T2K and $\nu/\bar{\nu}$ oscillation analysis

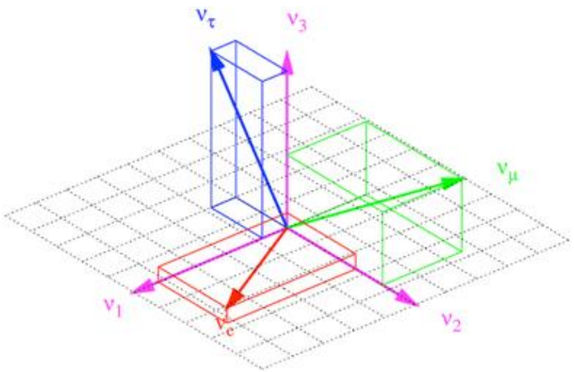
Presented by Jaiden Parlone

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & c_{23}c_{13} \end{bmatrix}.$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} {\rm Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j}{\rm Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$

The primary purpose of any neutrino oscillation experiment is to explore the oscillation probability, and therefore the mixing parameters.



3 Mixing angles:

θ_{12}

θ_{23}

θ_{13}

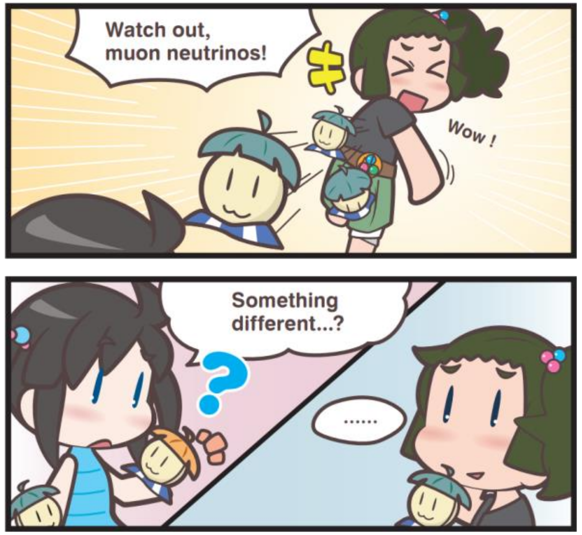
2 Mass splittings:

Δm^2_{21}

Δm^2_{32} or Δm^2_{31}

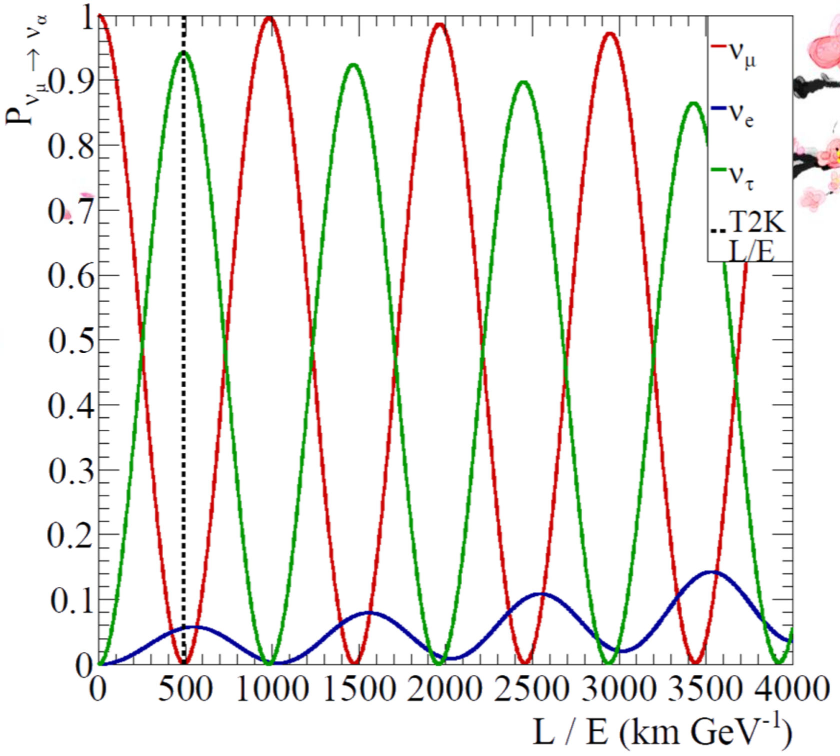
CP violating phase factor:

δ_{CP}



https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/files/NF-pamph-EN.pdf

Assuming 3 flavour PMNS mixing in a pure ν_μ beam with a fixed baseline, L.

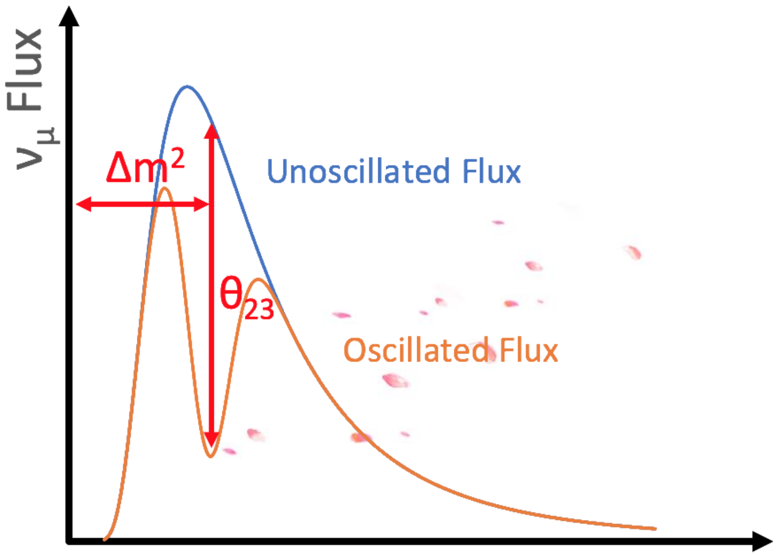


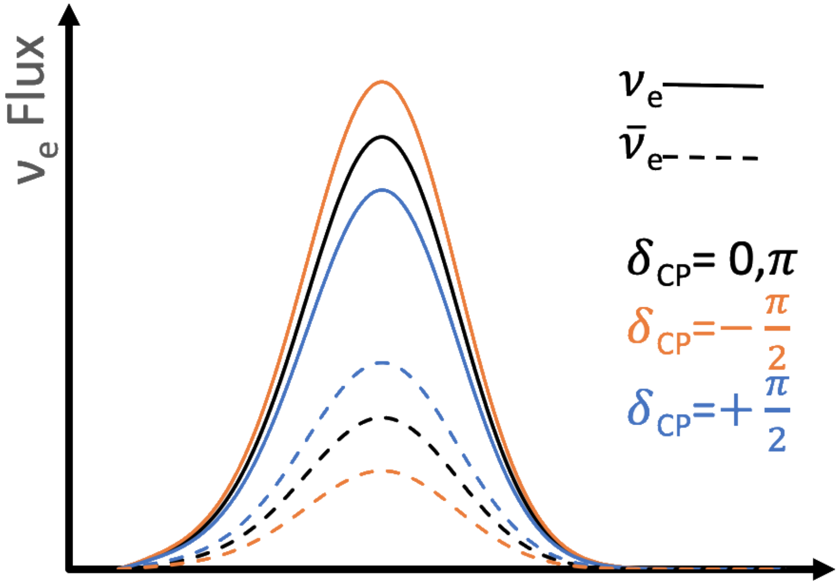
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \sin^2\left(1.27\Delta m^2_{32} \frac{L}{E_\nu}\right)$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2\left(1.27\Delta m^2_{32} \frac{L}{E_\nu}\right)$$

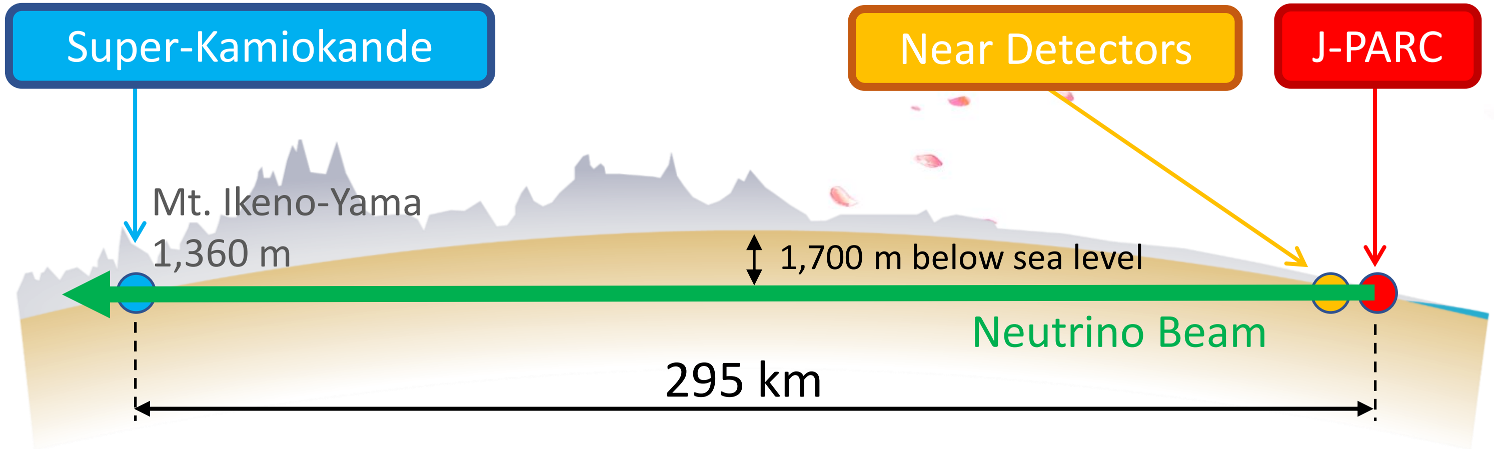
$$\mp 1.27\Delta m^2_{32} \frac{L}{E_\nu} 8 J_{CP} \sin^2\left(1.27\Delta m^2_{32} \frac{L}{E_\nu}\right)$$

