3-Flavour Neutrino Oscillations from the T2K Experiment

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On behalf of T2K

NuFact, ANL
Monday 16th September, 2024

What is T2K trying to measure?

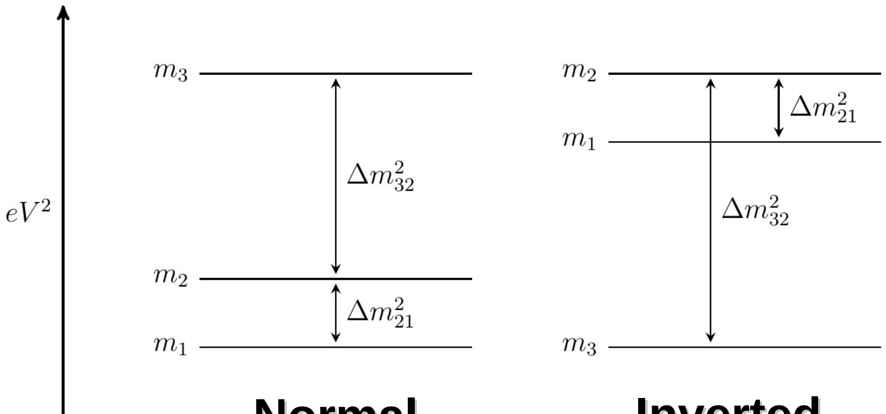
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12}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

T2K aims to measure the 6 parameters which describe neutrino oscillation probability

- Three mixing angle, $\boldsymbol{\theta_{23}, \theta_{13}, \theta_{12}}$
- Two mass splittings: $\boldsymbol{\Delta m^2_{32}, \Delta m^2_{13}}$
- Complex-phase $\boldsymbol{\delta_{CP}}$

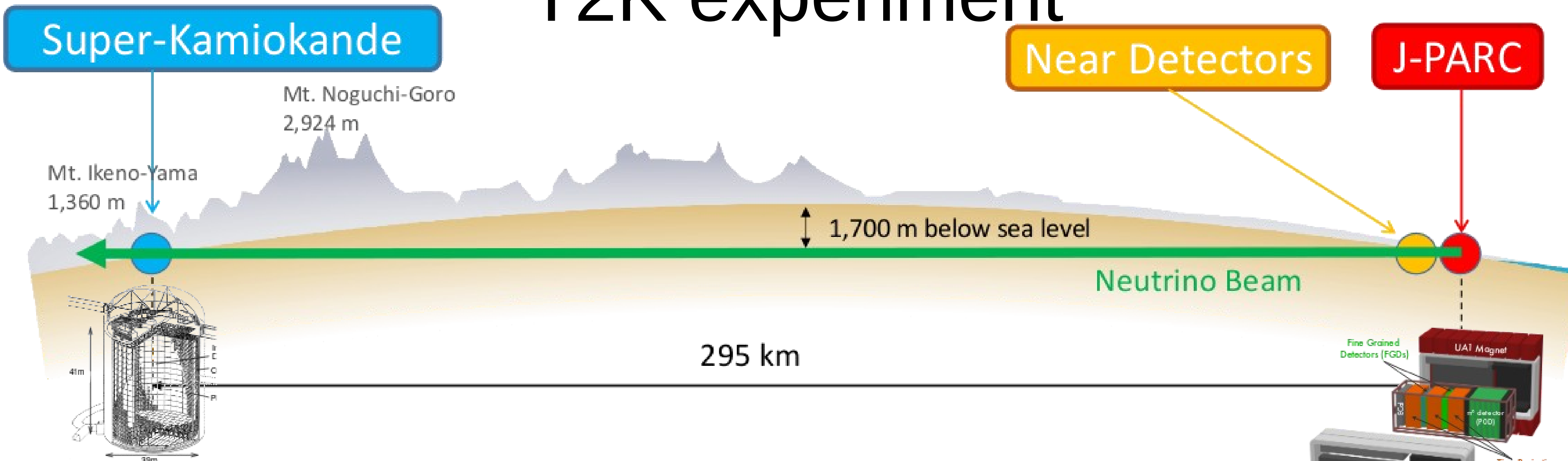
Key questions to answer:

- **Discovery of CP violation (δ_{CP} not 0 or π)**
- **Determination of mass ordering ($\Delta m^2_{32} > 0$?)**
- **Octant of θ_{23} ($\sin^2\theta_{23} > 0.5$?)**
- **Precise measurements of $\delta_{CP}, \theta_{23}, \Delta m^2_{32}$**



Normal Ordering (NO / NH) **Inverted Ordering (IO / IH)**

T2K experiment



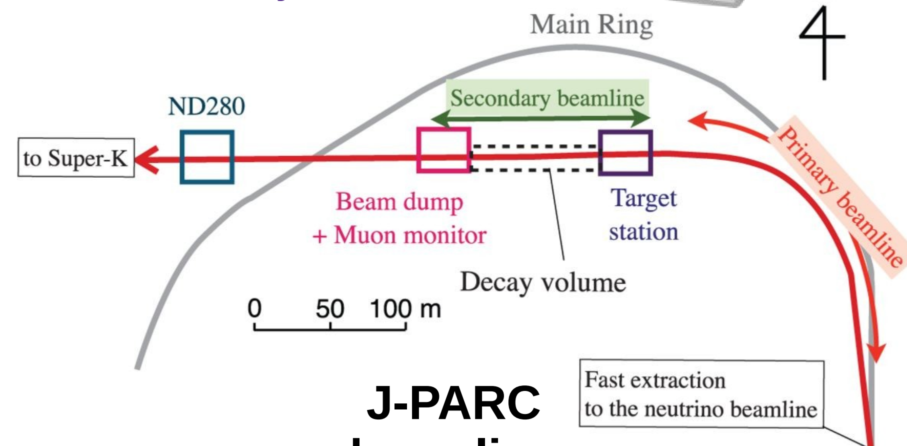
See Tristan Doyle's talk on Friday!

~750 kW neutrino beam produced at J-PARC

- Proton beam collides with graphite target
- Charged mesons are focused by magnetic horns
- Mesons decay to produce (anti-)neutrino beam

