An Oscillation Analysis of the latest $\nu/\bar{\nu}$ T2K Dataset

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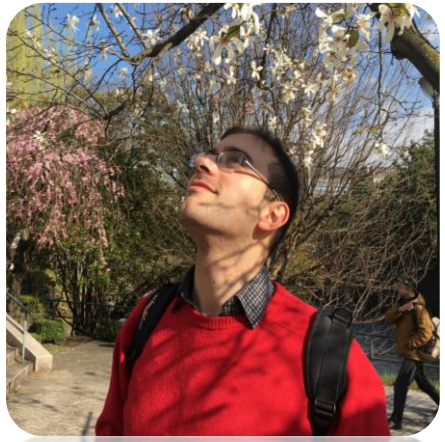
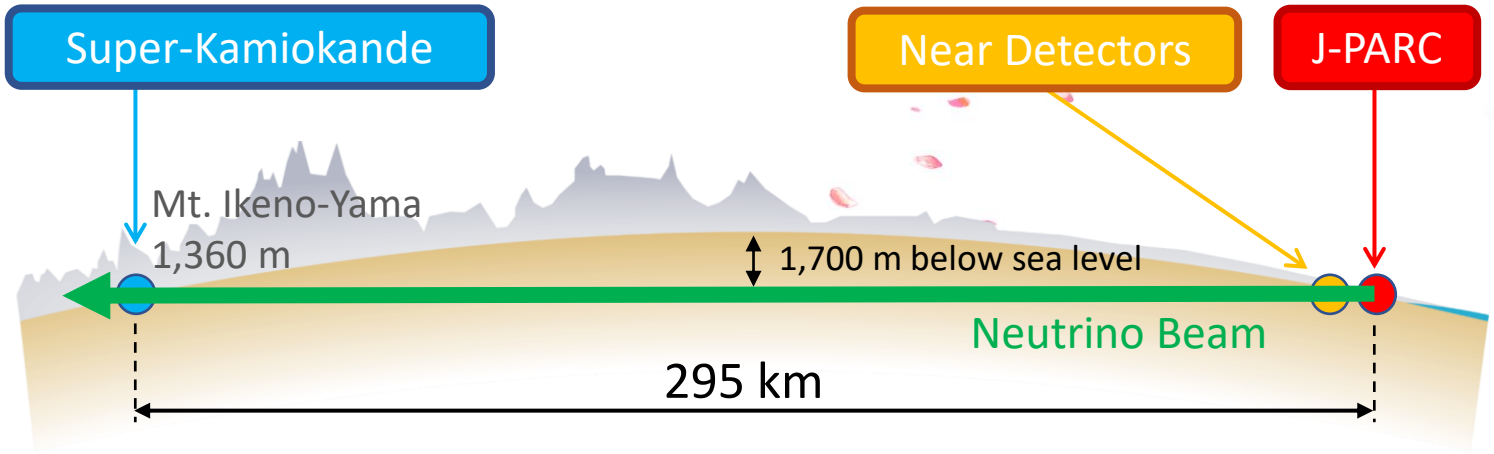
Maria Antonova + Jaiden Parlone + Francis Bench



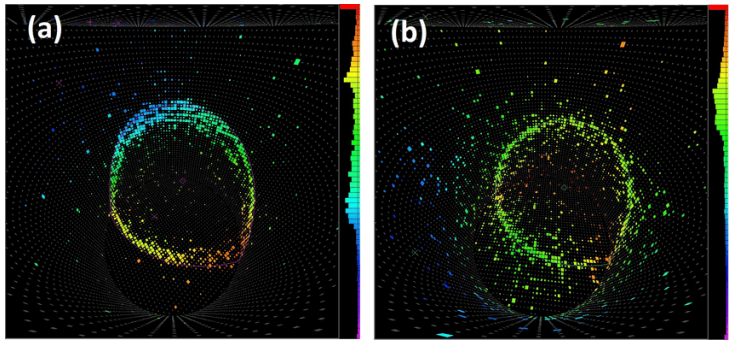
VALOR-T2K arises from the 3 analyser eigenstates

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.



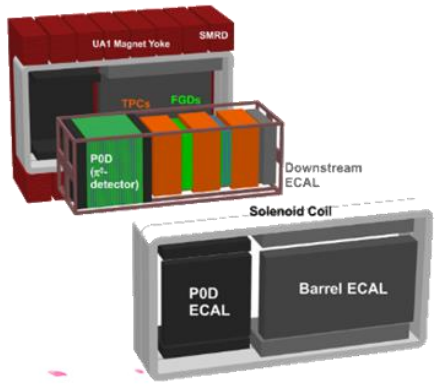
Super-K

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



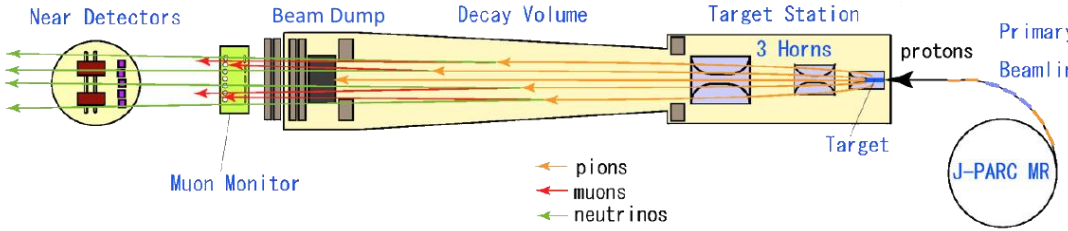
Cerenkov rings detected at SK. (a) is a muon event, (b) is an electron event.