- θ_{23}
- Δm^2_{32} or $(|\Delta m^2_{31}|)$
- θ_{13}
- δ_{CP}



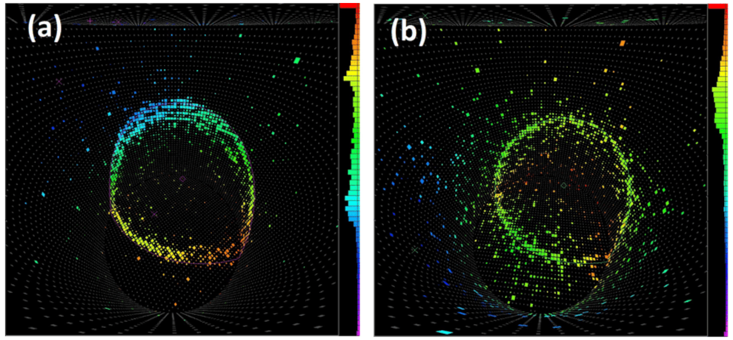


T2K (Tokai to Kamioka) is a long-baseline neutrino experiment that utilises multiple detectors in the goal of measuring the properties of neutrinos and their oscillations.



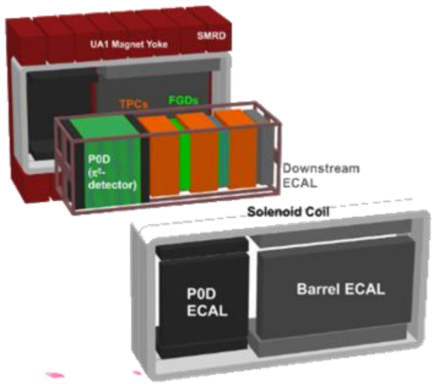
Super-K

- Off-axis water-based Cerenkov far detector.
- Topology based PID.
- CCQE dominant interactions.



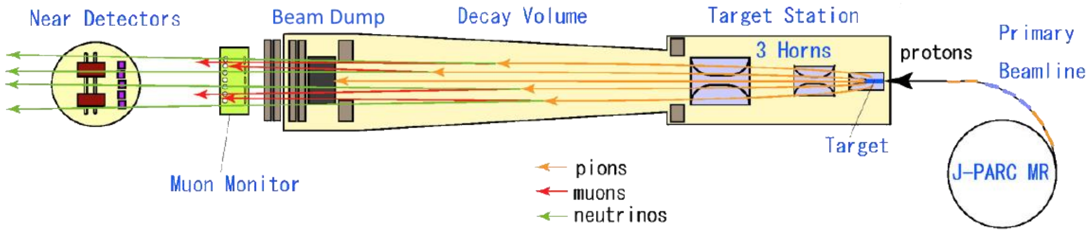
Cerenkov rings detected at SK. (a) is a muon event, (b) is an electron event.

ND280



- Magnetised composite near detector.
- Off-axis (replicates SK energy spectra).
- Constrains flux and cross-section uncertainties.

J-PARC

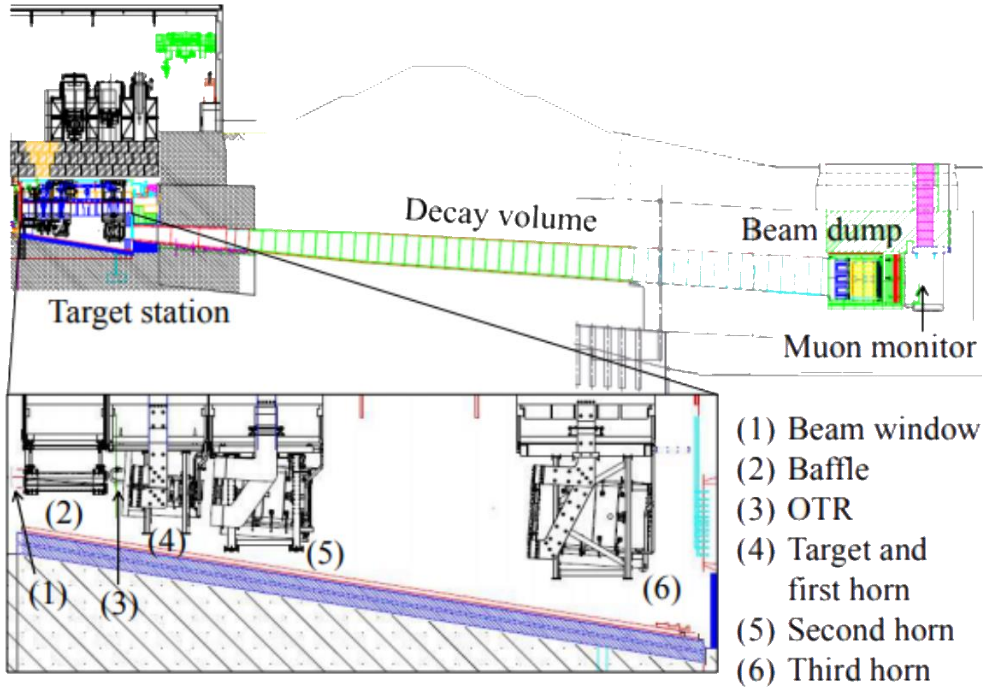


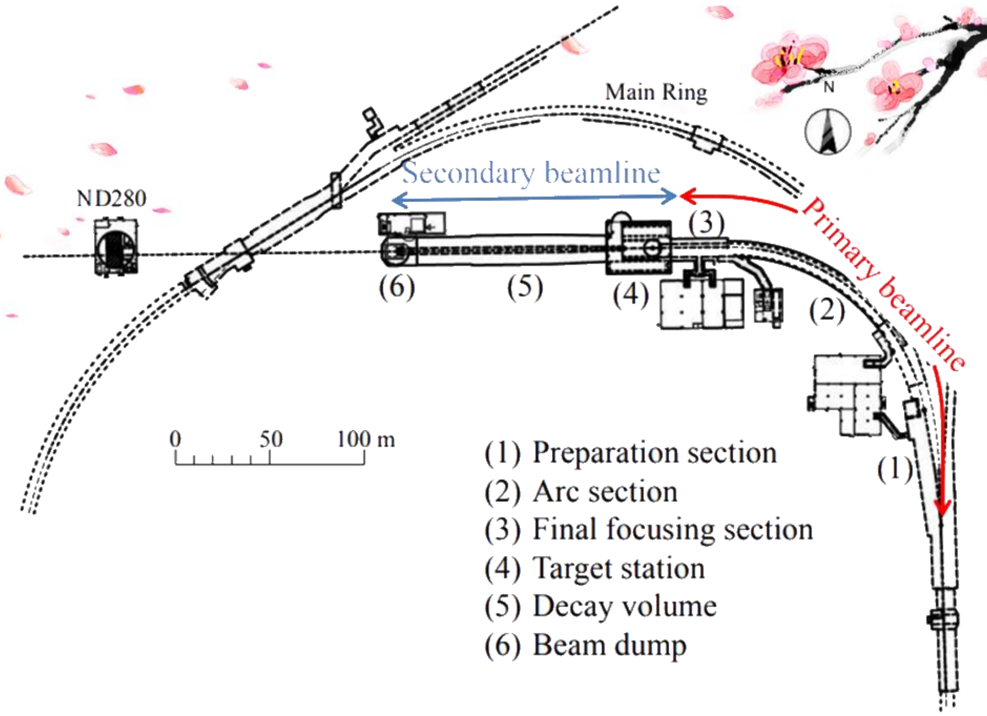
- ‘Off axis’ beam tuned to 0.6 GeV for oscillation max at SK.
- Produces pure $\nu_\mu/\bar{\nu}_\mu$ flux.
- Able to be run in ν or $\bar{\nu}$ mode.

The T2K collaboration has about 500 members from 70 institutes in 12 countries. We always need more bright minds!

1999: The T2K experiment was first proposed by Koichiro Nishikawa and Yoji Totsuka in order to search for oscillations from muon neutrinos to electron neutrinos.
2006: Submission of T2K experiment proposal.
2009: First neutrino beam produced by the proton accelerator at J-PARC.
2010: First physics data taken in the ND280 near detector and the SuperK far detector.