Near detectors on the east coast of Japan

Far detector Super-Kamiokande on the west coast



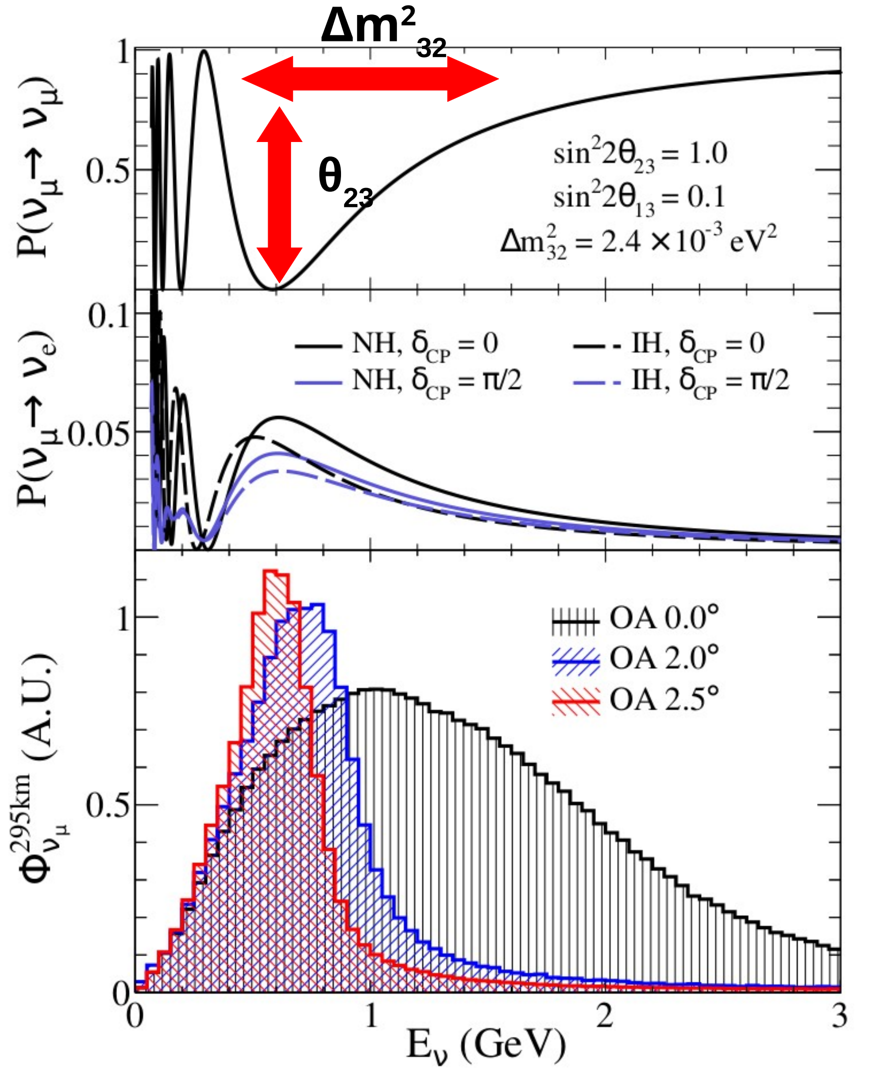
J-PARC beamline

Neutrino Oscillations at T2K

- Measure neutrino oscillation using **muon neutrino and anti-neutrino beams**
- ND280 and Super-K are both placed 2.5° away from neutrino beam axis

- Muon (anti-)neutrino **disappearance**:
  - **Location** of dip determined by **Δm^2_{32}**
  - **Depth** of dip determined by **$\sin^2 2\theta_{23}$**

- Electron (anti-)neutrino **appearance**:
  - Leading terms depend on $\sin^2\theta_{13}$, Δm^2_{32} and $\sin^2\theta_{23}$
  - Dependence on $\boldsymbol{\delta_{CP}}$
    - If $\delta_{CP} = \pi/2$ **fewer neutrinos** than anti-neutrinos
    - If $\delta_{CP} = -\pi/2$ **more neutrinos** than anti-neutrinos
  - Important to study both neutrinos and anti-neutrinos to measure $\boldsymbol{\delta_{CP}}$



T2K

IMPERIAL

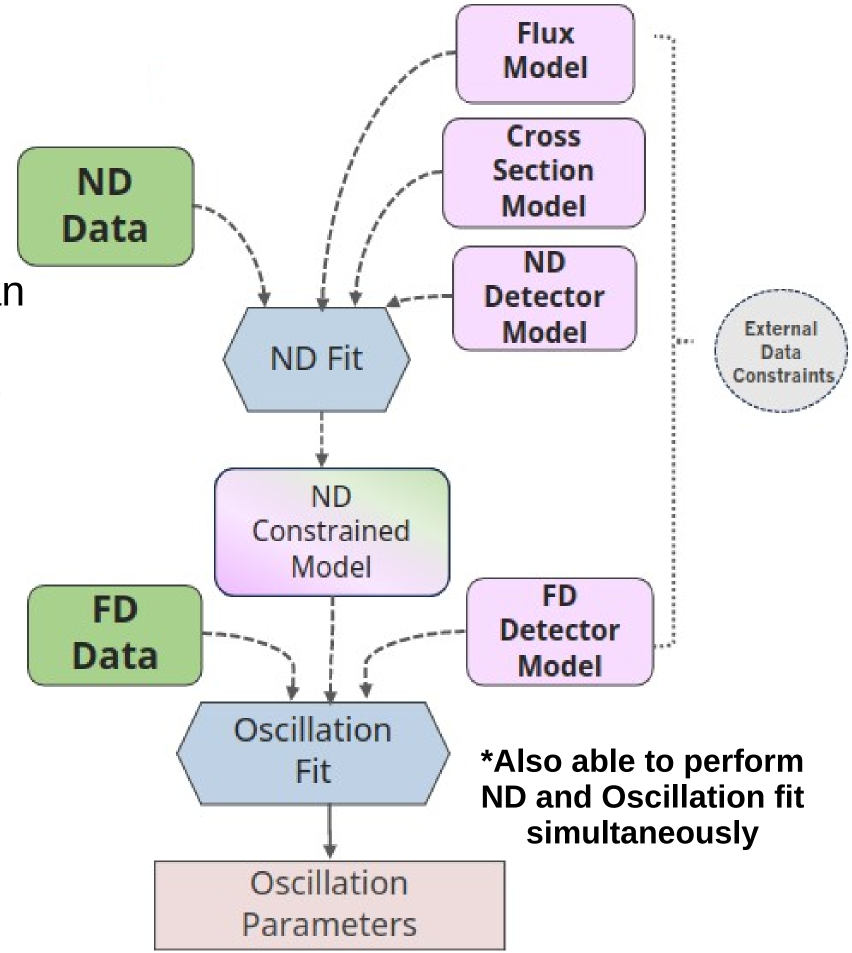
T2K Analysis Strategy

Develop model from external data, calibration and experimental data.

High-stats **ND constrains systematic parameters** before oscillations. S**ignificantly reduces uncertainty at SK.**

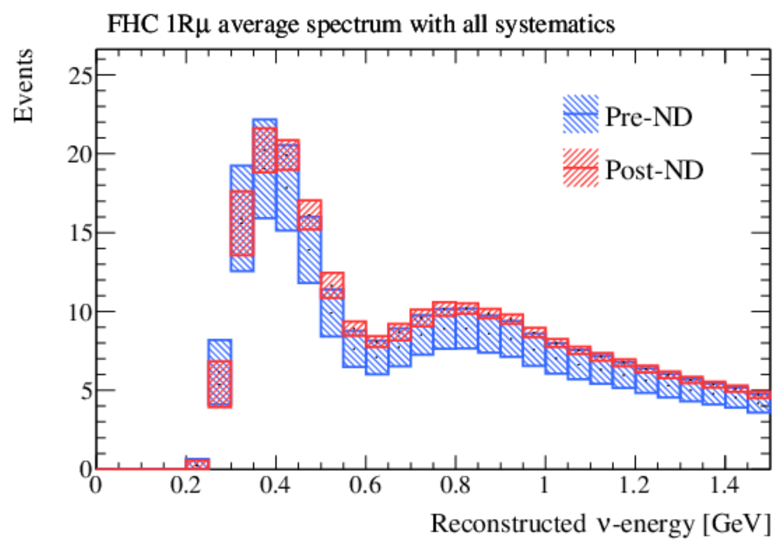
Two different Far Detector analyses:

- **Hybrid-Frequentist:** use post-ND fit constraint to throw marginalisation toys, fit oscillation parameters and use Feldman Cousins to construct intervals
- **Bayesian:** jointly fit ND and SK using MCMC to build posterior distributions of all parameters



***Also able to perform ND and Oscillation fit simultaneously**

See Ewan Miller's talk on T2K ND analysis!



