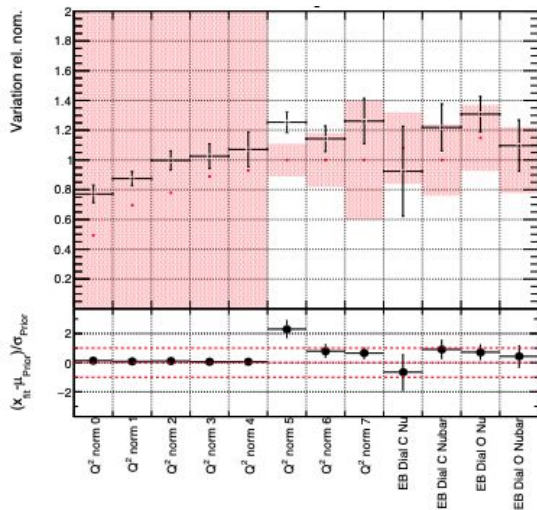
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Near Detector Constraints

18 Samples based on:

- Horn current
- Target (CH/H₂O)
- Number of π and protons

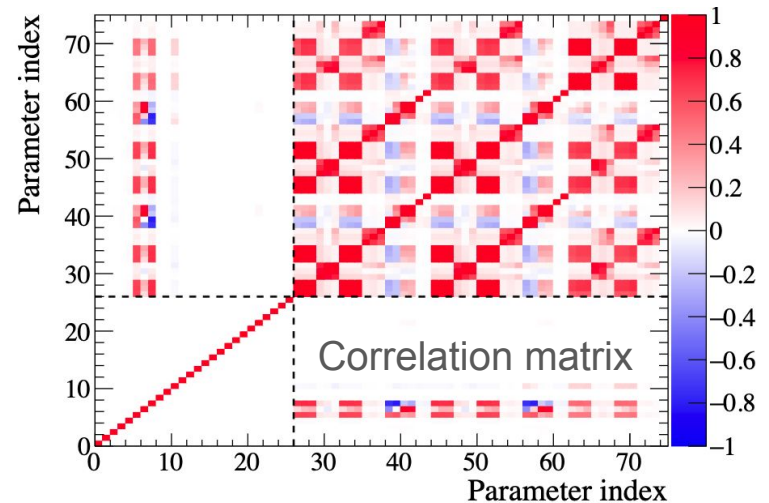
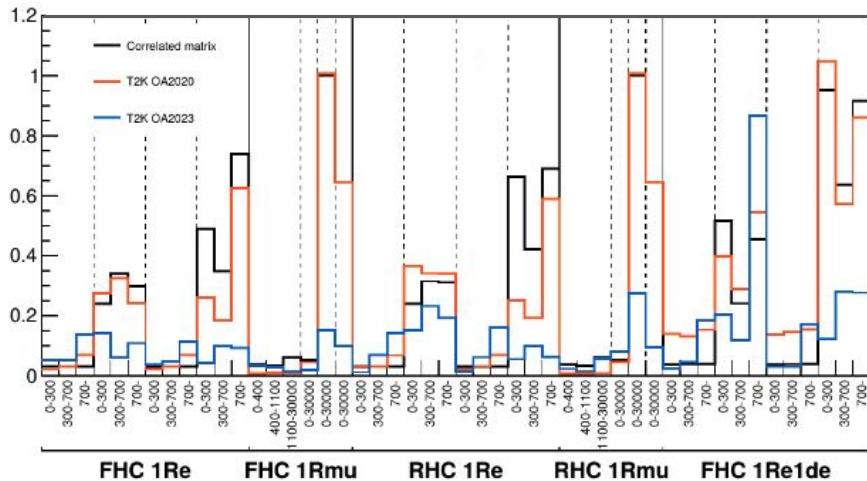
Tune flux and cross-section:



Detector Uncertainties

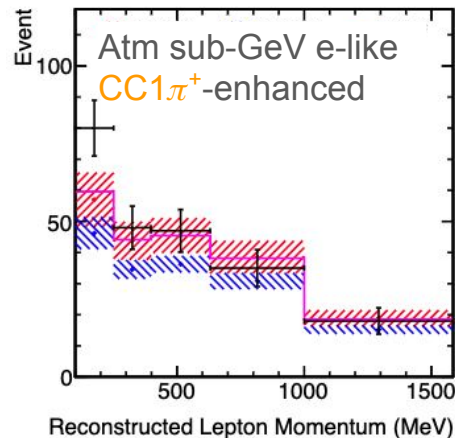
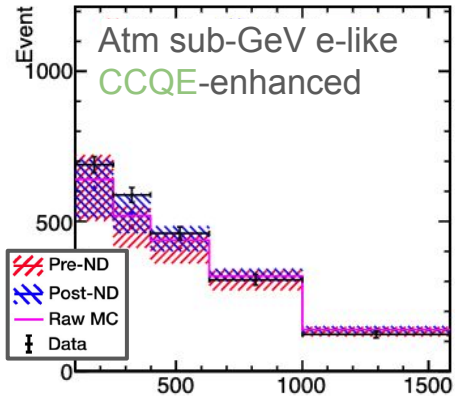
$$\text{Number of events} = \text{Flux of neutrinos} \times \text{Probability of } \nu \text{ interacting} \times \text{Efficiency of detecting } \nu \times \text{Oscillation probability}$$

Individual analysis: Uncertainty model for beam and atmospheric analyses are different
 → Utilise the atmospheric analysis uncertainty model and propagates to beam samples
 → Validated approach gives similar behaviour as usual T2K errors



Correlations introduced → Particularly FV, ring counting, 1R particle-identification