J-PARC beam production facility





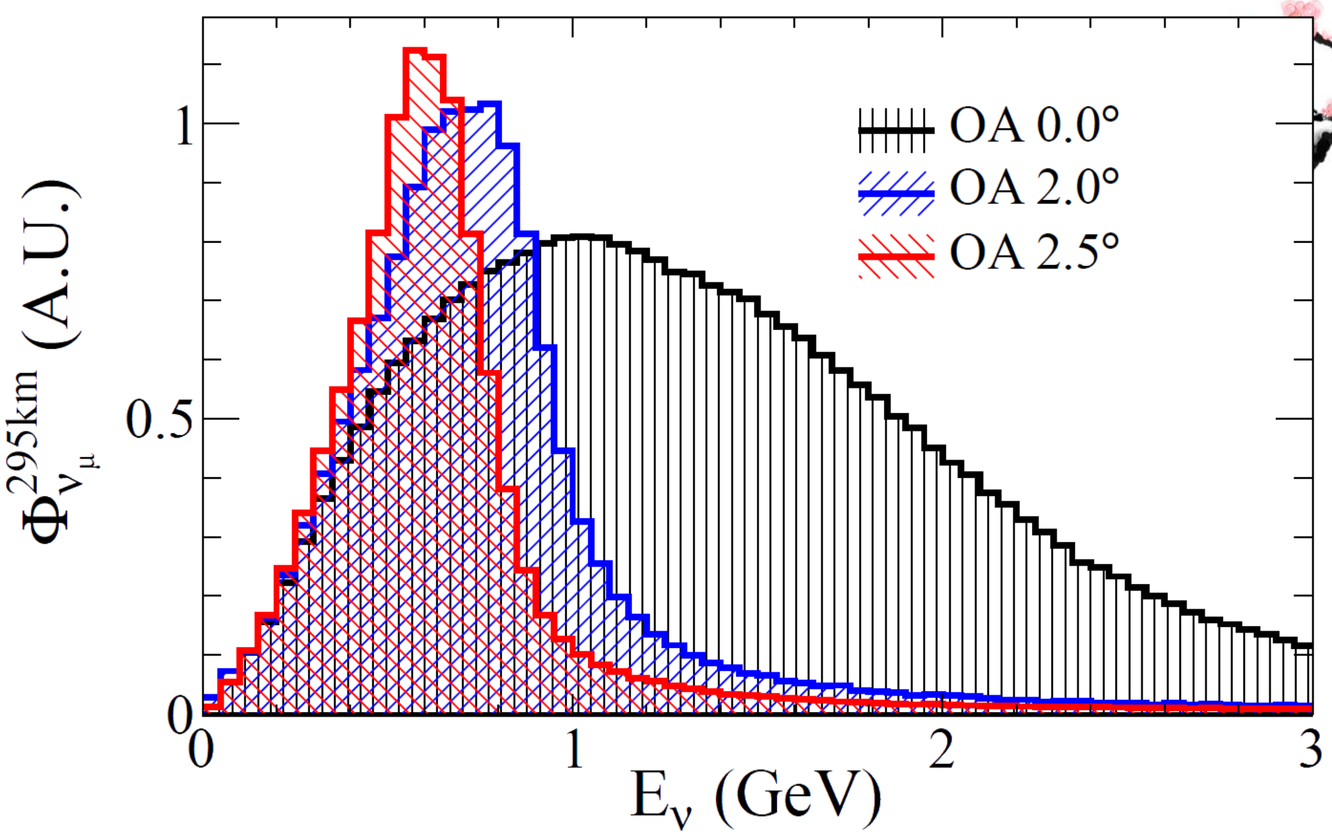
Multi-purpose beam production facility (meaning that not all the time is neutrino time ☹)
Utilises pion decay to produce almost pure flavour beam.
Able to run in ν or $\bar{\nu}$ mode by selection of pion charge. This is known as Forward or Reverse Horn Current.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$E = \frac{E^*}{\gamma(1 - \beta\cos\theta)}$$

E* is neutrino energy in centre of mass frame of the decaying meson.
γ is the neutrino's Lorentz factor.
β is the neutrino's Lorentz velocity.
θ is the neutrino's angle in the lab frame.



T2K is the first experiment in which the off-axis concept was implemented. This decreases the amount of neutrinos at high energies (decreasing more complicated interaction types and also tightening flux around osc max).

ND280 detector suite

- Same off-axis angle as Super-K (2.5 degrees).
- Measures ν_μ and ν_e spectrum before the oscillation → TPCs + FGDs
- Measure background processes to oscillation (NCπ0, NC1π, CC1π…)
- Compare Carbon and Oxygen interactions (FGD2 and P0D)

ND280 installed in ex-UA1 magnet (0.2 T) 3.5x3.6x7.3 m

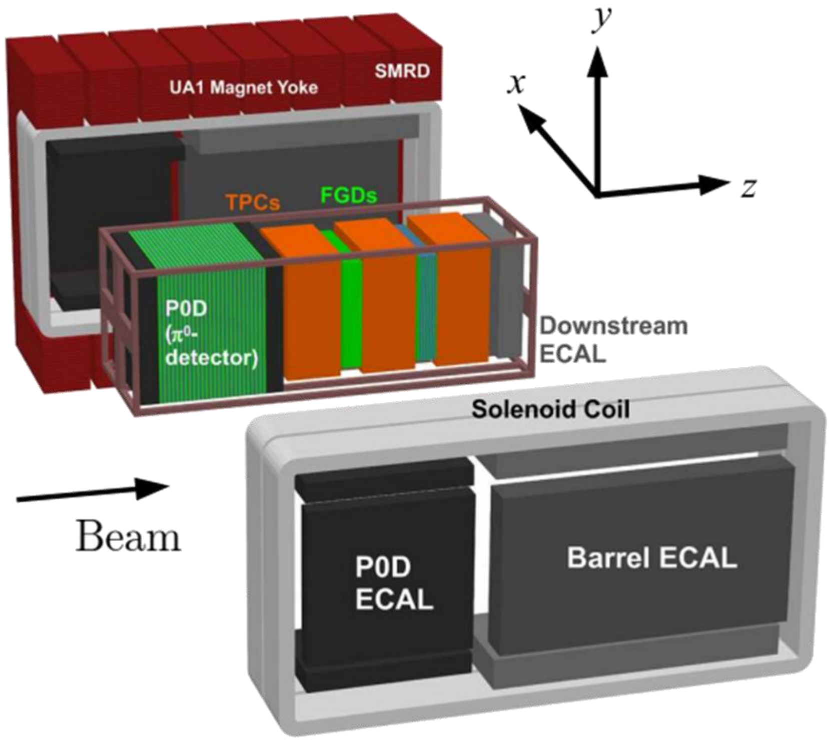
SMRD (Side Muon Range Detector): scintillator planes in magnet yokes. Measure high angle muons

2 FGDs (Fine Grained Detector): active target mass for the tracker, optimized for p/π separation Carbon+Water target in FGD2

P0D (π0 detector): scintillator bars interleaved with fillable water target bags and lead and brass sheets. Optimised for γ detection

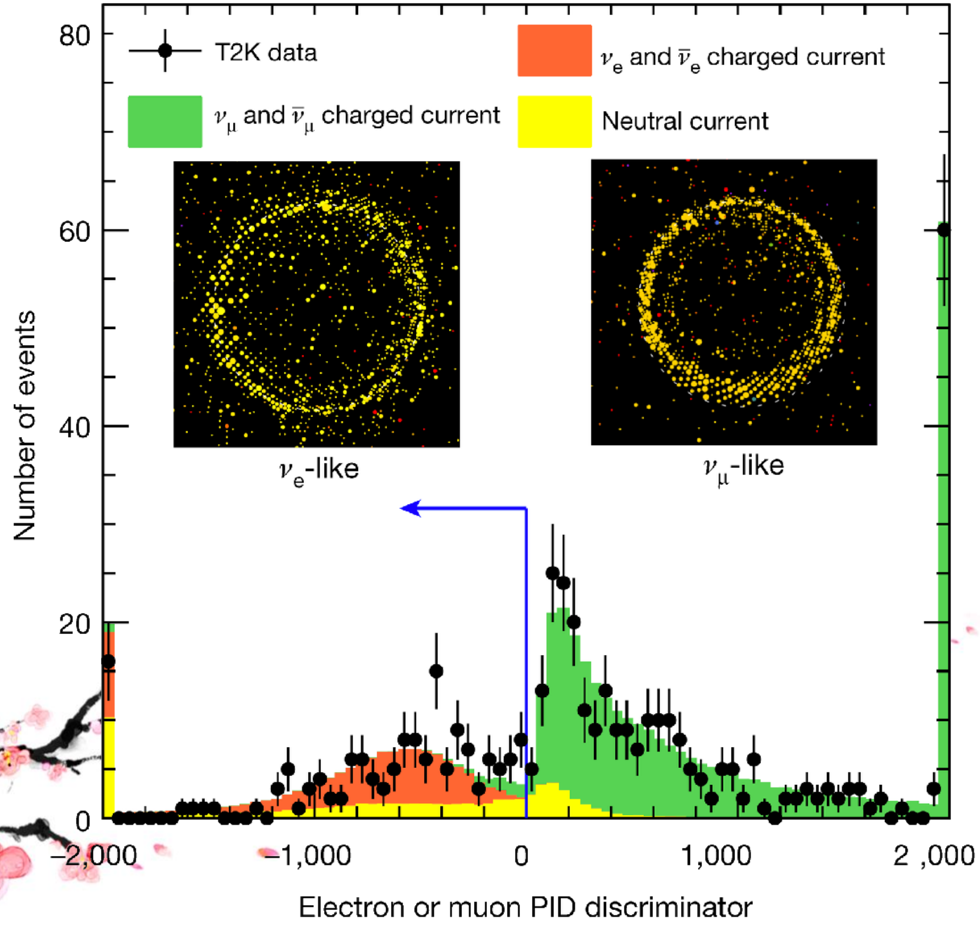
3 TPCs (Time Projection Chambers): measure momentum and charge of particles from FGD and P0D, PID capabilities through dE/dx