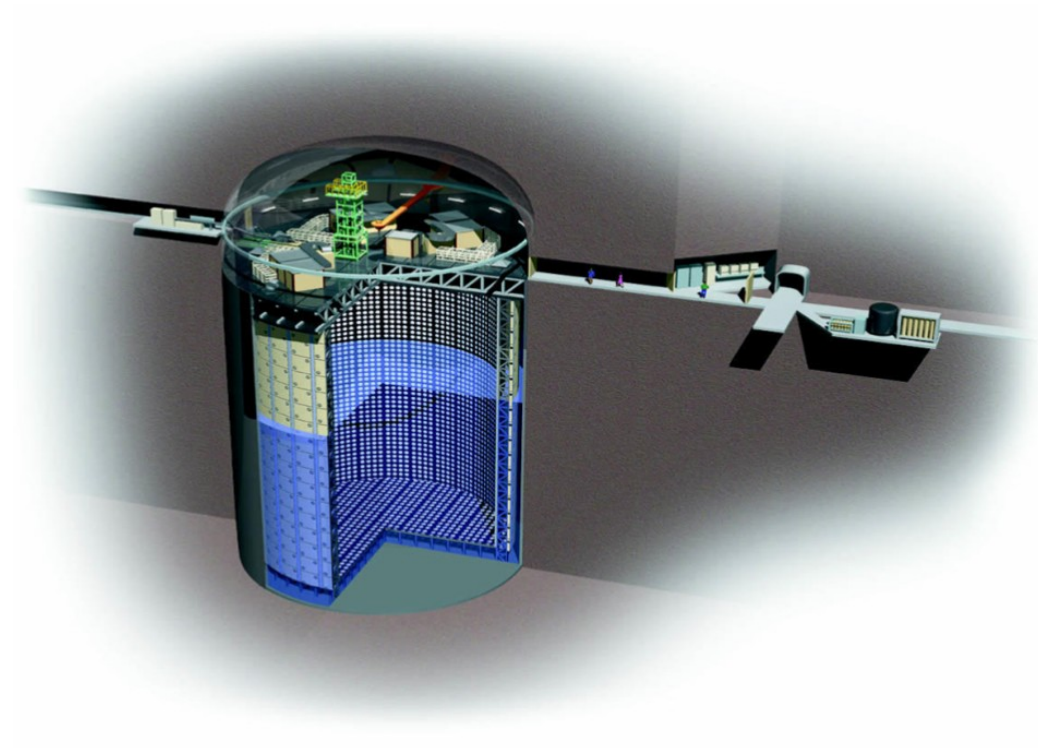
Super-Kamiokande

50 kt water-Cherenkov detector

Split into two regions:

- Outer detector – rejects background events
- Inner detector – events selected for use in analyses

Instrumented with **PMTs**



As of 2021 Super-K has Gd-doping

- Gd used for neutron capture
- Initially 0.01% Gd-doped
- Now 0.03% Gd-doped
- Primarily for relic neutrino search
- Potential to add neutron tagging for T2K samples in the future!

SK Data samples

- Selections based on Cherenkov ring PID
  - **Muon-like:** sharp ring
  - **Electron-like:** “fuzzy” ring
- Number of **decay electrons** and number **Cherenkov rings**
- Energy Reconstruction uses lepton kinematics:

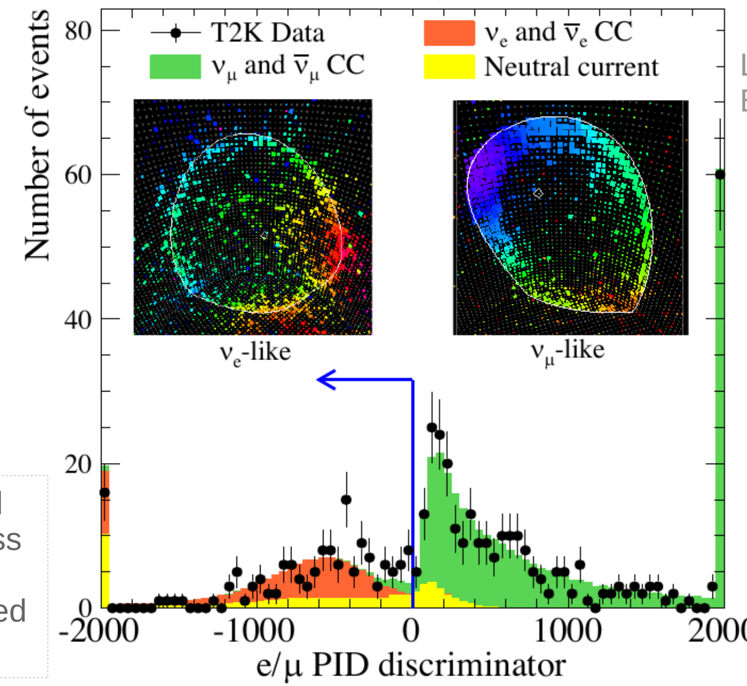
$$E_{reco} = \frac{m_p^2 - m_n^2 - m_l^2 + 2m_n E_l}{2\,(m_n - E_l + p_l \cos\theta_{\nu l})}$$

*nucleon mass replaced with delta resonance mass for CC1pi samples
**nuclear effects accounted for systematic model

- **Muon-like samples**
  - Disappearance channel ($\nu_\mu \rightarrow \nu_\mu$)
  - Most sensitive to $\sin^2 2\theta_{23}$, $|\Delta m^2_{32}|$
- **Electron-like samples**
  - Most sensitive to appearance channel ($\nu_\mu \rightarrow \nu_e$)
  - Most sensitive to $\sin^2\theta_{23}$, δ_{CP}, $\sin^2\theta_{13}$ and sign of Δm^2_{32}

Study samples in both neutrino mode (FHC) and anti-neutrino mode (RHC) operations

Adapted from arXiv:1910.03887v2



Lukas Berns

Selection	Run 1-11 POT	Events in Data
FHC 1Rμ	21.428×10^{20}	357
FHC ν_μCC1π		140
FHC 1Re		102
FHC 1Re1d.e		15
RHC 1Rμ	16.34556×10^{20}	137
RHC 1Re		16

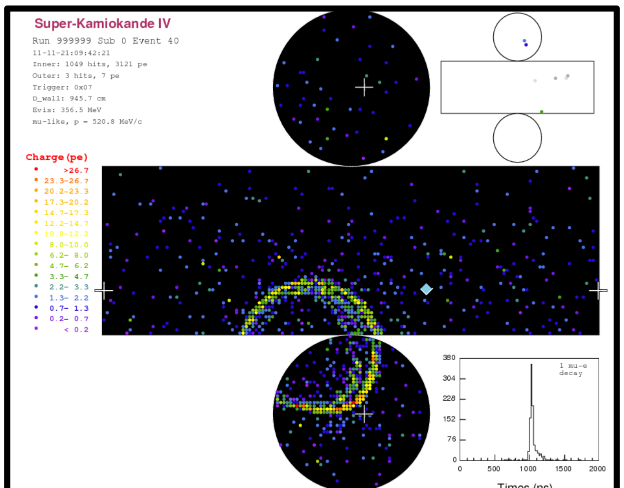
SK Data samples: muon-like

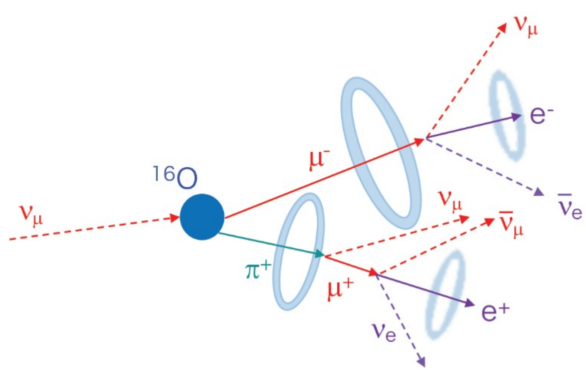
Neutrino & Anti-neutrino mode 1Rmu:

- 1 muon-like ring
- 0 or 1 decay electron
- Predominantly CCQE interactions

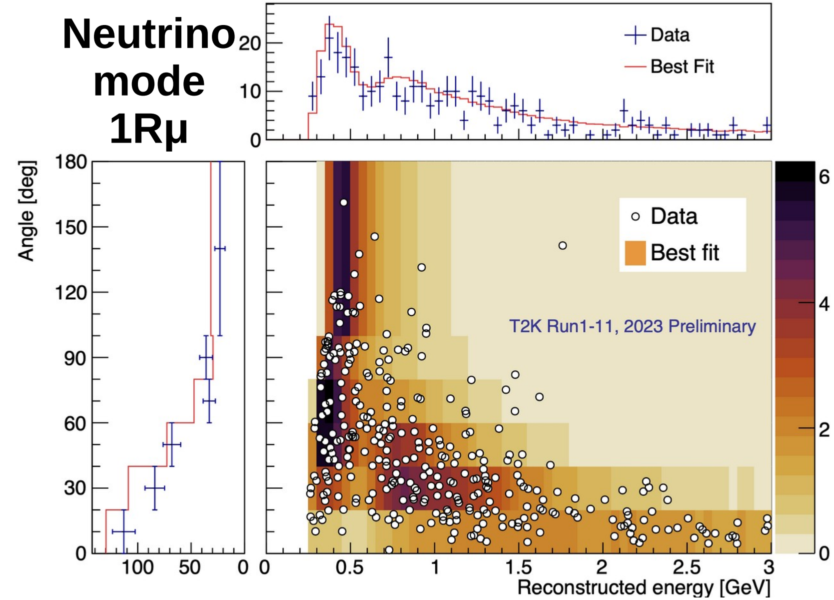
Neutrino-mode ν_μCC1π:

- Targeting ν_μCC1π interactions
- Higher energy sample, less sensitive to oscillations
- 1 Cherenkov ring and 2 decay electrons
- 2 Cherenkov rings and 1 decay electron

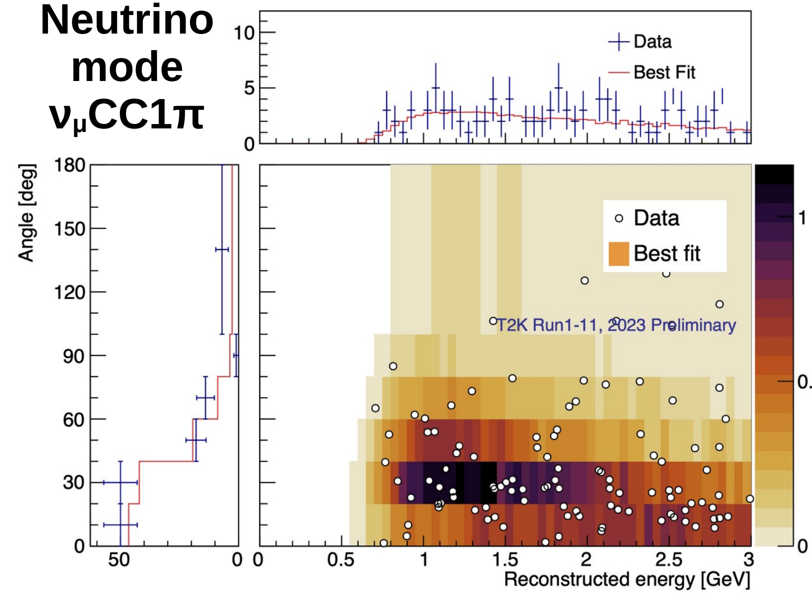




Neutrino mode 1Rμ



Neutrino mode ν_μCC1π



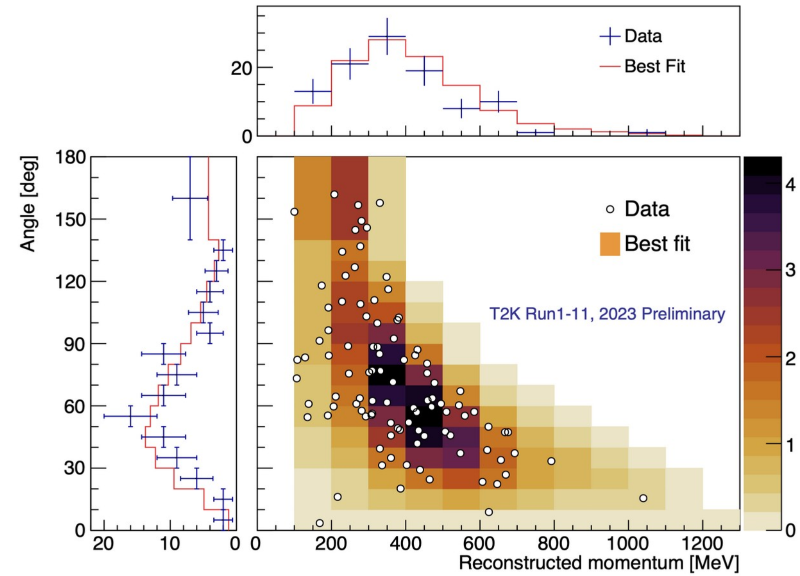
SK Data samples: electron-like

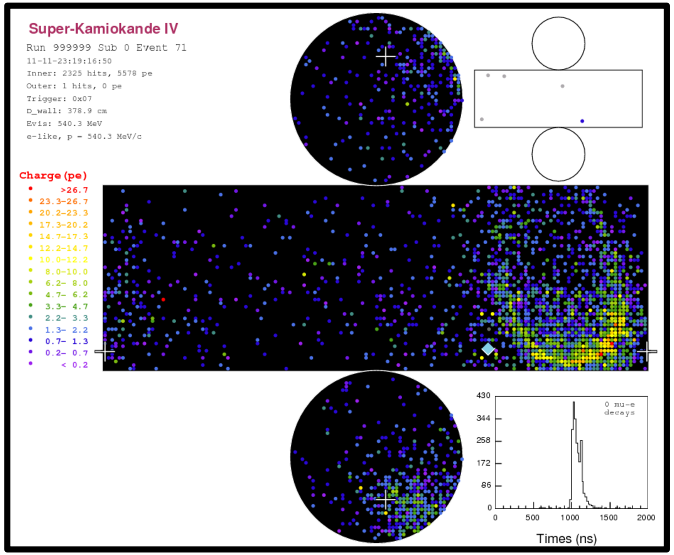
Neutrino & Antineutrino mode 1Re:

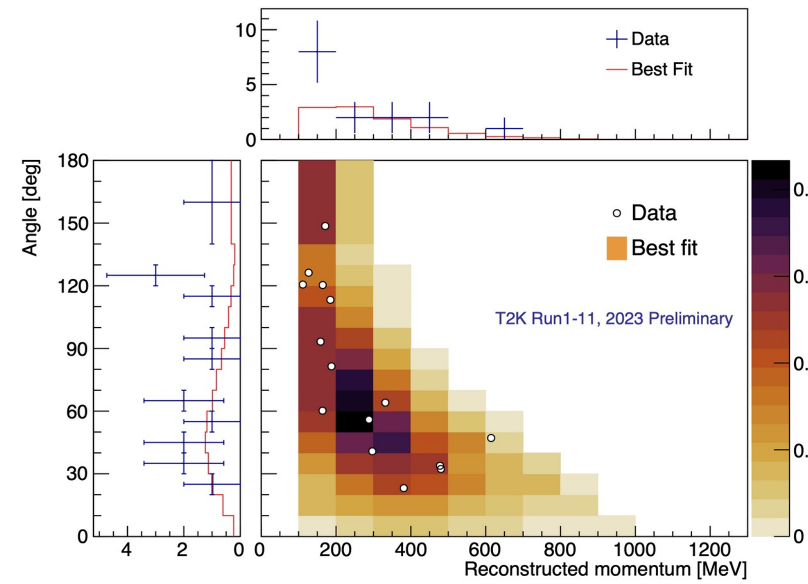
- 1 reconstructed e-like ring
- 0 decay electrons i.e. no pions
- Predominantly CCQE interactions

Neutrino mode 1Re1de:

- Targeting ν_eCC1π interactions
- 1 e-like ring
- 1 decay electron i.e. 1 pion below threshold



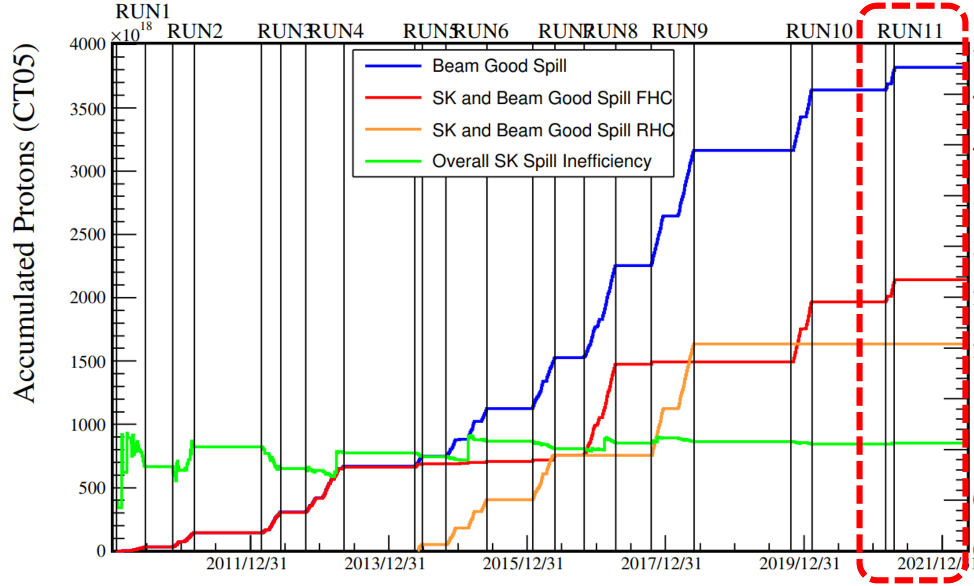




Improvements to the analysis: more data!