Exploring Atmospheric Control Samples



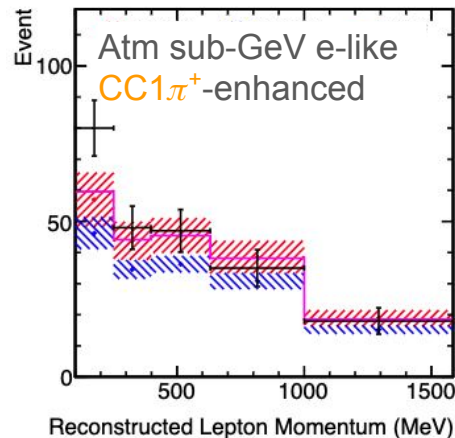
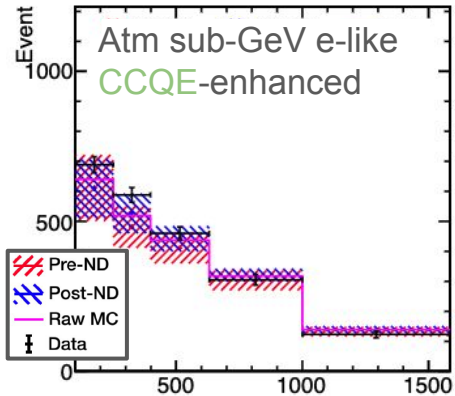
Test the unified uncertainty model on down-going (non-oscillated) atmospheric data:

- No disagreement seen in CCQE samples
- Data excess observed in CC1 π^+ samples
→ Increased when the near-detector constraints are applied

Several additional uncertainties were included to address the excess:

- Decay-electron counting: excess potentially due to mis-id of neutron-capture
- Cross-section: Excess in production of low-momentum pions
- 1R PID: Mis-id of low energy muons as electrons

Exploring Atmospheric Control Samples

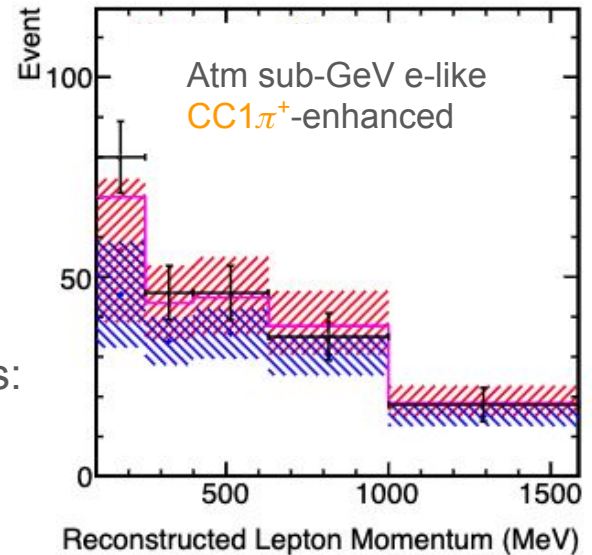


Test the unified uncertainty model on down-going (non-oscillated) atmospheric data:

Data/MC comparison after the additional systematics now in better agreement:

Also performed many fake data tests which mimic the data excess:

- No significant bias in results





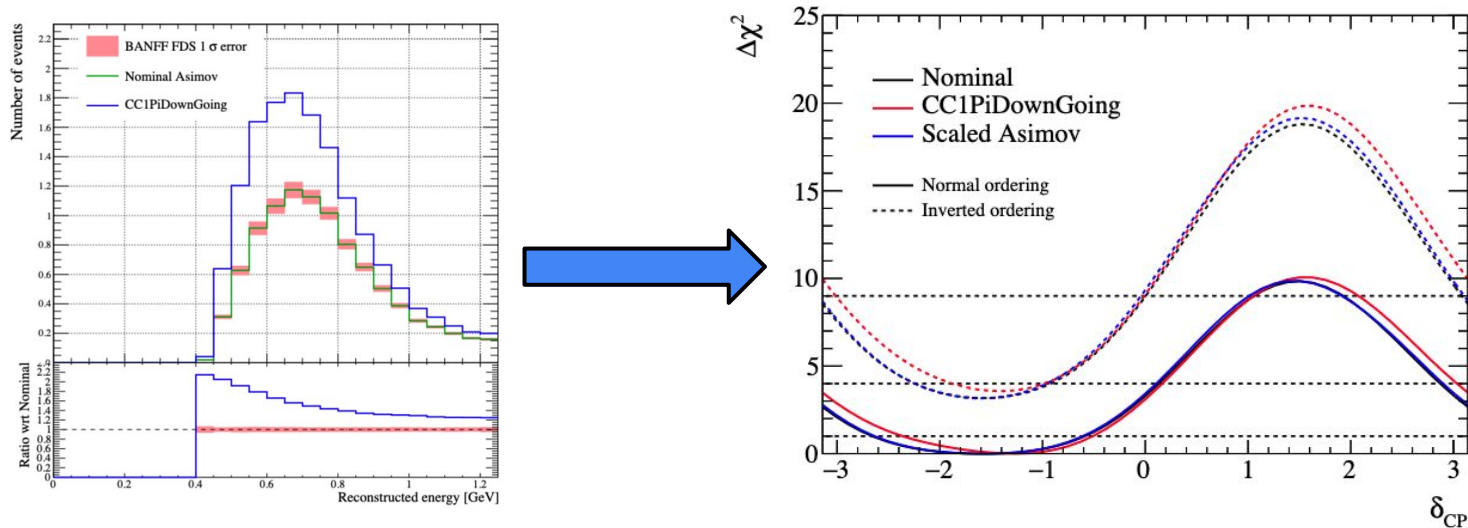
Analysis Results

Results of both Frequentist and Bayesian analyses

“Fake Data” Studies (FDS)