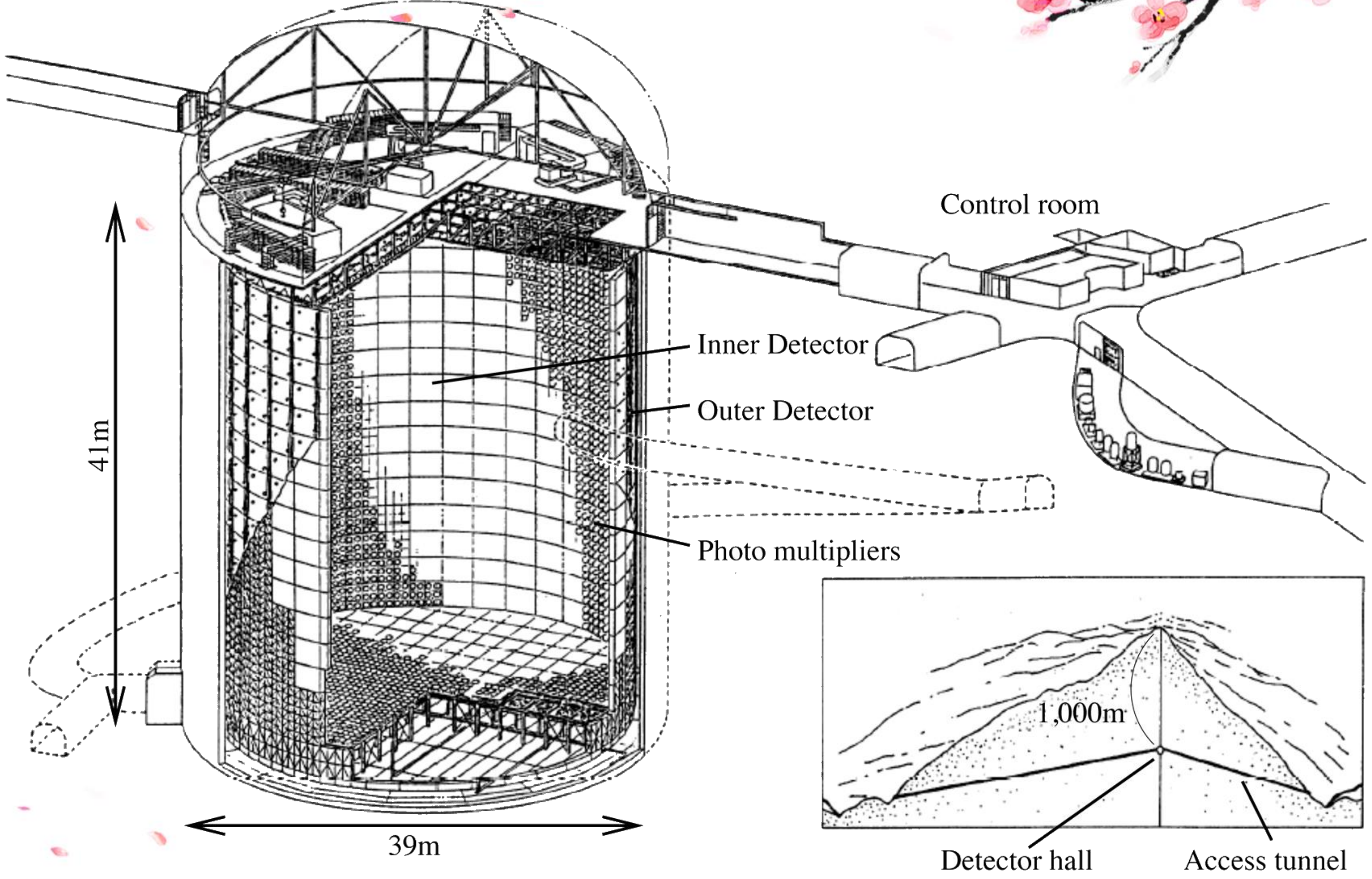
P0D, Barrel and Downstream ECAL: scintillator planes with radiator to measure EM showers



Super-Kamiokande

50kton water Cerenkov detector.
~11,000 20” PMTs
Vertex reconstruction
Mis-ID of less than 1%.