- Latest results include several updates and improvements to the analysis.

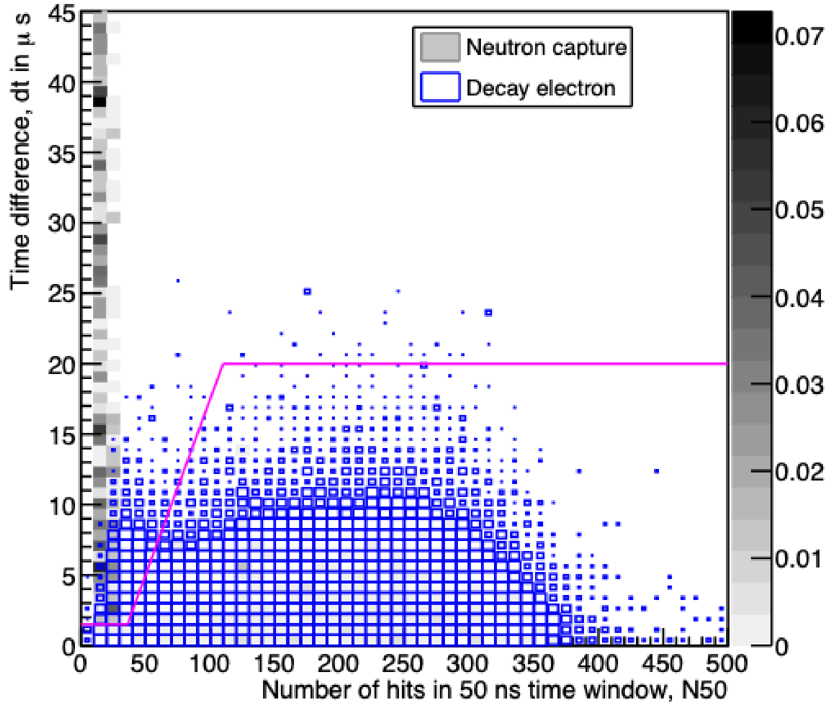
- Previous analysis included data collected up until 2020.
- Now include "Run 11" collected in December 2021
- **Increase of FHC POT by ~9%**
- RHC POT the same as previous analysis
- Expect increase in sensitivity due to increased data statistics.



<table>
<tr><th>SK sample</th><th>Additional POT</th><th>Total POT</th><th>Additional data</th><th>Total Data</th></tr>
<tr><td>FHC 1Rmu</td><td rowspan="4">1.79×10^{20}</td><td rowspan="4">21.43×10^{20}</td><td>39</td><td>357</td></tr>
<tr><td>FHC numuCC1pi</td><td>5</td><td>140</td></tr>
<tr><td>FHC 1Re</td><td>8</td><td>102</td></tr>
<tr><td>FHC 1Re1de</td><td>1</td><td>15</td></tr>
<tr><td>RHC 1Rmu</td><td rowspan="2">0</td><td rowspan="2">16.35×10^{20}</td><td rowspan="2">0</td><td>137</td></tr>
<tr><td>RHC 1Re</td><td>16</td></tr>
</table>

Improvements to the analysis: new decay electron cut

- First data collected with 0.01% Gd-doping at SK
- Gd neutron capture causes delayed signal which could be mistaken for decay electron
- New cut **removes neutron capture background**: function of number of PMT hits in 50ns after vertex time and time difference but main ring event and secondary event
- Also applied to all pure water runs (where Hydrogen neutron capture has tiny affect)



Samples	Run 11 (0.01% Gd)		
	Old cut	New cut	Δ
FHC1Re	5	7	40%
RHC 1Re	-		
FHC 1Re1de	2	1	50%
FHC 1Rμ	35	35	0
RHC 1Rμ	-		
ν_μCC1π	5	5	
	6	4	-33%

Improvements to the analysis: SK detector errors

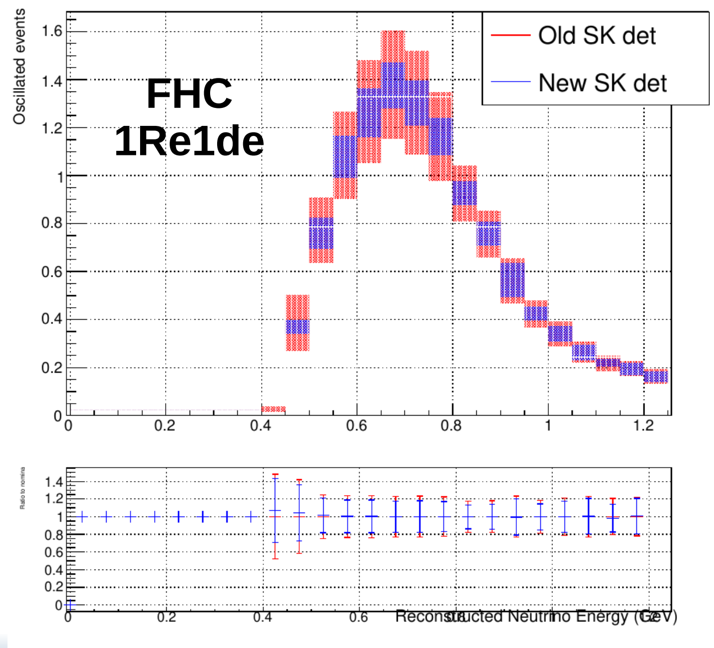
SK detector uncertainties constrained using a fit to atmospheric data