Used T2K “Fake Data Studies” procedure to test robustness of the analysis

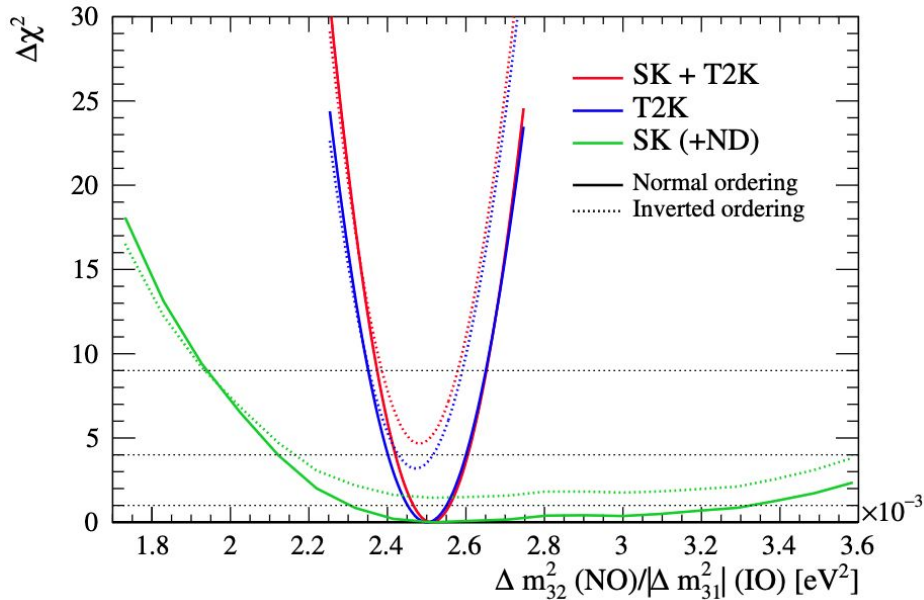
- Check how results would be biased if data was described by different model than what we use in our fits



Perform 14 fake data studies for effects on cross-section and detector effects:

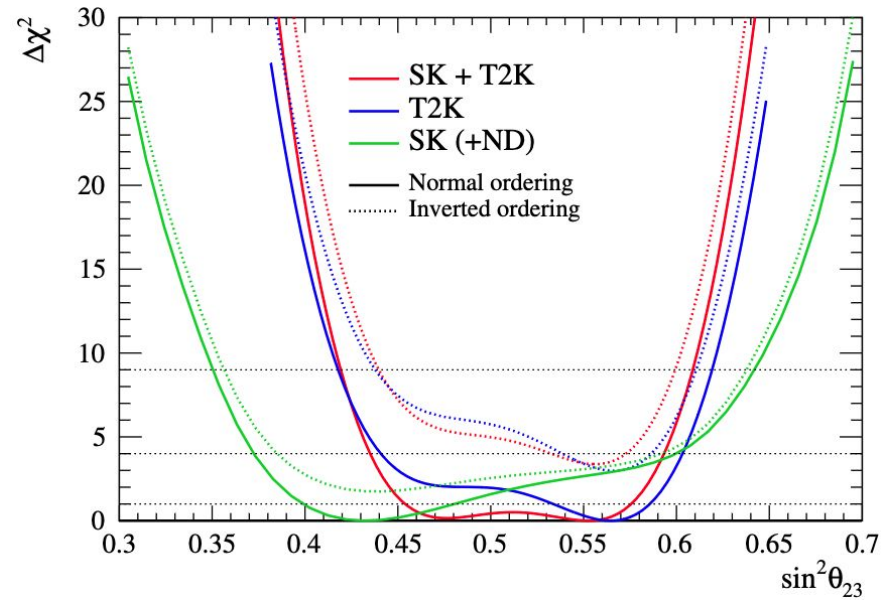
- “Smear” data contours by value calculated from the quadrature-sum of all FDS shifts

T2K+SK Oscillation Analysis Results



Uncertainty on Δm_{32}^2 largely driven by T2K:

- Marginal increase in precision
- Bayes factor for NO = 8.98 ± 0.06
→ **p-value** for IO = **0.08**
→ Inverted ordering excluded at 90% CL

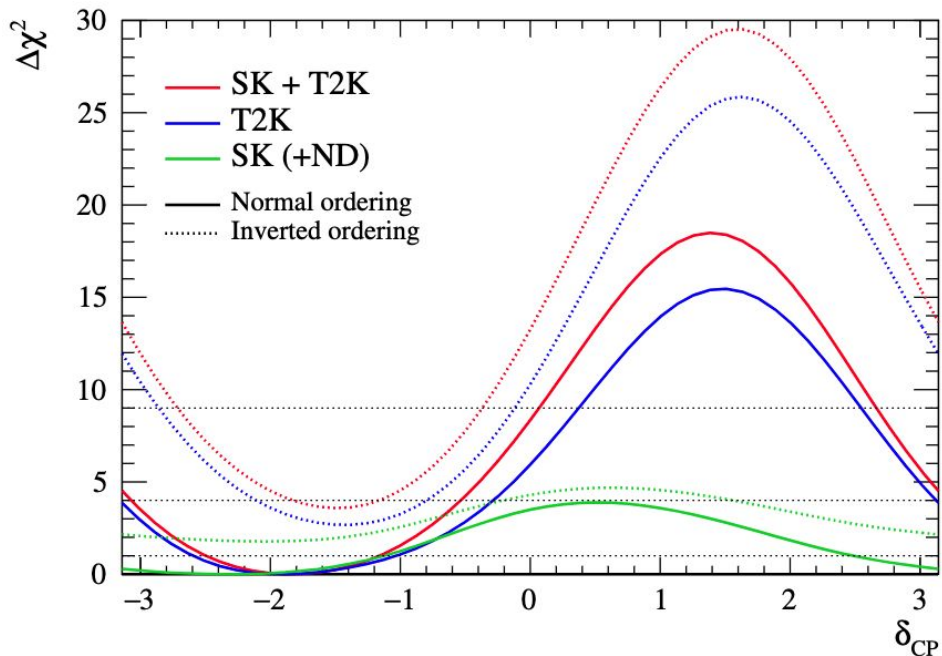


Difference in preference of octant:

- T2K prefers upper octant
- SK prefers lower octant

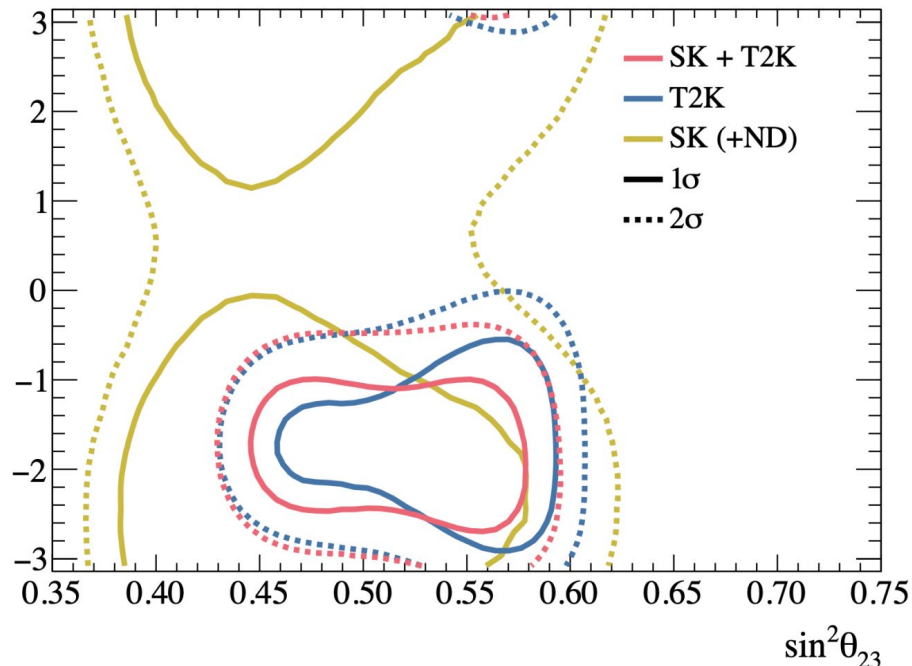
Joint analysis compatible with maximal θ_{23}

T2K+SK Oscillation Analysis Results



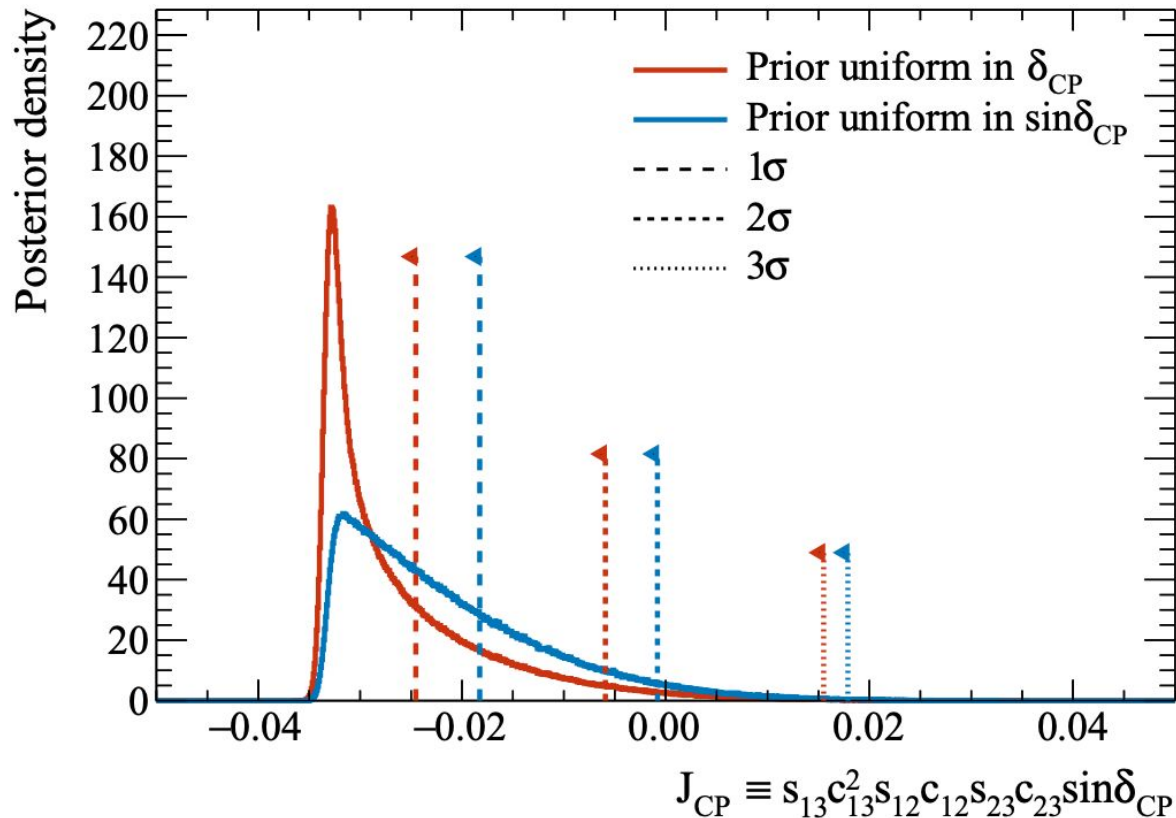
Clear enhancement using SK samples:

- Both favour $\delta_{CP} = -\pi/2$
- Especially excluding $\delta_{CP} = 0$



Width of uncertainty in δ_{CP} less sensitive to value of $\sin^2(\theta_{23})$ compared to T2K-only

T2K+SK Oscillation Analysis Results



Remembering that PMNS matrix is one parameterisation of oscillations:

- Jarlskog (J) is independent measure of CP violation

$J = 0$ corresponds to CP-conserving

Exclusion of CP-conserving values

- **2.2 σ** for flat δ_{CP} prior
- **1.9 σ** for flat $\sin \delta_{CP}$ prior



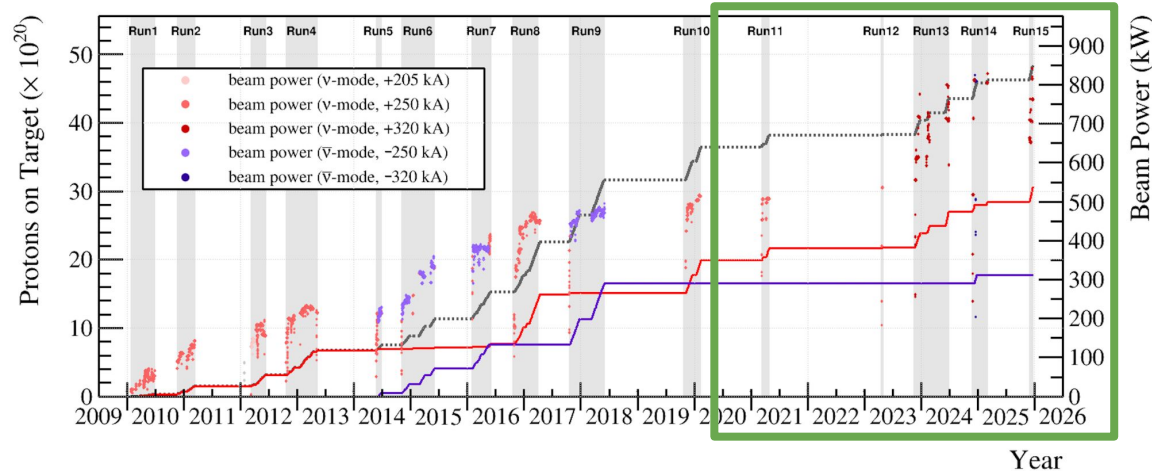
Future Prospects

Improvements towards a second analysis

More Data: Beam

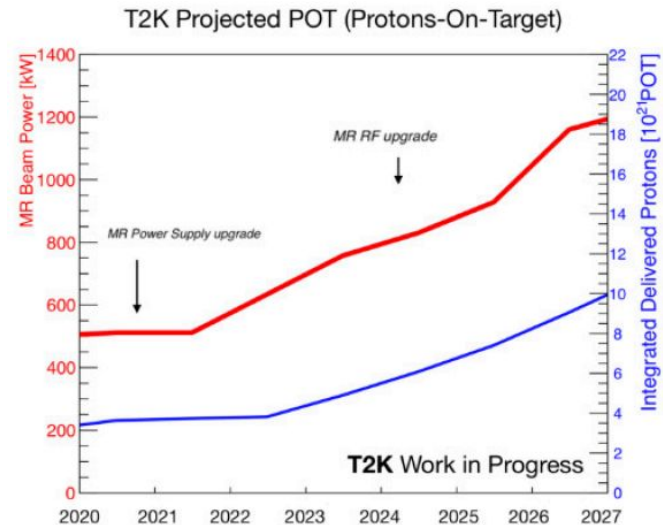
New **data** already taken - Aim 10×10^{21} POT

- Total Accumulated POT for Physics
- ν -Mode Accumulated POT for Physics
- $\bar{\nu}$ -Mode Accumulated POT for Physics
- ν -Mode Beam Power
- $\bar{\nu}$ -Mode Beam Power

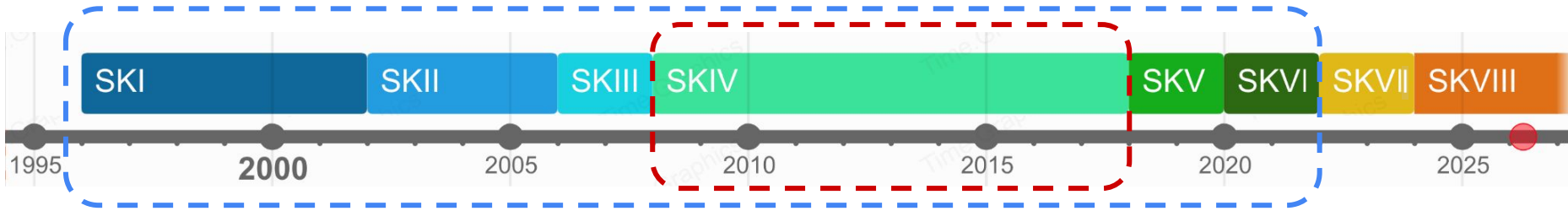


Higher beam power upgrades:

- 800 kW already achieved



More Data: Atmospheric



Target to use atleast SKI-VI

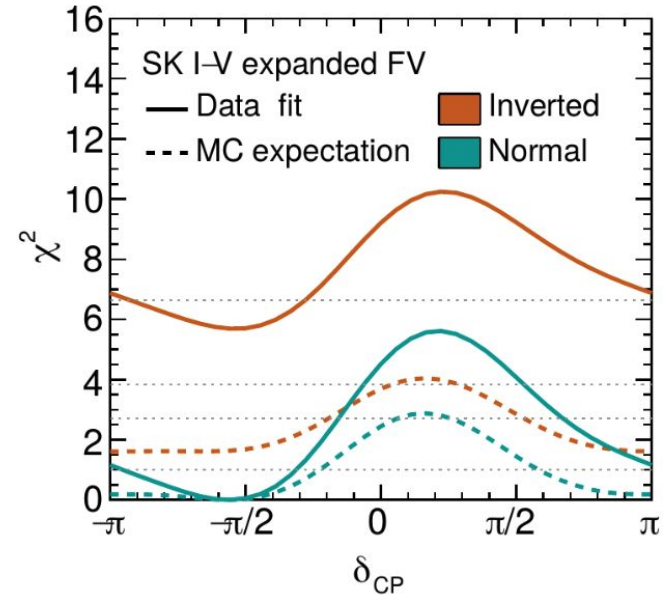
→ Increases the livetime from 3244.4 to 7075 days:

Includes SKVI:

→ Gadolinium-doping for improved neutron capture

SK collaboration performed SKI-V analysis:

- Improved rejection of inverted ordering $>2\sigma$



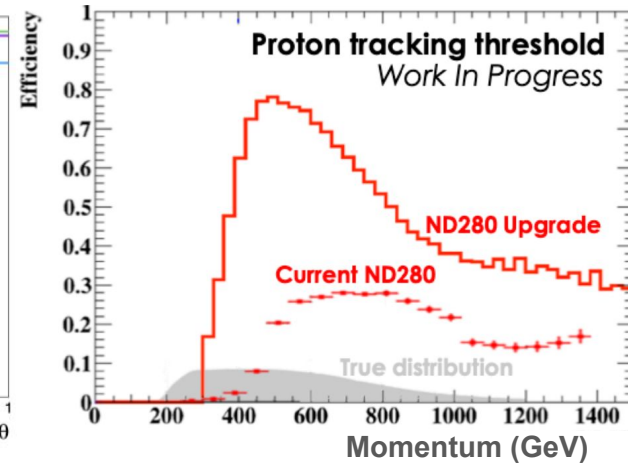
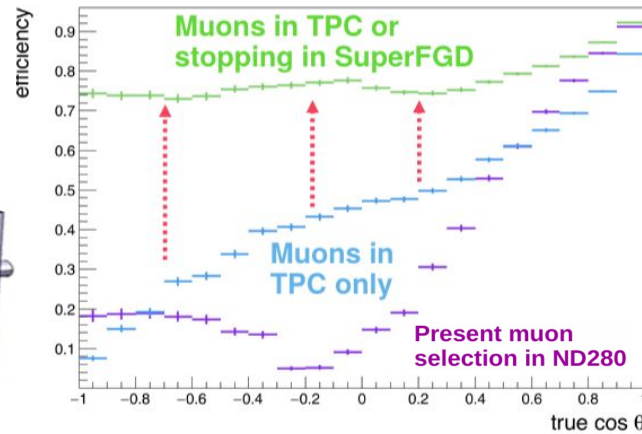
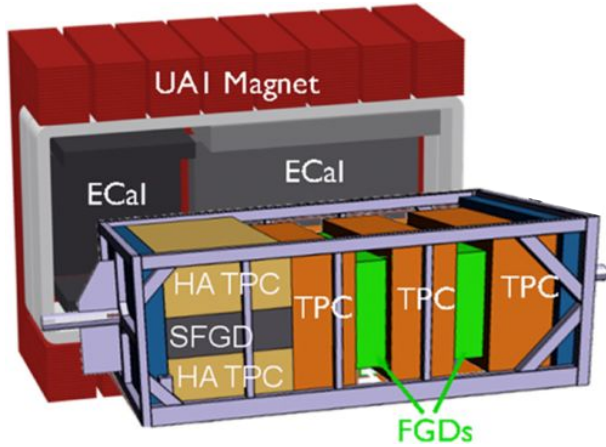
Upgrade of T2K Near Detector

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



Leads to precision constraints on flux and cross-section uncertainties

Extension to Hyper-Kamiokande

HK benefits from beam-upgrades and ~ 8 times larger fiducial volume:

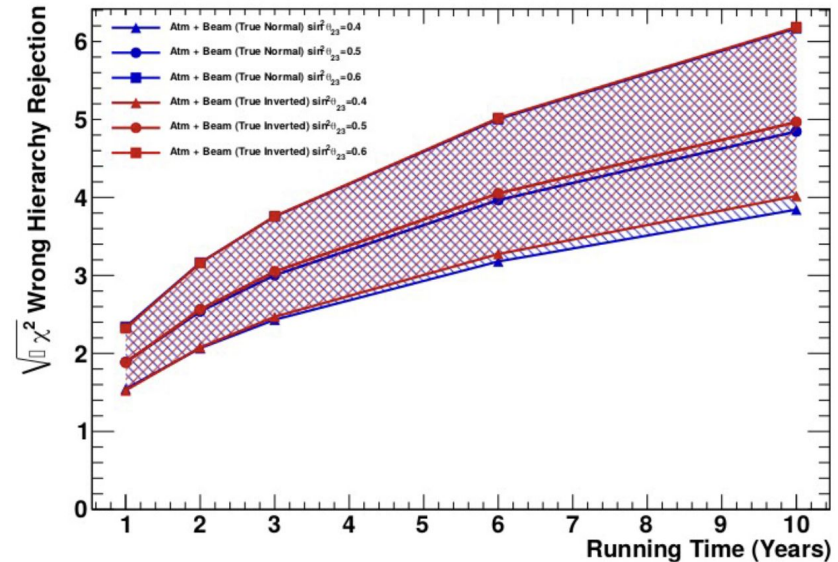
- Will collect T2K-level beam statistics in $O(\text{few})$ years
- 30 years of SK atmospheric data in 4 years