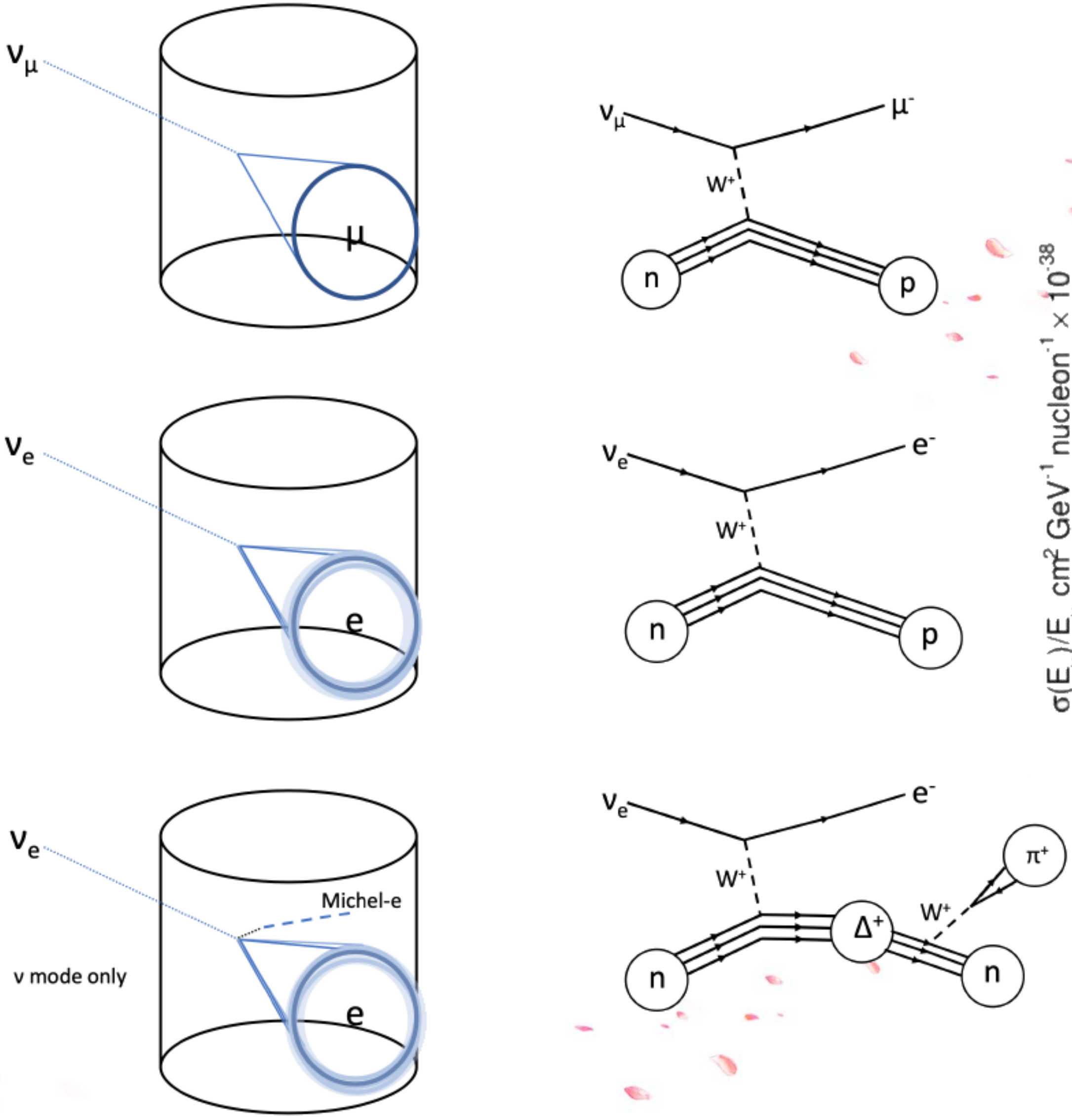


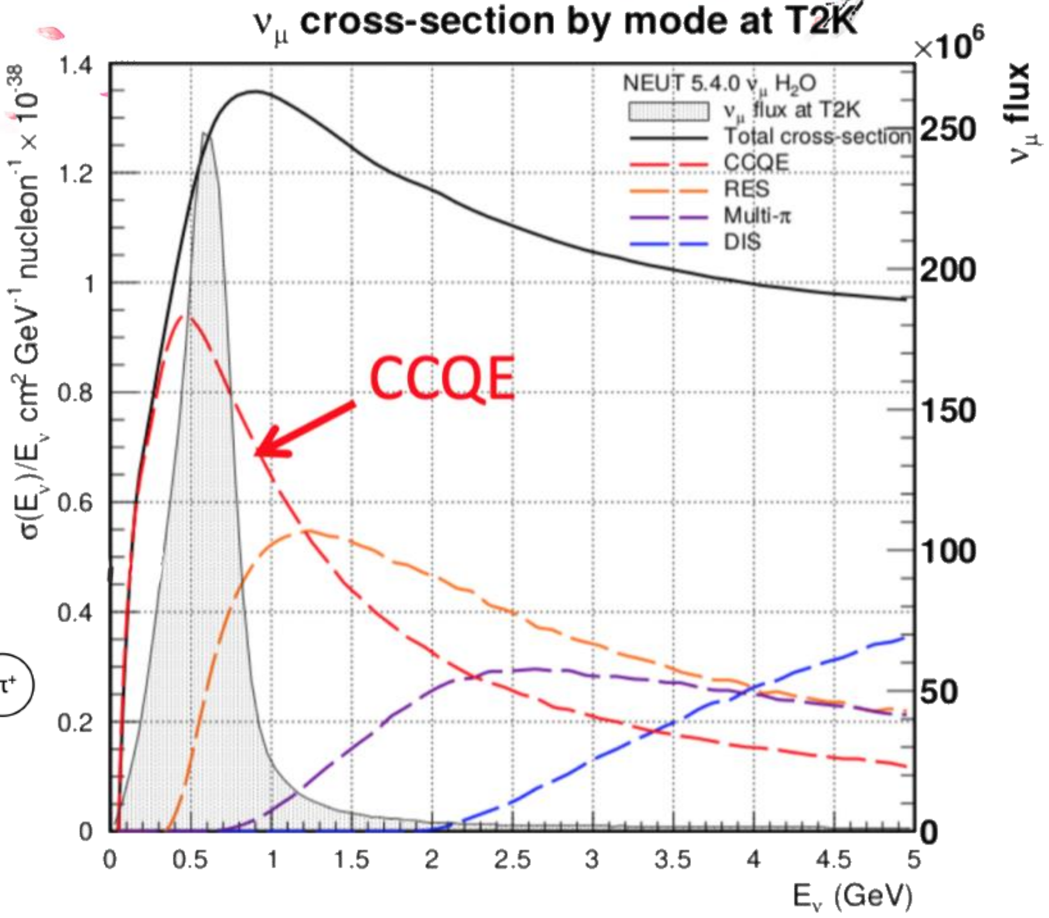


1-Ring ν_μ:

1 Ring ν_e:

1 Ring ν_e 1 decay e: ν mode only



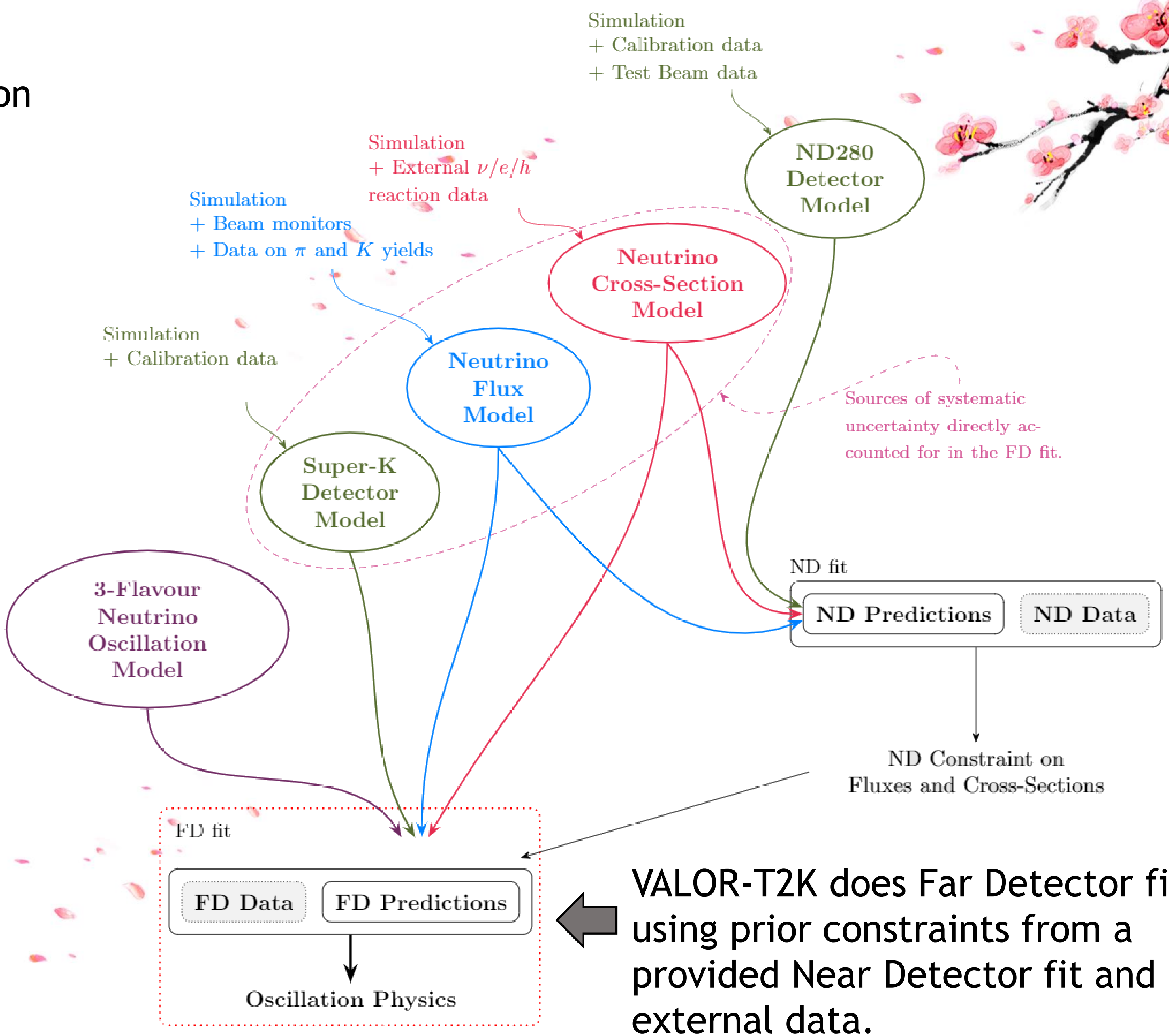


We look to constrain the neutrino oscillation parameters;

- θ_{23}
- Δm^2_{32} ($|\Delta m^2_{31}|$)
- θ_{13}
- δ_{CP}, the CP violating phase factor.

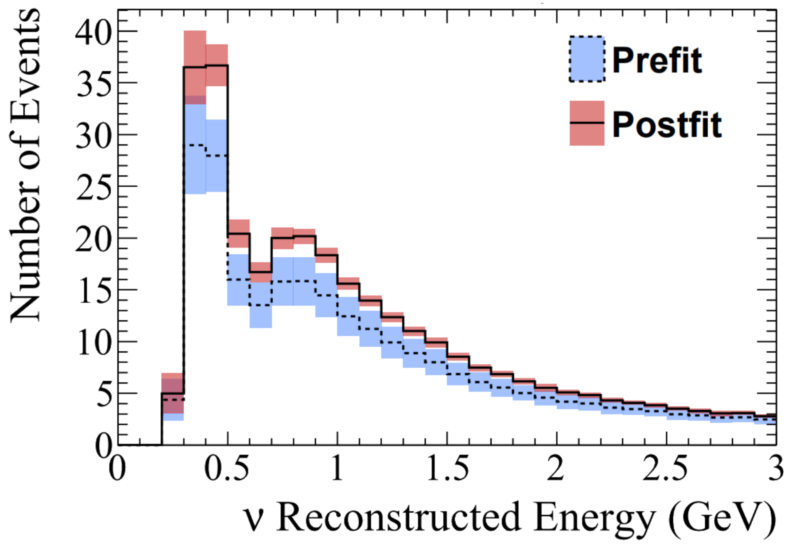
We achieve this through analysis of the $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance channels.

Oscillation analysis requires inputs from many parts of the overall model.