ND280



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

J-PARC



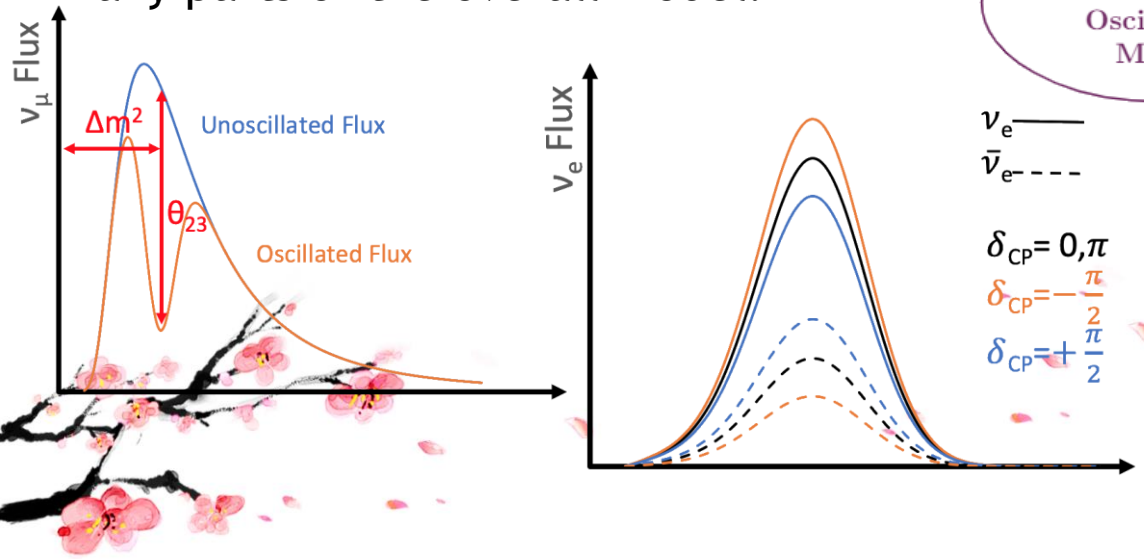
- 'Off axis' beam tuned to 0.6 GeV for oscillation max at SK.
- Produces pure $\nu_\mu/\bar{\nu}_\mu$ flux.
- Able to be run in ν or $\bar{\nu}$ mode.

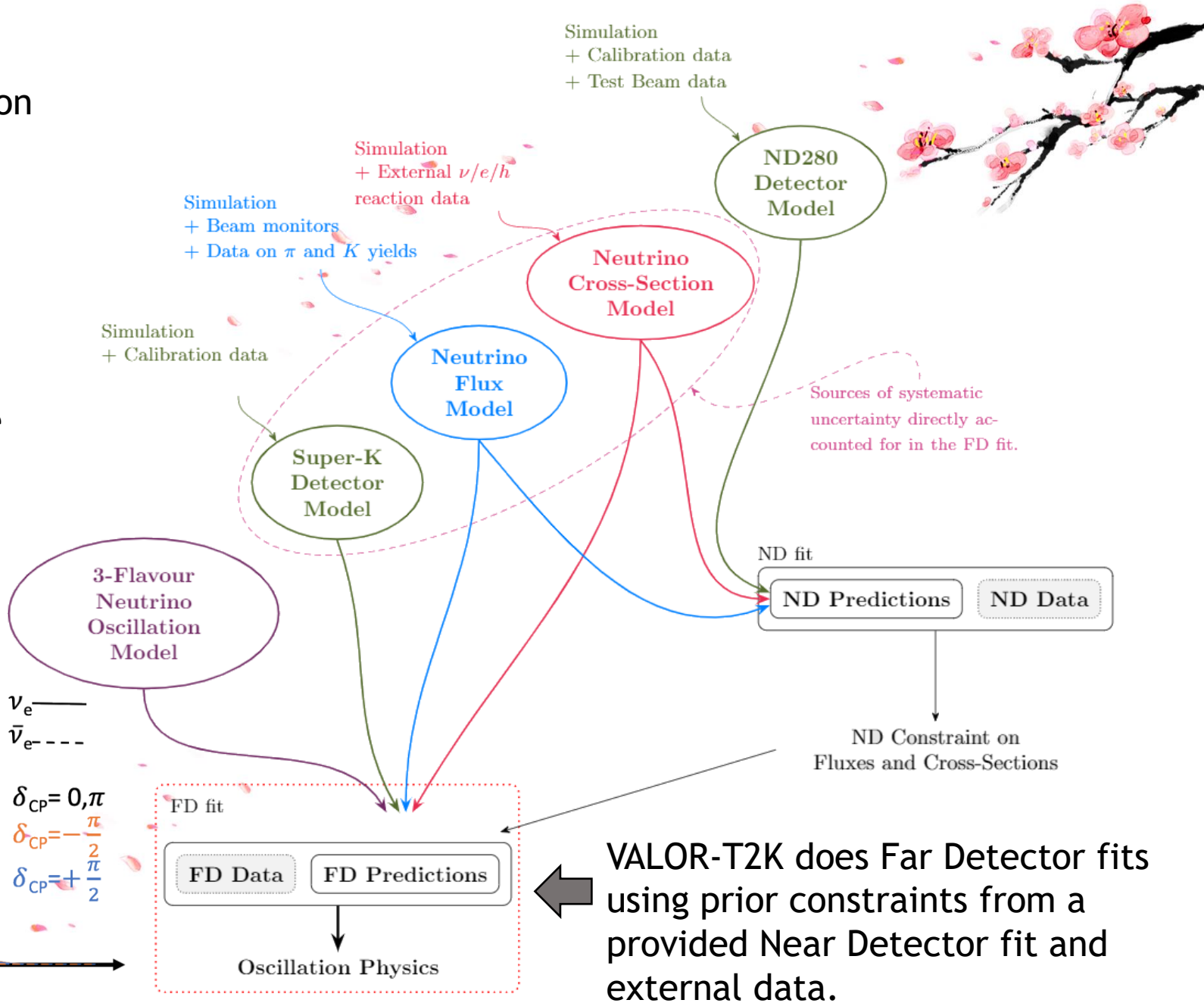
We look to constrain the neutrino oscillation parameters;

- 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.