Mass hierarchy and CP-violation degeneracy still problematic:

- Same beamline, matter density, etc.

As with T2K, joint analysis of beam and atmospheric data will lift degeneracies:

- Higher statistics to improve sensitivity to the unanswered questions





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 and second-analysis already progressing:

- SKIV (3244.4 days) \rightarrow SKI to SKV (~ 7000 days)
- T2K Run 1-10 \rightarrow Run 1-11 (10% increase in ν -mode data)
- Updates to systematic uncertainty models and better understanding of data-excess

Sets the stage for joint beam and atmospheric analyses in the next-generation of neutrino experiments

Backup Slides



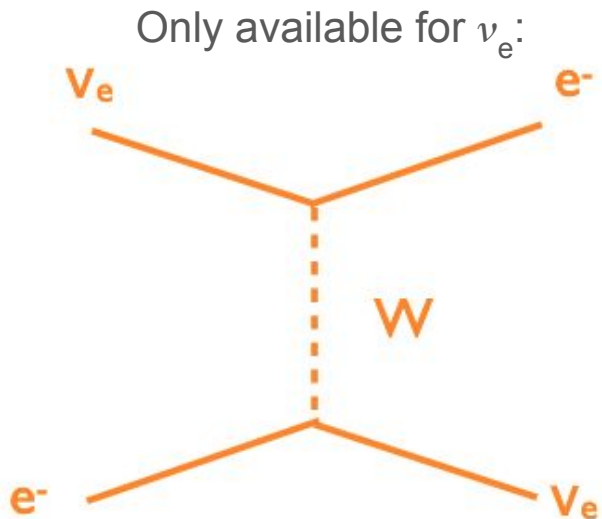
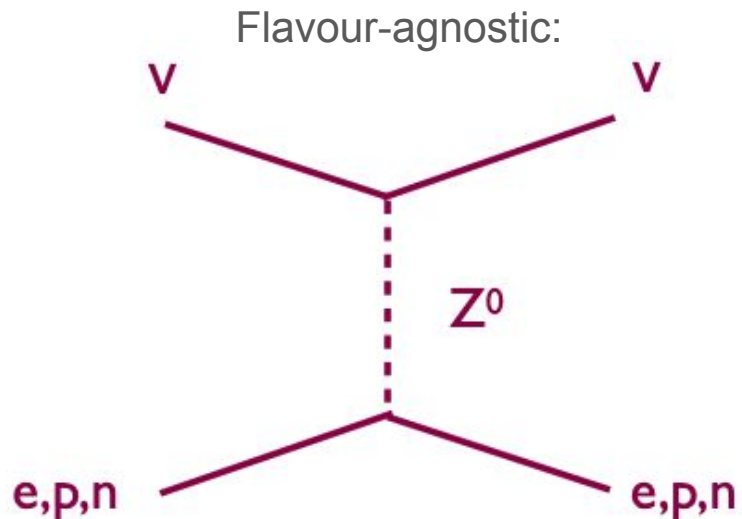
T2K Collaboration