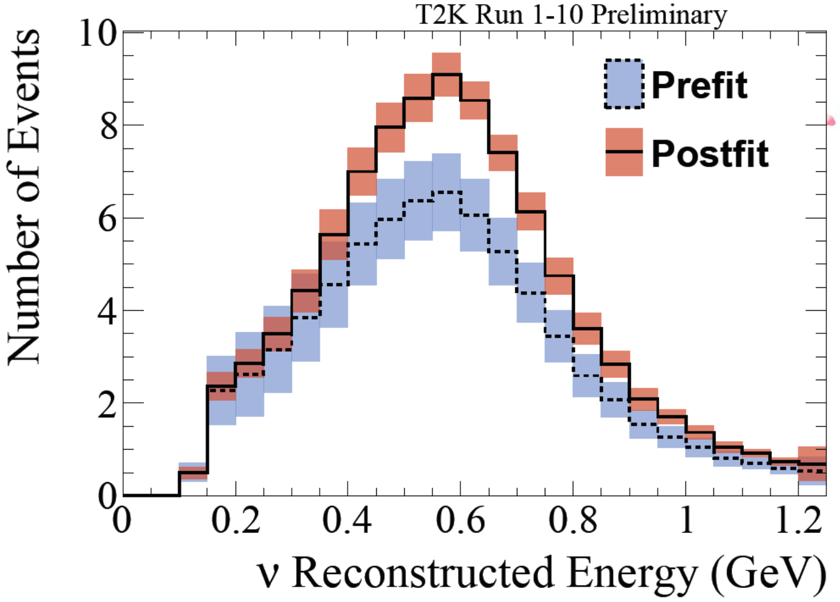


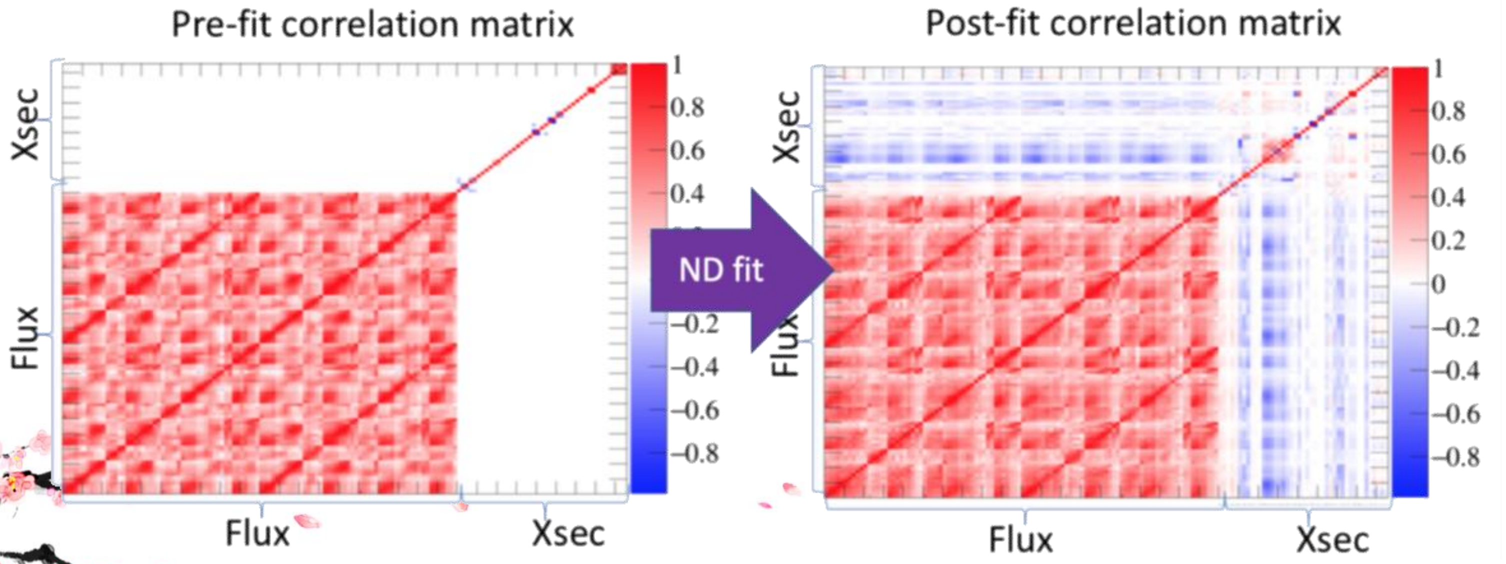
VALOR-T2K does Far Detector fits using prior constraints from a provided Near Detector fit and external data.

ν-mode ν_μ CCQE:



ν-mode ν_e CCQE:



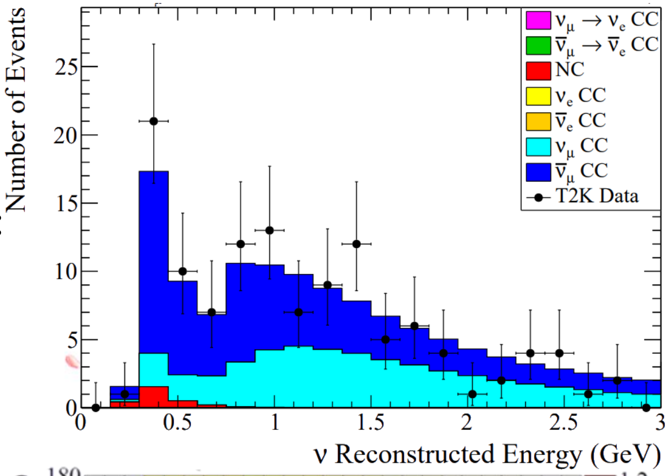


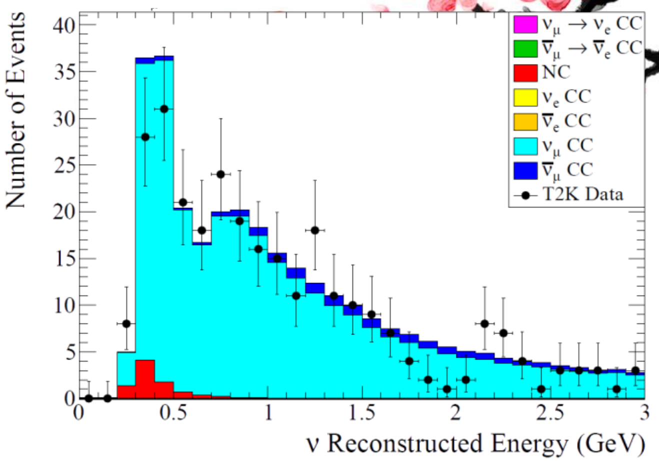
- So that oscillation parameters can be constrained with accuracy, uncertainties need to be understood.
- The Near-Detector provides the Oscillation Analysis with a correlated flux and cross-section model & respective error covariance matrix.
- The Far Detector provides the Oscillation Analysis with a detector error constraint from atmospheric data, and more complex interaction systematics (Secondary interactions and Photonuclear effect).

- To achieve results, our Monte-Carlo model predictions are compared to our observed data.
- Our model is split into 5 samples, seen on the right.
- The latest T2K dataset (Run 1-10) was obtained with a total exposure of 1.99(1.65)$\times 10^{21}$ Protons on Target in $\nu(\bar{\nu})$ mode.
- 94 1-Ring ν_e events were observed.
- *Currently e-like events are binned in 2D, E-θ, and μ-like in 1D, E.*
- *E-θ (lepton angle) dimensionality provides increased $\nu/\bar{\nu}$ separation (among other benefits).*

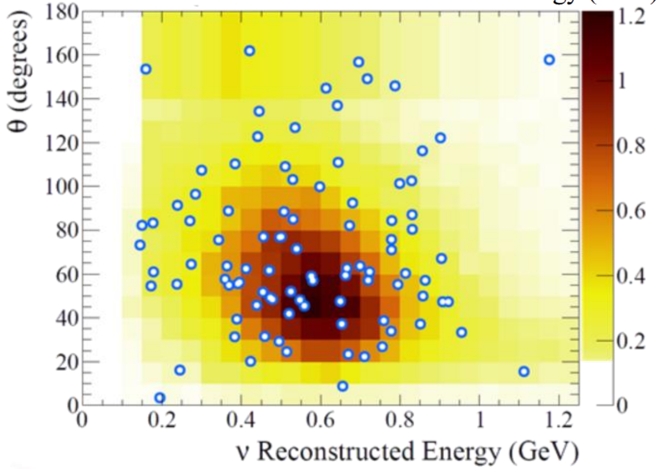
ν mode: | $\bar{\nu}$ mode:

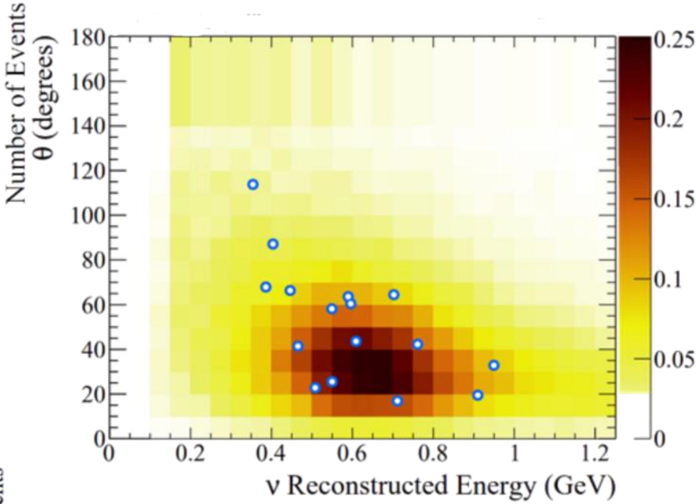
1-Ring ν_μ:



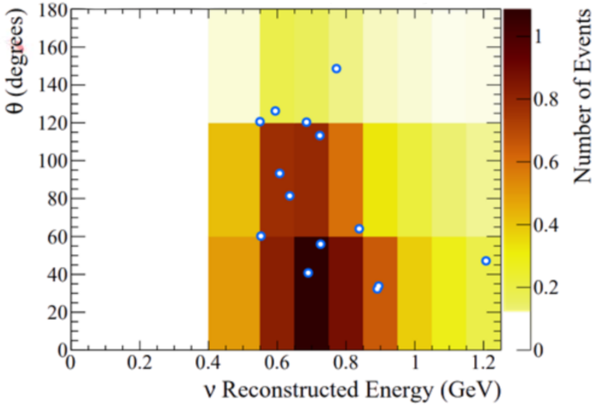


1 Ring ν_e:





1 Ring ν_e 1 decay e:

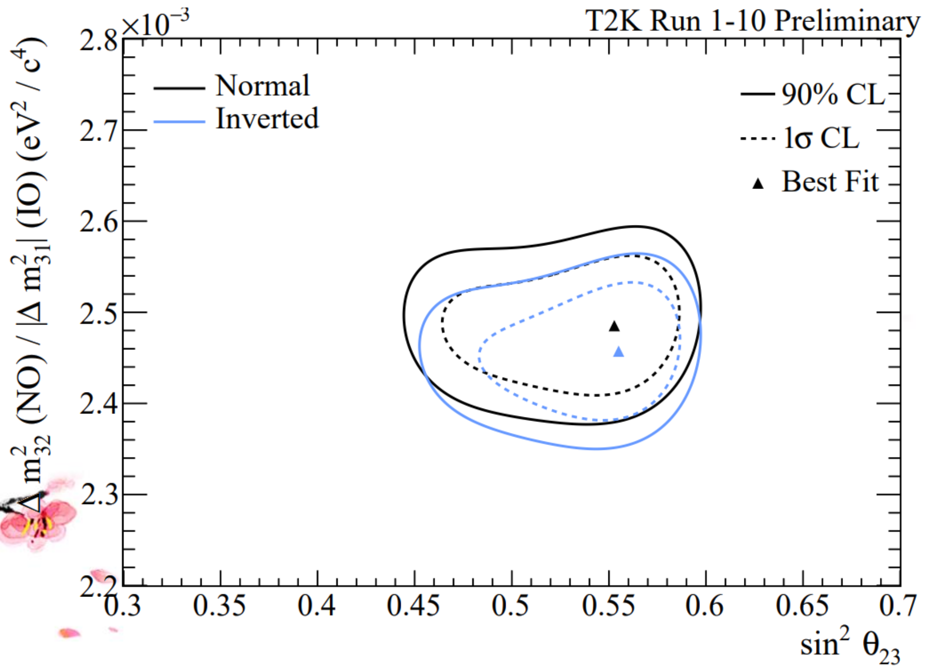


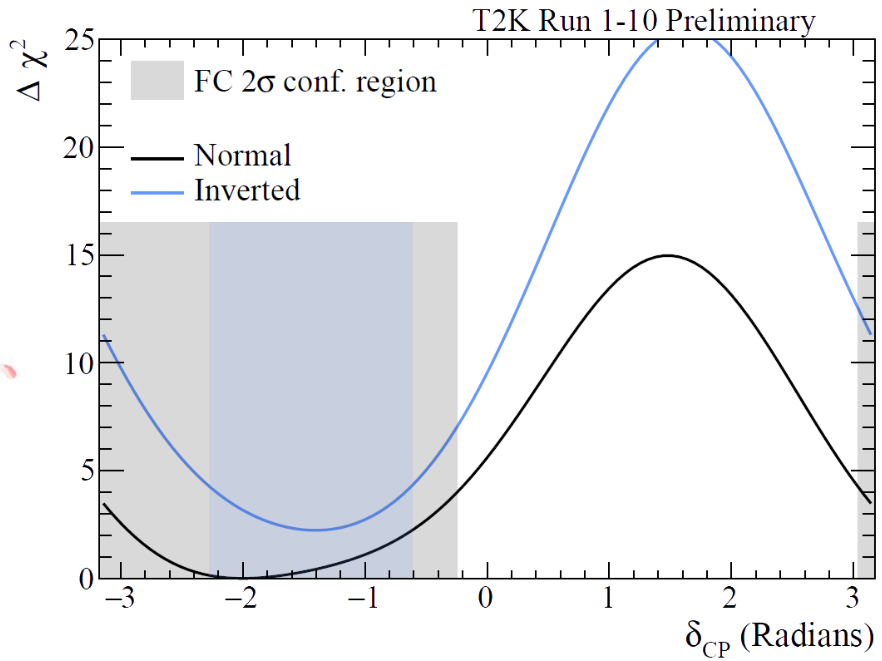
MC generated event distributions overlayed with T2K Run1-10 data.

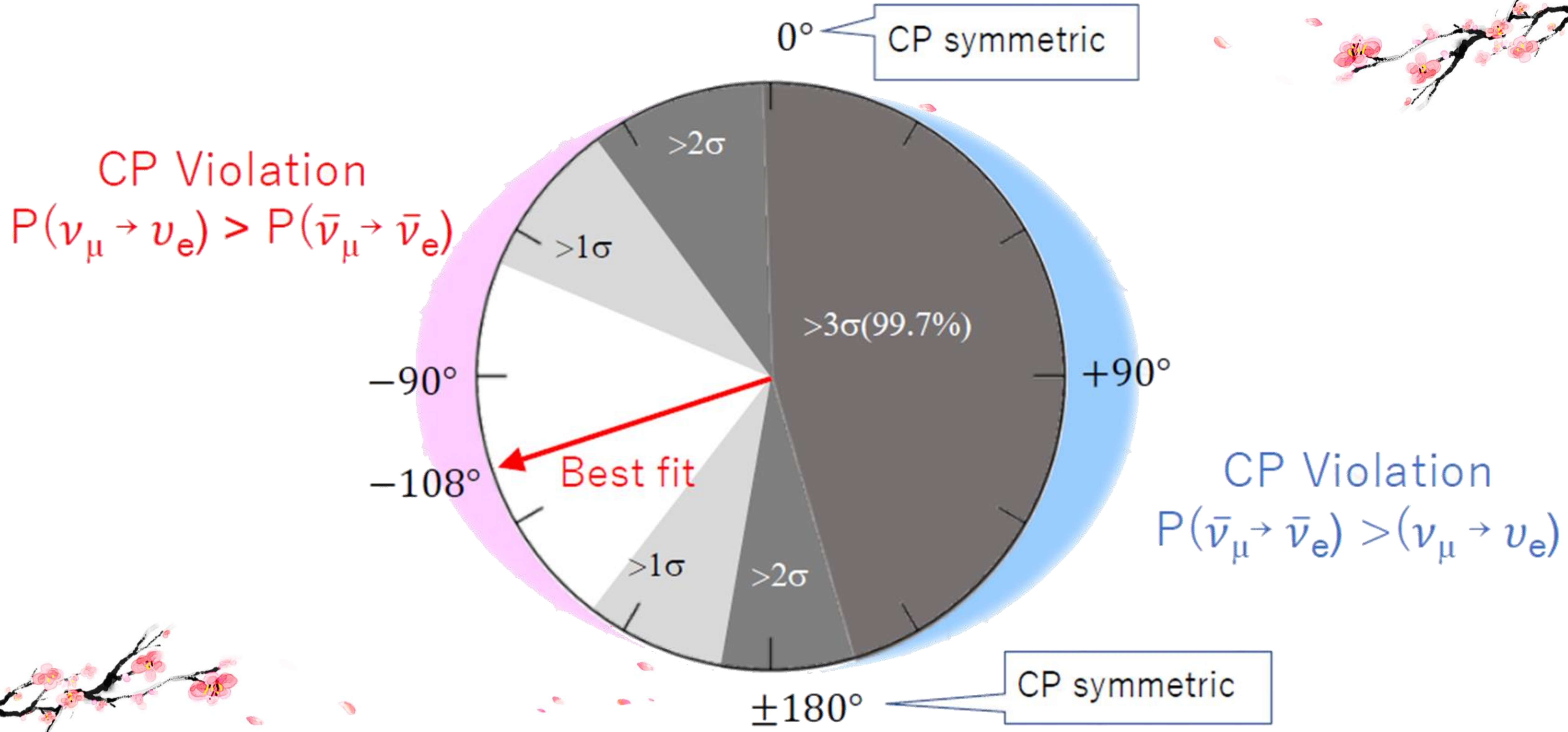
Speaking of constraints…

These are official results that mirror those released at Neutrino 2020, and are from our T2K internal tech note.

- Binned log-likelihood method compares predicted and observed event spectra over parameter space.
- Systematics (and nuisance oscillation parameters) are marginalised over using their prior constraints.
- This leaves us with a likelihood dependant only on parameters of interest.
- Confidence intervals are constructed using const. ΔX^2 (left) or Feldman-Cousins (right).