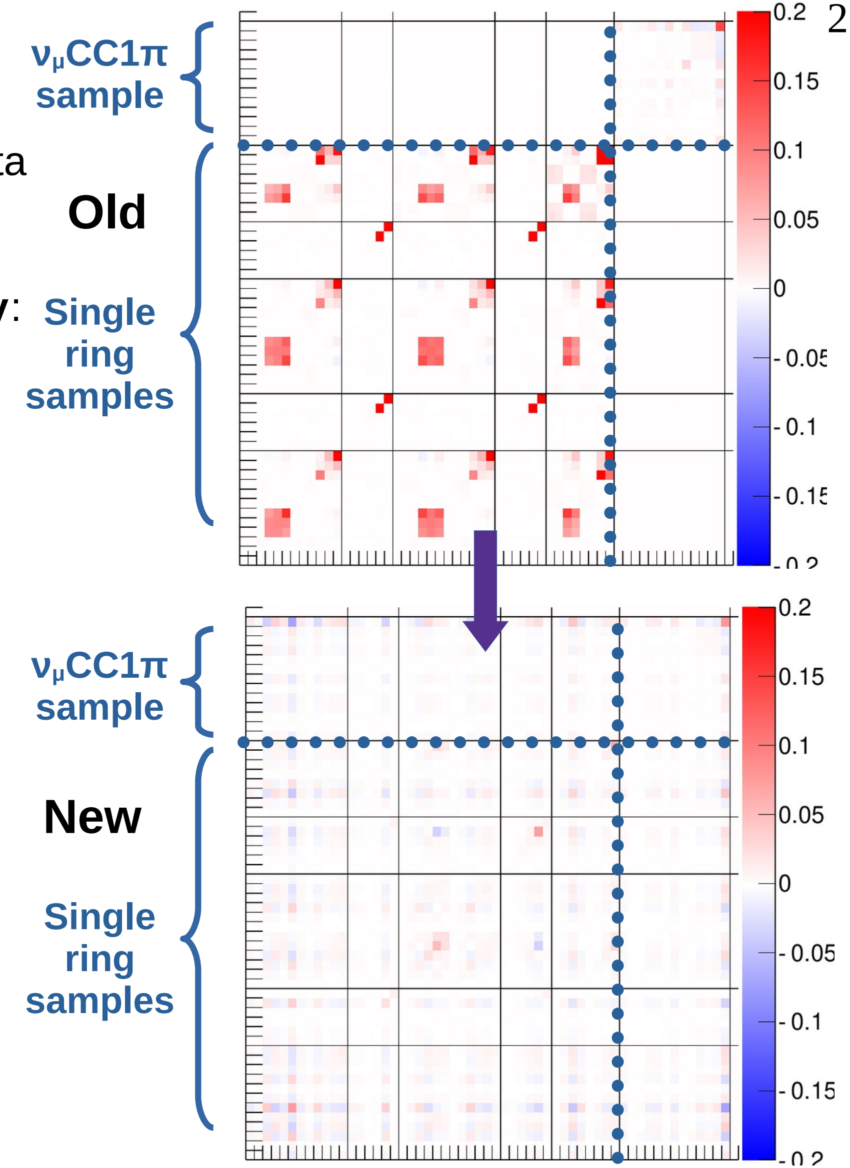
- **See Michael Reh's talk!**

Improvements to procedure have **reduced the overall uncertainty**:

- Correlations between single-ring and $\nu_\mu CC1\pi$ samples
- Uses visible energy information in fit to data
- Removed some external errors, now constrained in the fit

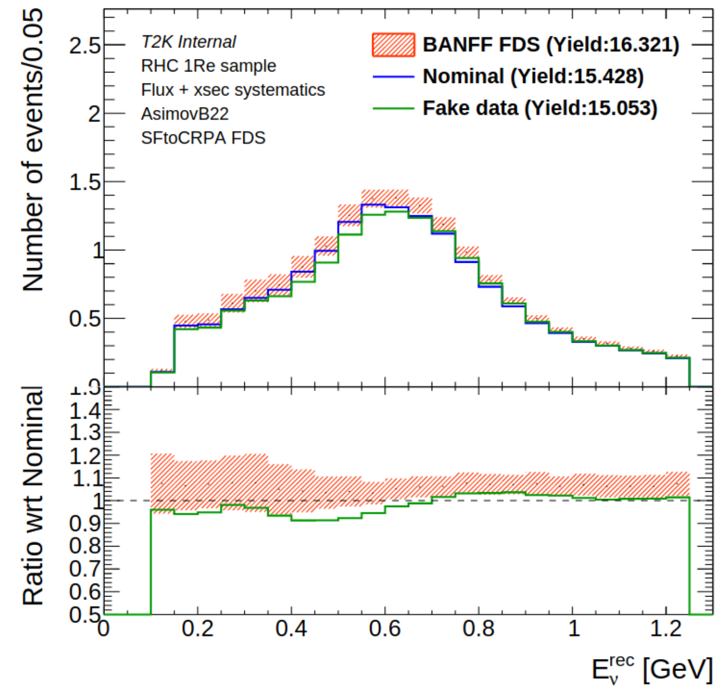
Reduces uncertainty on predictions at SK





Studying Alternate Models

- Test current systematic model by studying **robustness** against **alternate neutrino interaction models**
  - **Generate mock data** by changing MC simulation to use alternate model
  - Fit these mock data at Near and Far detectors
  - Check impact of alternate model on our results
  - Pre-decided thresholds for bias:
    - **"Size": Change in the width** of 1D 2σ intervals should be no larger than **10%**
    - **"Syst": Change in central value** should be no larger than **50% of systematic uncertainty**
  - **Example**: suppression in single pion channel seen in the MINERvA results
  - **New study for this analysis:**
    - Low-momentum enhancement for 1Re1de sample
    - Slight change to δ_{CP} interval such that 0 is now included in 90% interval **[-3.156, -0.202]**

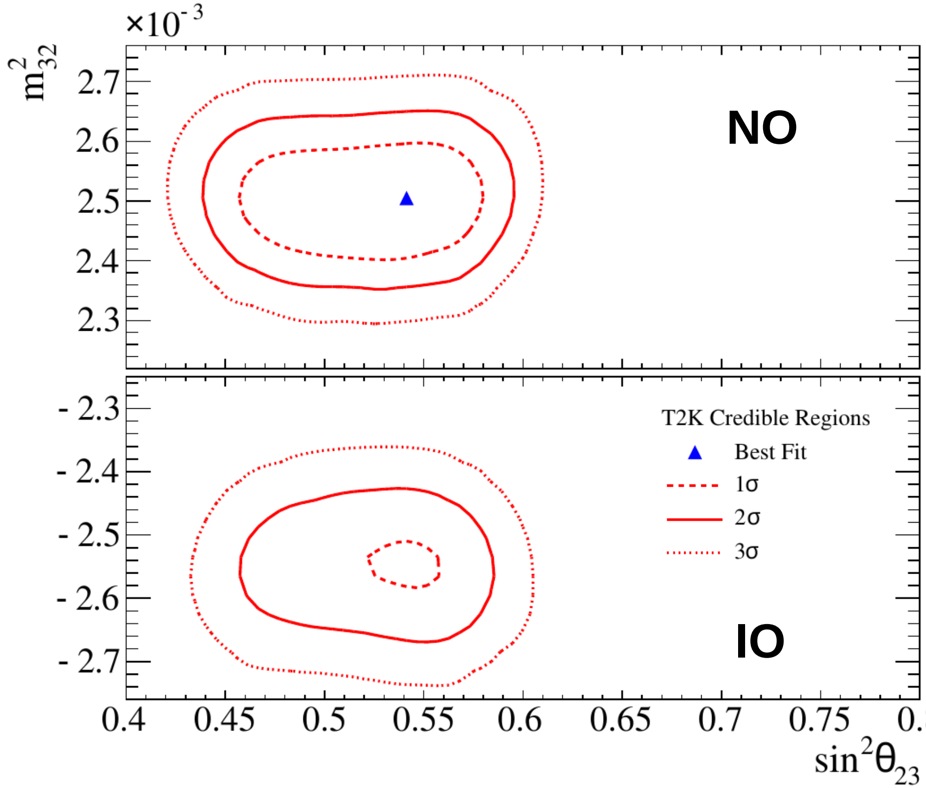


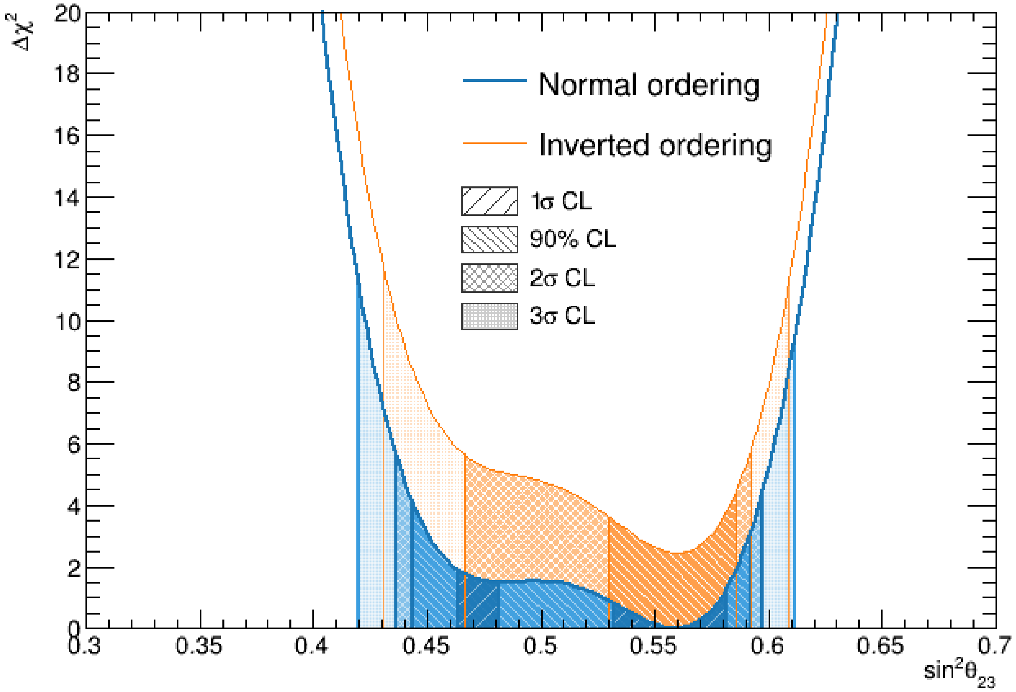
Simulated data set	Relative to	$\sin\theta_{23}$	Δm^2_{32}	δ_{CP}
HF CRPA	Total	−11.7%	33.8%	−2.8%
	Syst.	−25.1%	84.9%	−11.2%
	Size	2.0%	−5.4%	1.0%
Martini 1π	Total	−1.5%	−7.3%	−0.4%
	Syst.	−3.2%	−18.5%	−1.7%
	Size	−0.2%	−1.0%	2.0%
Non-CCQE	Total	4.9%	−30.0%	−0.1%
	Syst.	10.4%	−76.3%	−0.5%
	Size	3.0%	−1.0%	−3.0%
SPP Low-Q^2 suppression	Total	6.5%	7.4%	−1.5%
	Syst.	14.1%	18.6%	−6.11%
	Size	2.0%	−1.6%	−2.2%