Large collaboration: ~560 members from 74 institutes

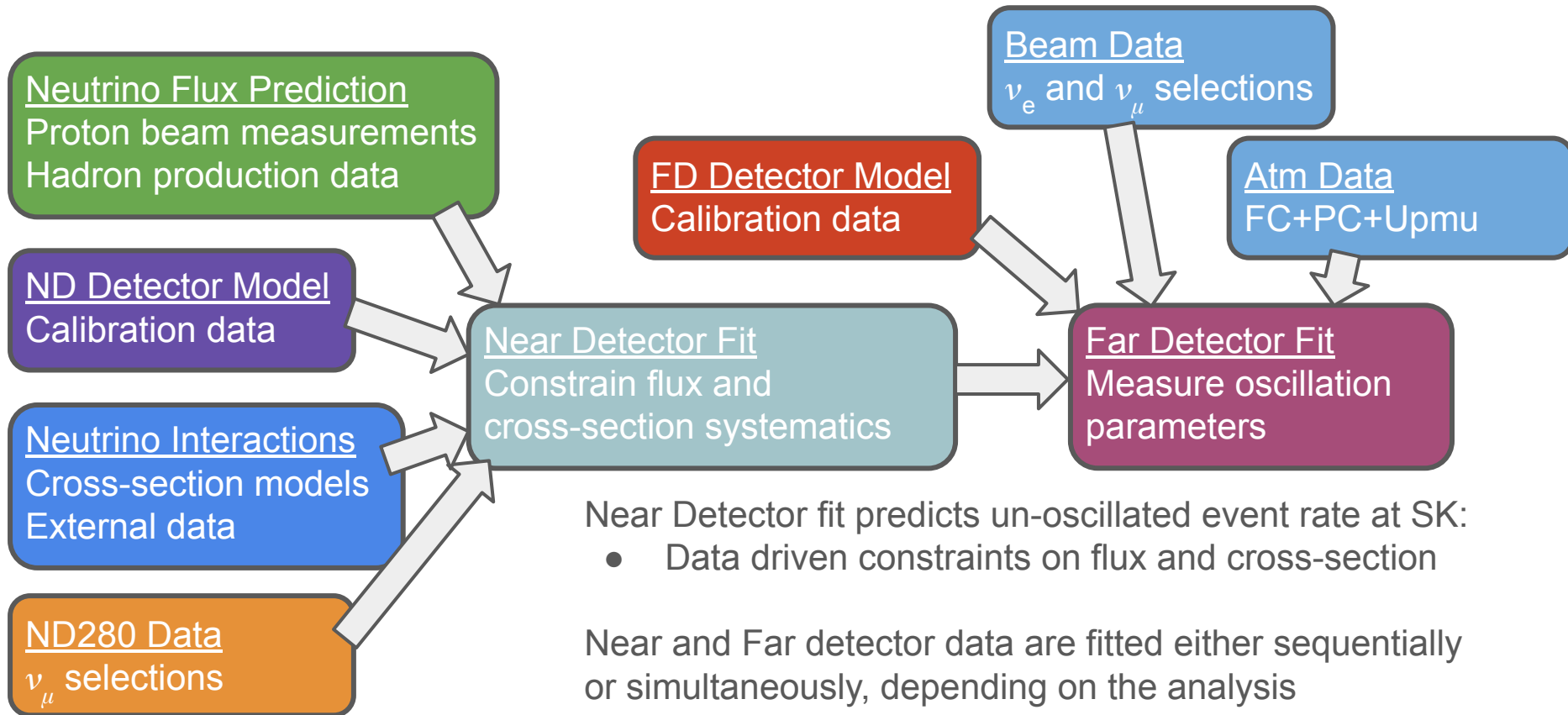
Measuring the Mass Hierarchy

Long baseline experiments sensitive to mass hierarchy through matter effects:



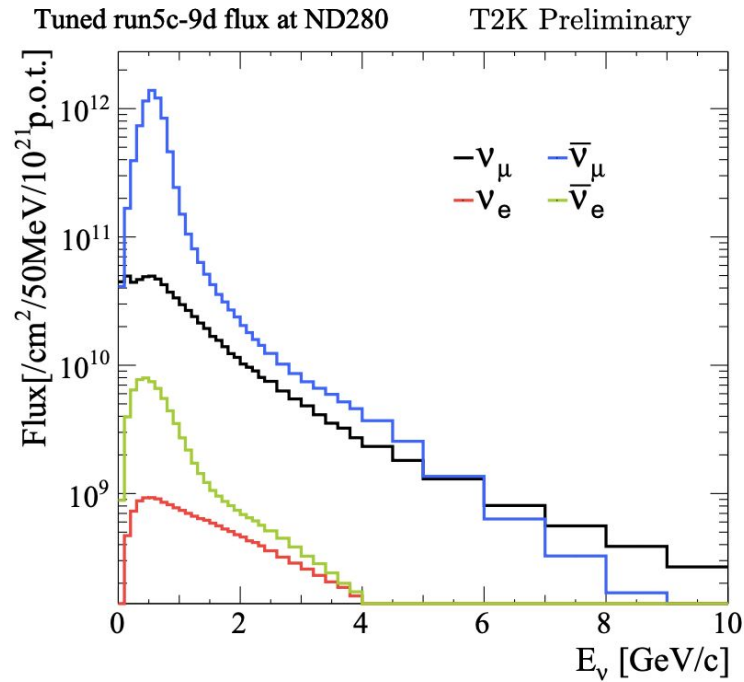
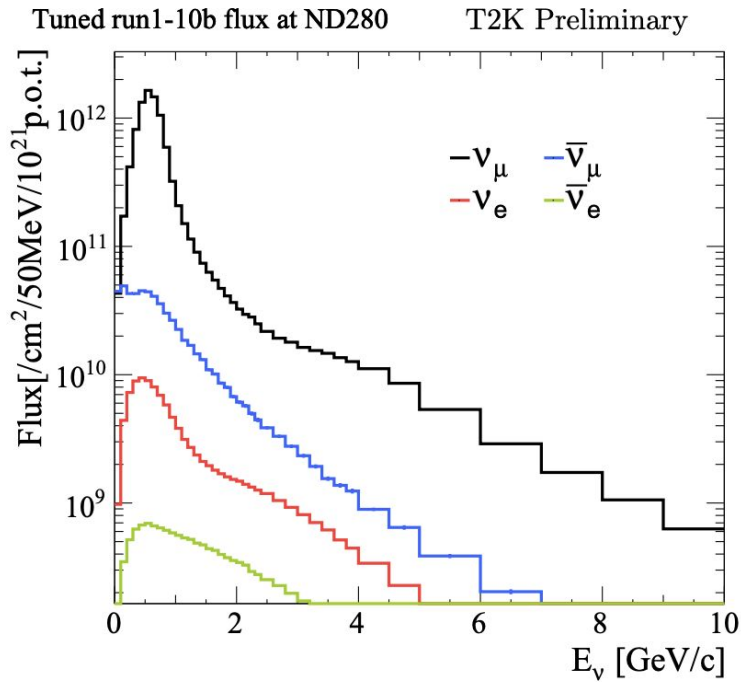
“Extra” potential for ν_e break mass-hierarchy symmetry:

- Depends on which mass state contains the most ν_e contribution



ν -mode

$\bar{\nu}$ -mode



T2K Beam Neutrino Flux Uncertainties