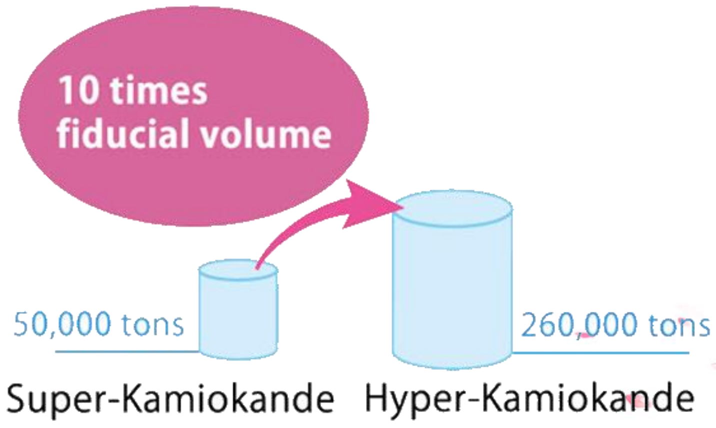

CP Violation
$P(\nu_\mu \to \nu_e) > P(\bar{\nu}_\mu \to \bar{\nu}_e)$
0°
CP symmetric
>2σ
>1σ
>3σ(99.7%)
−90°
+90°
−108°
Best fit
>1σ
>2σ
±180°
CP symmetric
CP Violation
$P(\bar{\nu}_\mu \to \bar{\nu}_e) > (\nu_\mu \to \nu_e)$

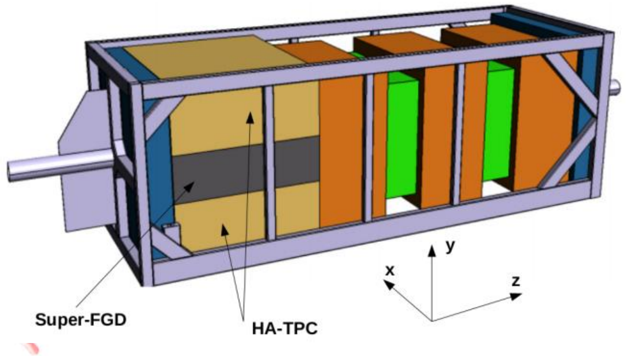
Analysis next steps:

- Re-analysing the data with model/method updates.
- Analysis of the Run1-11 data, being taken (roughly) now!

Future of LBL in Japan:

- Upgraded beam power to 750 kW (2022) & 1.3MW (2029). This means more data with each run!
- Near Detector Suite Upgrade with many additional reconstruction benefits.
- The Hyper-Kamiokande experiment (and a separate branch of VALOR).



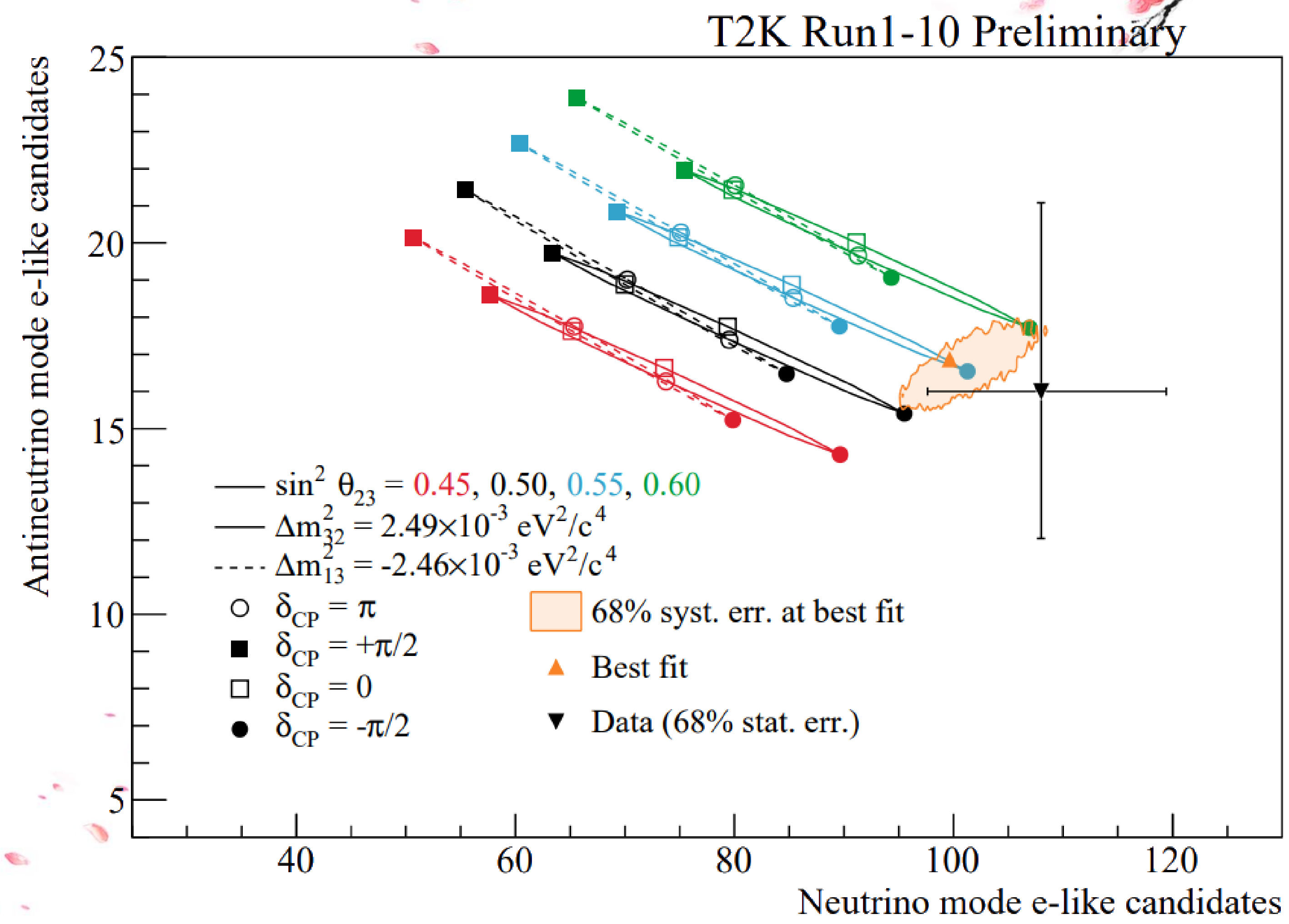


Acknowledgements: My comrades in code on the VALOR-T2K fitting framework, Francis Bench and Maria Antonova, as well as my co-collaborators in the OA group and beyond.

For sensitivity studies (among other purposes) a fake 'Asimov' dataset is generated using different values:

Sample	Predicted Oscillation Hypothesis				Observed
	No osc.	Asimov A	Asimov B	Asimov BF NO	
FHC μ-like sample	1571.4	345.5	361.8	354.0	318
FHC e-like sample	19.6	93.8	69.8	95.2	94
RHC μ-like sample	444.5	135.1	138.8	137.9	137
RHC e-like sample	6.3	15.9	16.4	16.9	16
FHC ν_e CC1π^+-like sample	2.9	8.8	6.8	8.9	14

- A fantastic way of presenting our data is these 'Bi-Probability' plots.
- The effects of changes to the oscillation model are easy to visualise.
- We can see from this that $\delta_{CP} = -\frac{\pi}{2}$ is favoured.



Prior distributions that nuisance oscillation parameters are marginalised over.

Parameter(s)	Prior PDF	Range
$\sin^2\theta_{23}$	Uniform	$[0.3, 0.7]$
$\sin^2\theta_{13}$ T2K-only	Uniform	$[0, 0.4]$
$\sin^2 2\theta_{13}$ reactors	Gaussian	0.0853 ± 0.0027
$\sin^2 2\theta_{12}$	Gaussian	0.851 ± 0.020
Δm^2_{32} (NO) / $\|\Delta m^2_{31}\|$ (IO)	Uniform	$[2.3, 2.8] \times 10^{-3}$ eV^2/c^4
Δm^2_{21}	Gaussian	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2/c^4
δ_{CP}	Uniform	$[-\pi, +\pi]$
Mass Ordering	Fixed	NO or IO

Number of points across parameter(s) of interest space where a likelihood is constructed.

Parameter(s) of interest	Number of Points	Range
$\sin^2\theta_{23}$	101	$[0.3, 0.7]$
$\sin^2\theta_{13}$ T2K-only	101	$[0.007, 0.053]$
$\|\Delta m^2_{32}\|$ (NO) / $\|\Delta m^2_{31}\|$ (IO)	101	$[2.2, 2.8] \times 10^{-3}$ eV^2/c^4
δ_{CP}	101	$[-\pi, \pi]$
$\sin^2\theta_{23}$, $\|\Delta m^2_{32}\|$ (NO) / $\|\Delta m^2_{31}\|$ (IO)	81×51	$[0.3, 0.7]$, $[2.2, 2.8] \times 10^{-3}$ eV^2/c^4
$\sin^2\theta_{13}$, δ_{CP} T2K-only	81×51	$[0.007, 0.053]$, $[-\pi, \pi]$
$\sin^2\theta_{13}$, δ_{CP} T2K+reactor	81×51	$[0.015, 0.036]$, $[-\pi, \pi]$