ν_μ disappearance results

Results shown here are **using the PDG reactor constraint**.

- Best-fit prefers **non-maximal $\sin^2\theta_{23}$**
- **Slight preference for normal ordering and upper octant**



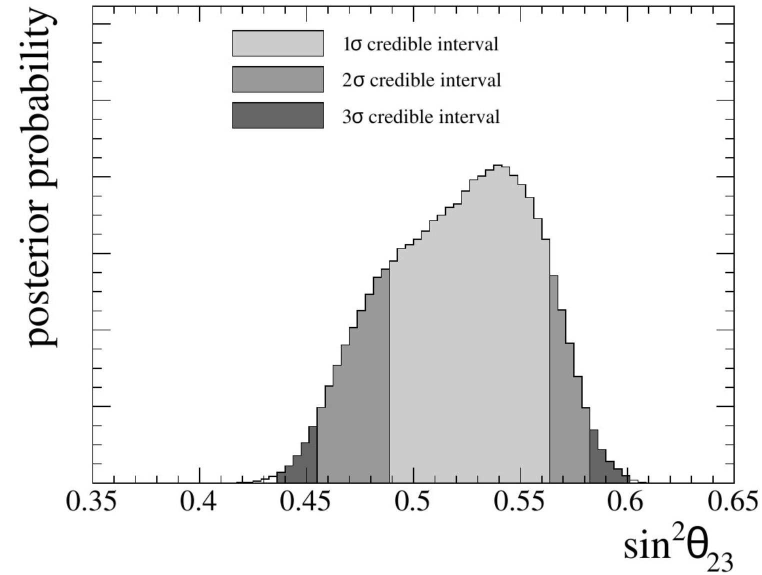


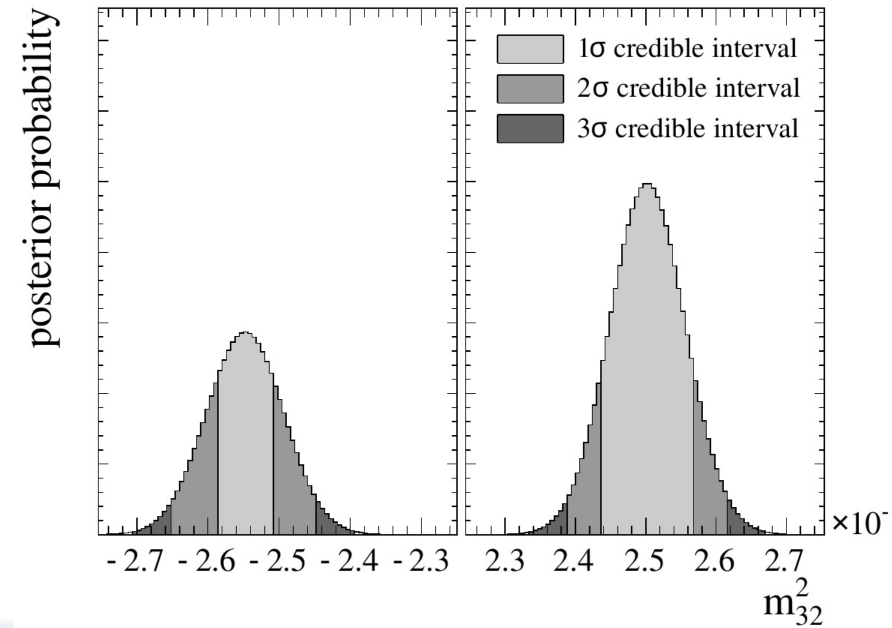
Mass Ordering and Octant

- Can report Bayes Factors for discrete hypotheses
  - Ratio of probability in different hypotheses

	No Reactor Constraint	**PDG** Reactor Constraint
Mass Ordering	**1.7** **63% :** 37% (**NO :** IO)	**2.3** **77%** : 33% (**NO :** IO)
Octant	**1.3** **57% :** 43% (**UO** : LO)	**2.6** 72% : 28% (**UO** : LO)

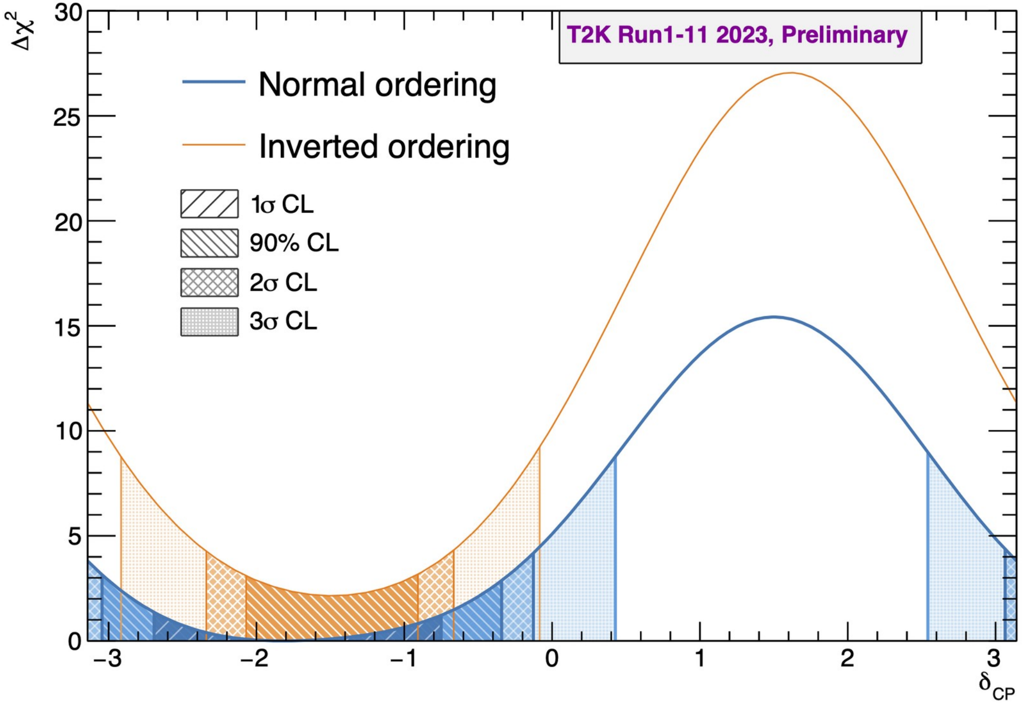
- **No conclusive statements** about preferred octant or mass ordering