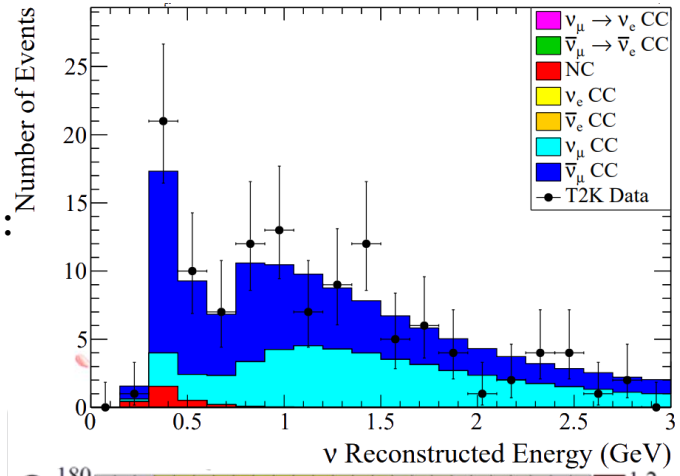
VALOR-T2K does Far Detector fits using prior constraints from a provided Near Detector fit and external data.

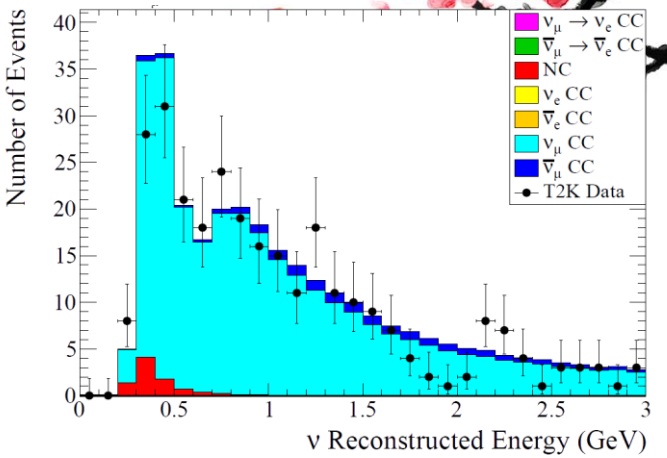
- To achieve results, our Monte-Carlo model predictions are compared to our observed data.
- Our model is split into 5 samples, seen on the right.
- The latest T2K dataset (Run 1-10) was obtained with a total exposure of $1.99(1.65)\times 10^{21}$ Protons on Target in $\nu(\overline{\nu})$ mode.
- 94 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 $\nu/\overline{\nu}$ separation (among other benefits).*

ν mode:

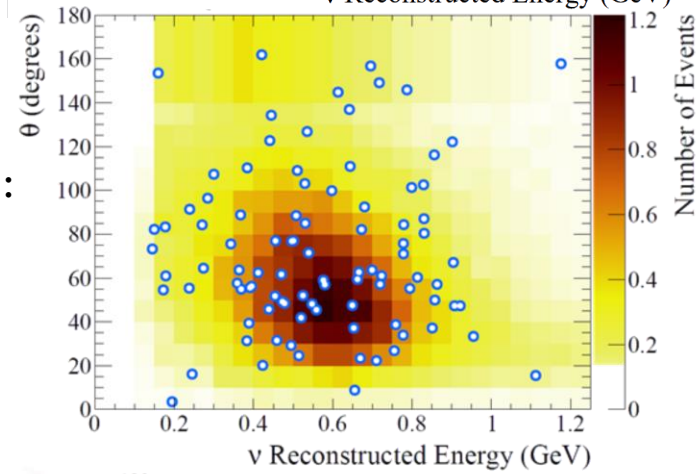
$\bar{\nu}$ mode:

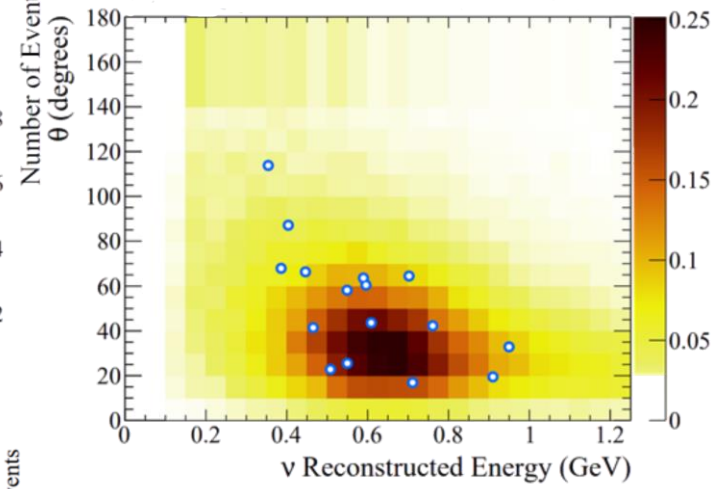
1-Ring ν_μ:



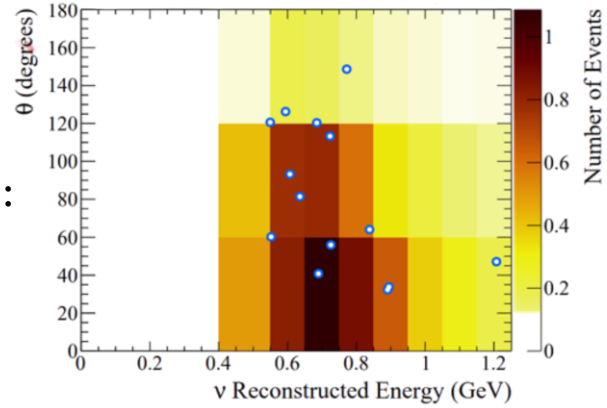


1 Ring ν_e:





Multi-Ring ν_e:

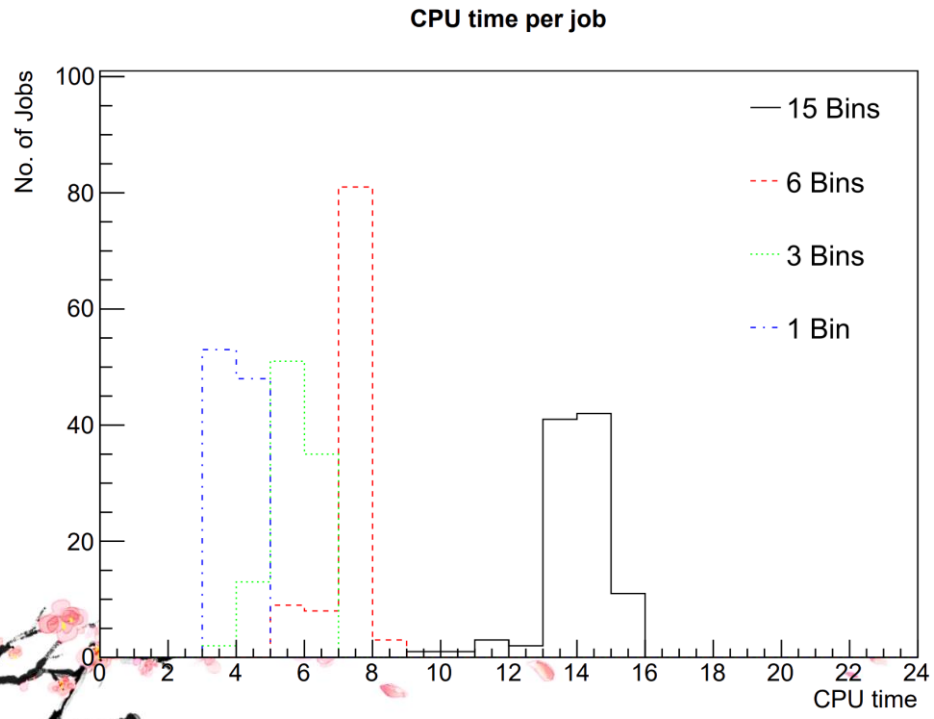


MC generated event distributions overlayed with T2K Run1-10 data.

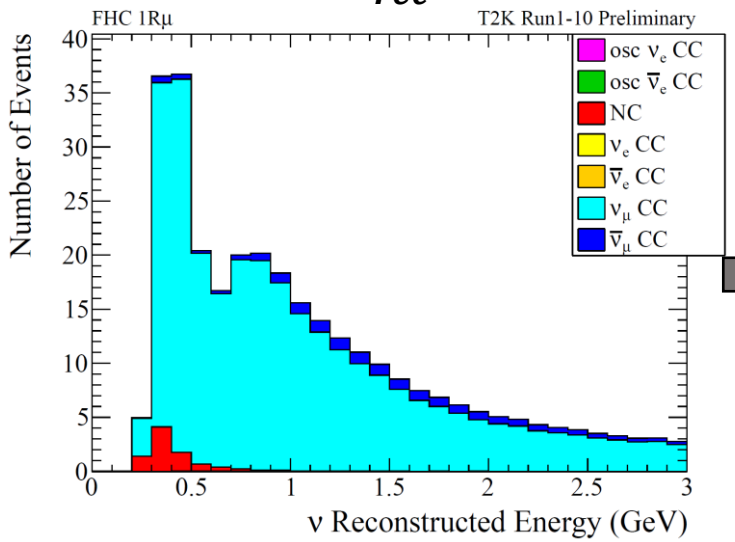
Additional binning studies

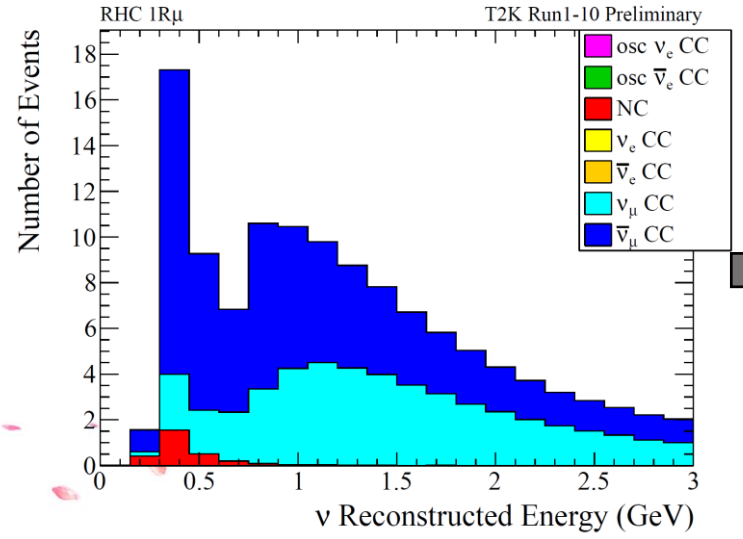
Adding a courser θ kinematic binning:

- Gives greater constraint on Δm^2_{32} (and minorly θ_{23}).
- Greater CC $\nu_\mu + \bar{\nu}_\mu$ from NC separation, and ad-hoc parameter constraint.
- Balance needed against CPU time.

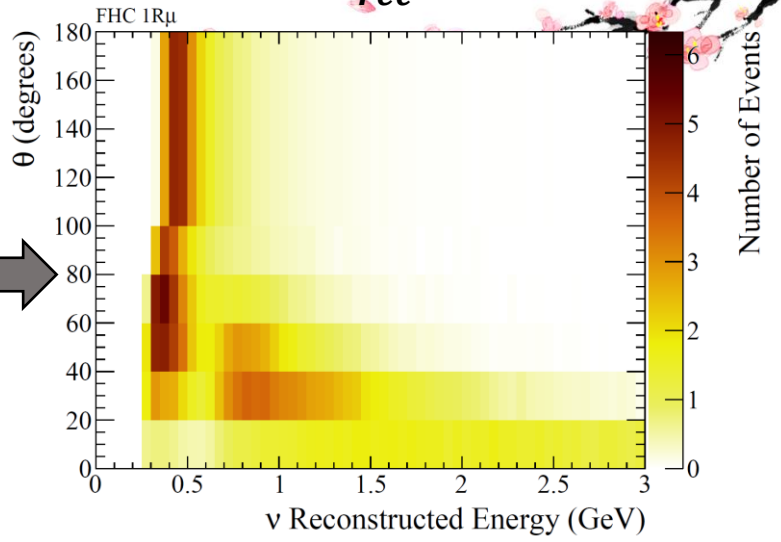


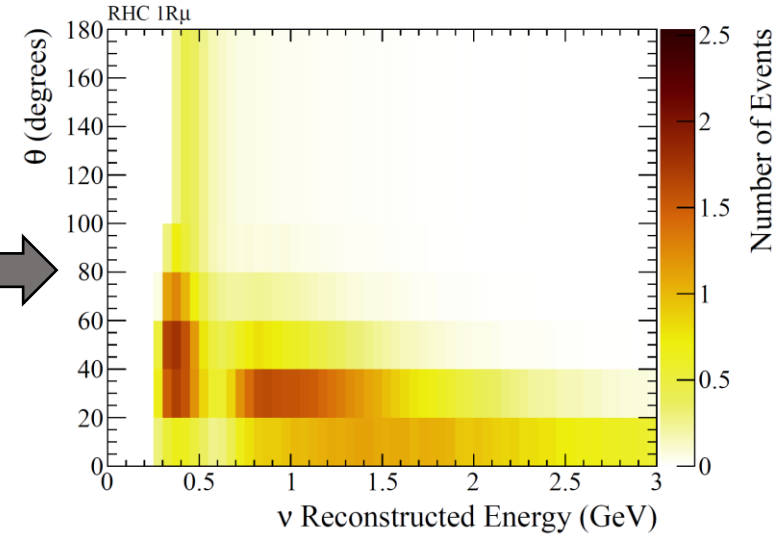
E_{rec}





E_{rec} − θ

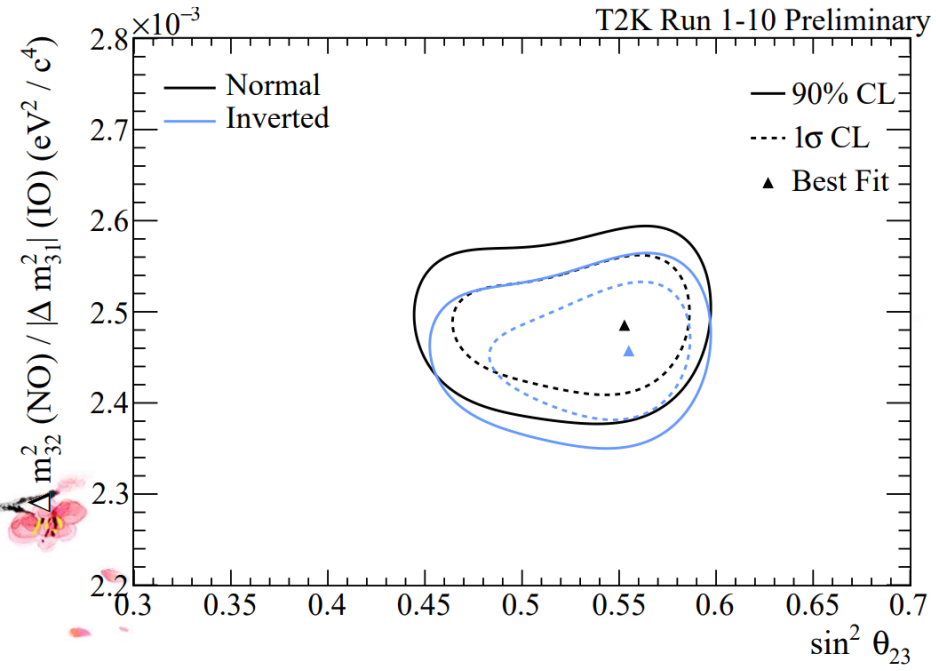


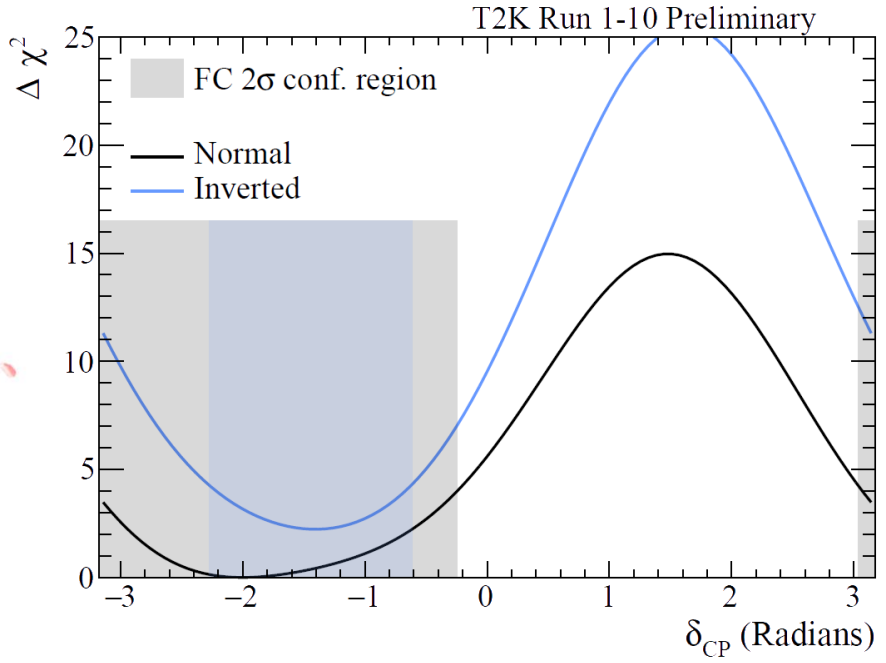


Speaking of constraints…

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).





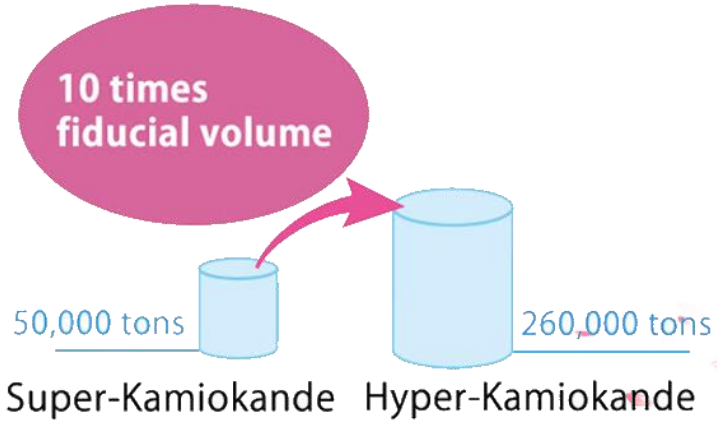
Analysis next steps:

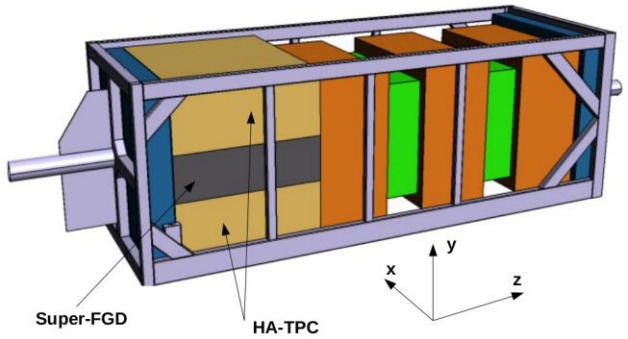
- Re-analysing the data with model/method updates.
- Analysis of the Run1-11 data, being taken (roughly) now!

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 (a separate branch of VALOR).

Merry April!



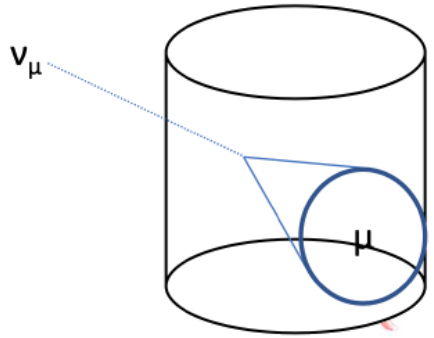


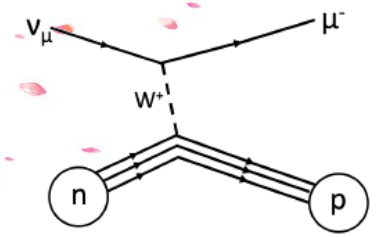
Acknowledgements: My comrades in code on the VALOR-T2K fitting framework, Francis Bench and Maria Antonova, as well as my co-collaborators in the OA group and beyond.

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

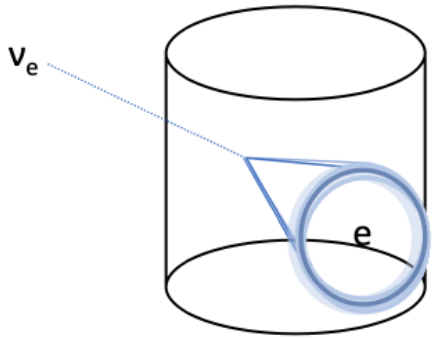
Sample	Predicted Oscillation Hypothesis				Observed
	No osc.	Asimov A	Asimov B	Asimov BF NO	
FHC μ-like sample	1571.4	345.5	361.8	354.0	318
FHC e-like sample	19.6	93.8	69.8	95.2	94
RHC μ-like sample	444.5	135.1	138.8	137.9	137
RHC e-like sample	6.3	15.9	16.4	16.9	16
FHC ν_e CC1π^+-like sample	2.9	8.8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

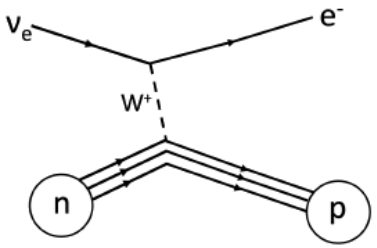
1-Ring ν_μ:



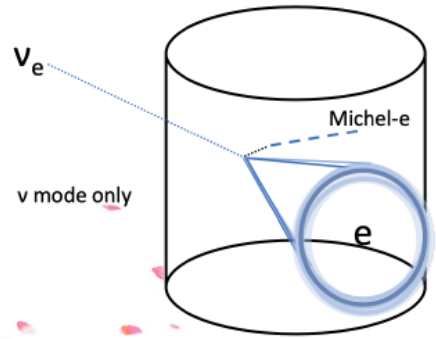


1 Ring ν_e:

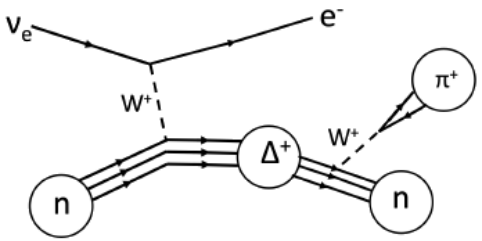




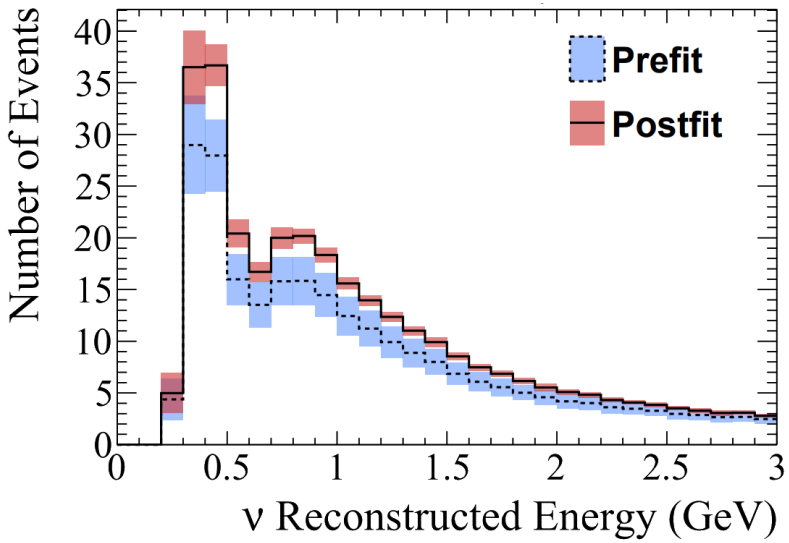
Multi-Ring ν_e:



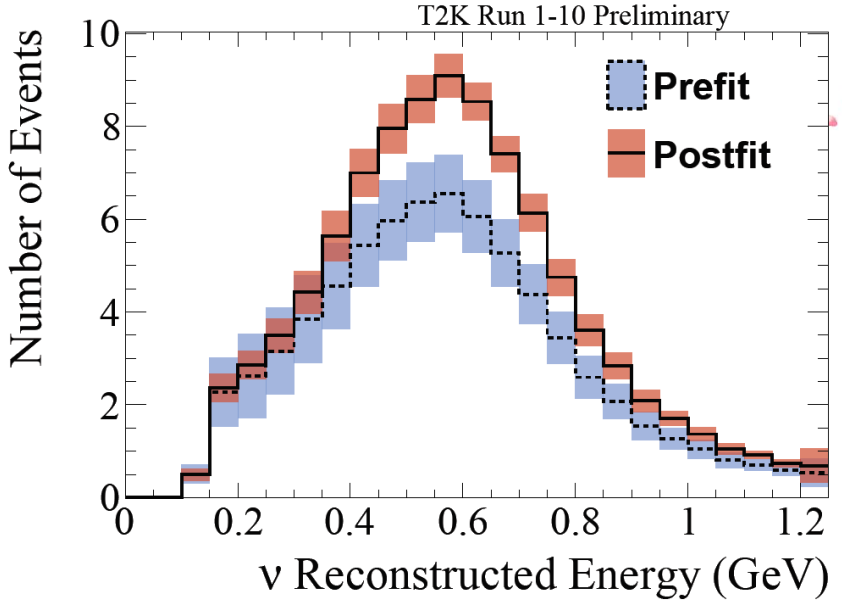
v mode only

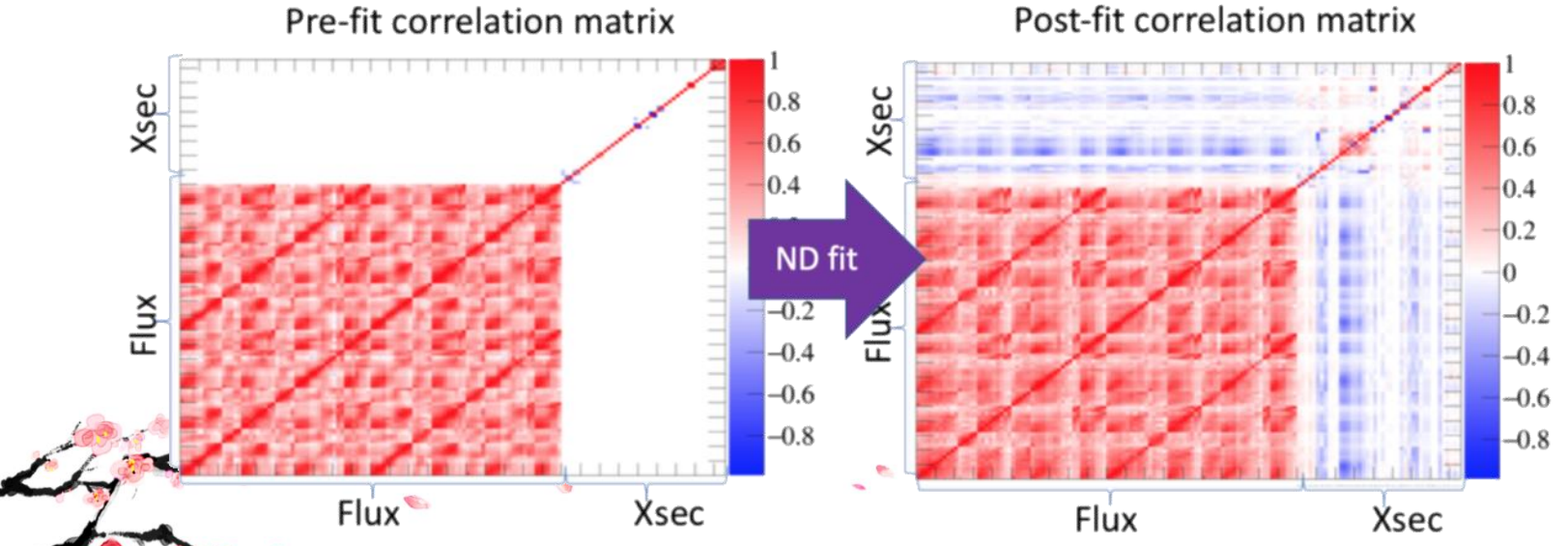


ν-mode ν_μ CCQE:



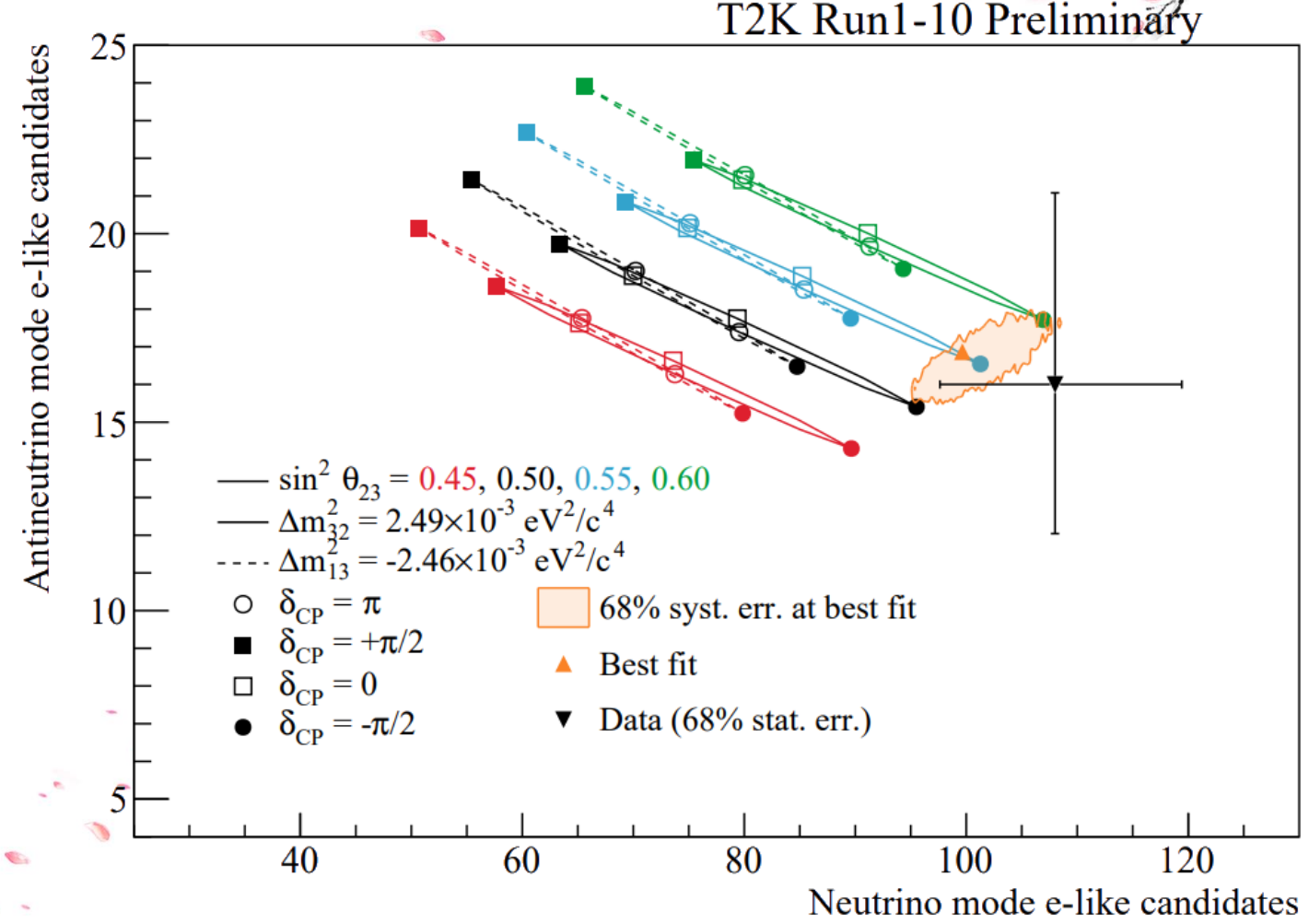
ν-mode ν_e CCQE:





- 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).

- 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) / $\lvert\Delta m^2_{31}\rvert$ (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	$[0.007, 0.053]$
$\lvert\Delta m^2_{32}\rvert$ (NO) / $\lvert\Delta m^2_{31}\rvert$ (IO)	101	$[2.2, 2.8] \times 10^{-3}$ eV^2/c^4
δ_{CP}	101	$[-\pi, \pi]$
$\sin^2\theta_{23}$, $\lvert\Delta m^2_{32}\rvert$ (NO) / $\lvert\Delta m^2_{31}\rvert$ (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	$[0.015, 0.036]$, $[-\pi, \pi]$