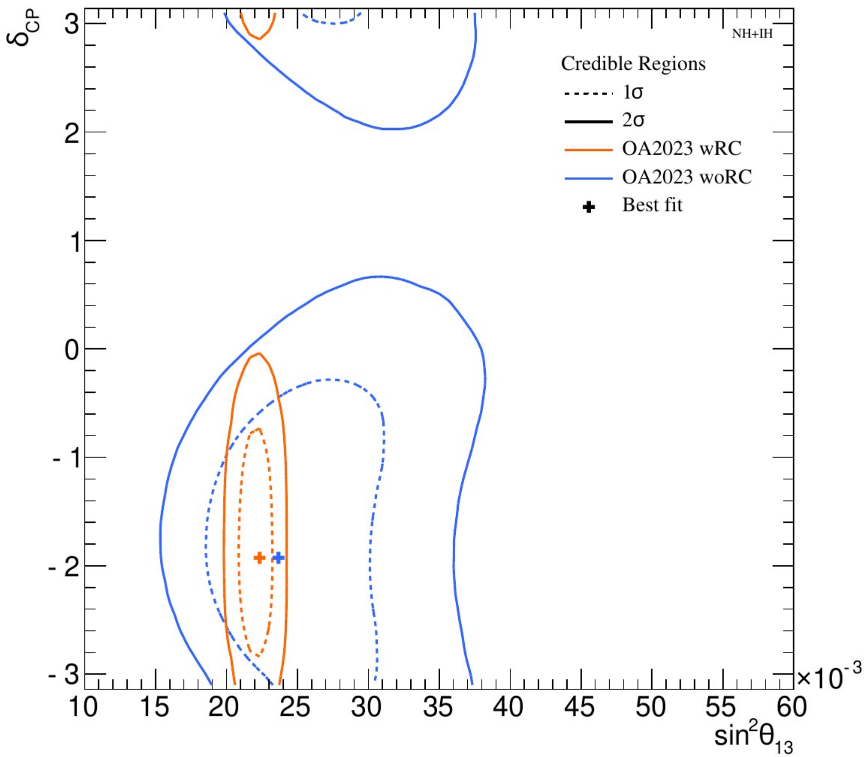




ν_e appearance results

- **T2K prefers value of $\delta_{CP} \approx -\pi/2$**
- **Disfavour** CP conserving values of 0 and π disfavoured in both orderings





- T2K-only measurement of θ_{13} compatible with PDG average.

Jarlskog Invariant

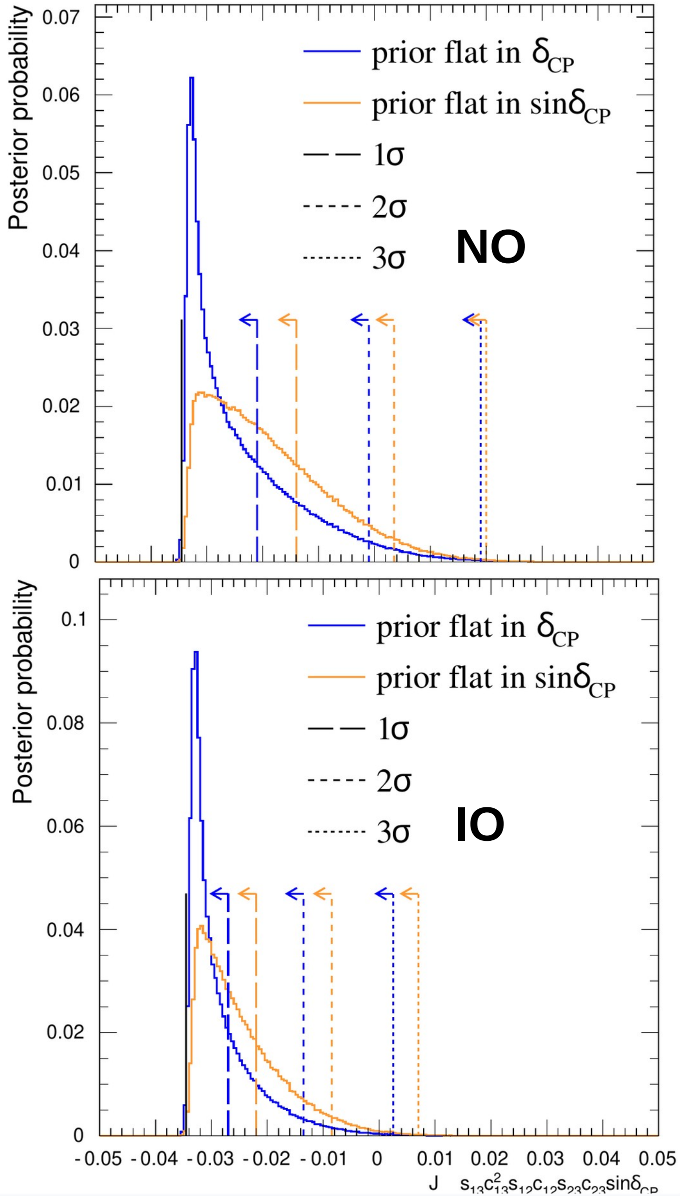
- Jarlskog Invariant measures CP-violation in a parameterisation independent way.
- Used for both Quark and Lepton mixing matrices:

$$J = s_{13}\, c_{13}^2\, s_{12}\, c_{12}\, s_{23}\, c_{23}\, s_{\delta_{CP}}$$

Where $s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$, $s_{\delta CP}=\sin\delta_{CP}$

J=0: CP conservation, J≠0: CP violation

- For both NO and IO see preference for J≠0
  - J = 0 not included in 2σ interval for IO
- Investigate impact of choice of prior on $\sin\delta_{CP}$
  - Doesn't dramatically change conclusion



T2K IMPERIAL

Future plans and joint-fits

New Upgraded Near Detector!

- Replaced section of detector with scintillator cubes sandwiched between two TPCs
- Will enable 3D reconstruction of events
- Lower proton and pion momentum thresholds
- Enable better understanding of neutrino interactions and reduce systematic uncertainties in oscillation analysis!

320kA horn-current

- Magnetic horn current increased from 280kA to 320kA
- Reduces “wrong-sign” component so produces a higher purity (anti-)muon beam

More data!

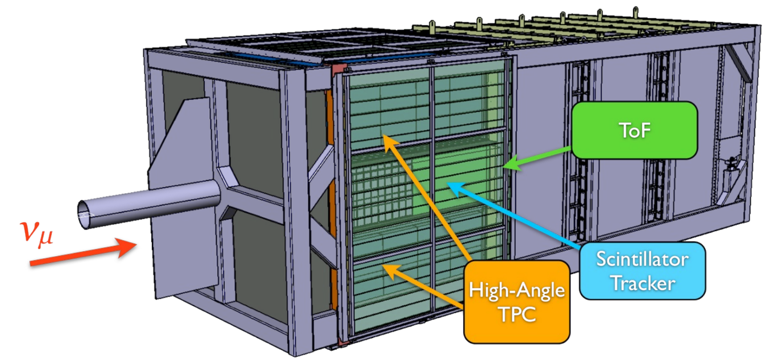
- Continue to collect data with high power ~750kW neutrino beam over the coming years!

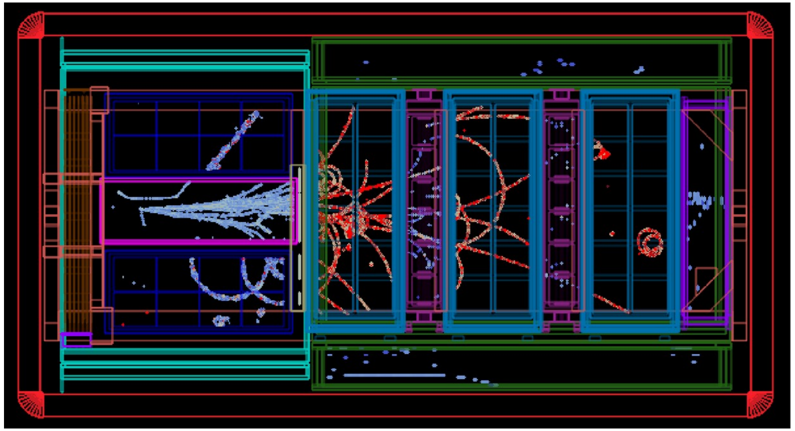
Joint Analysis with Super-K Atmospherics:

- **See Tristan Doyle’s talk!**

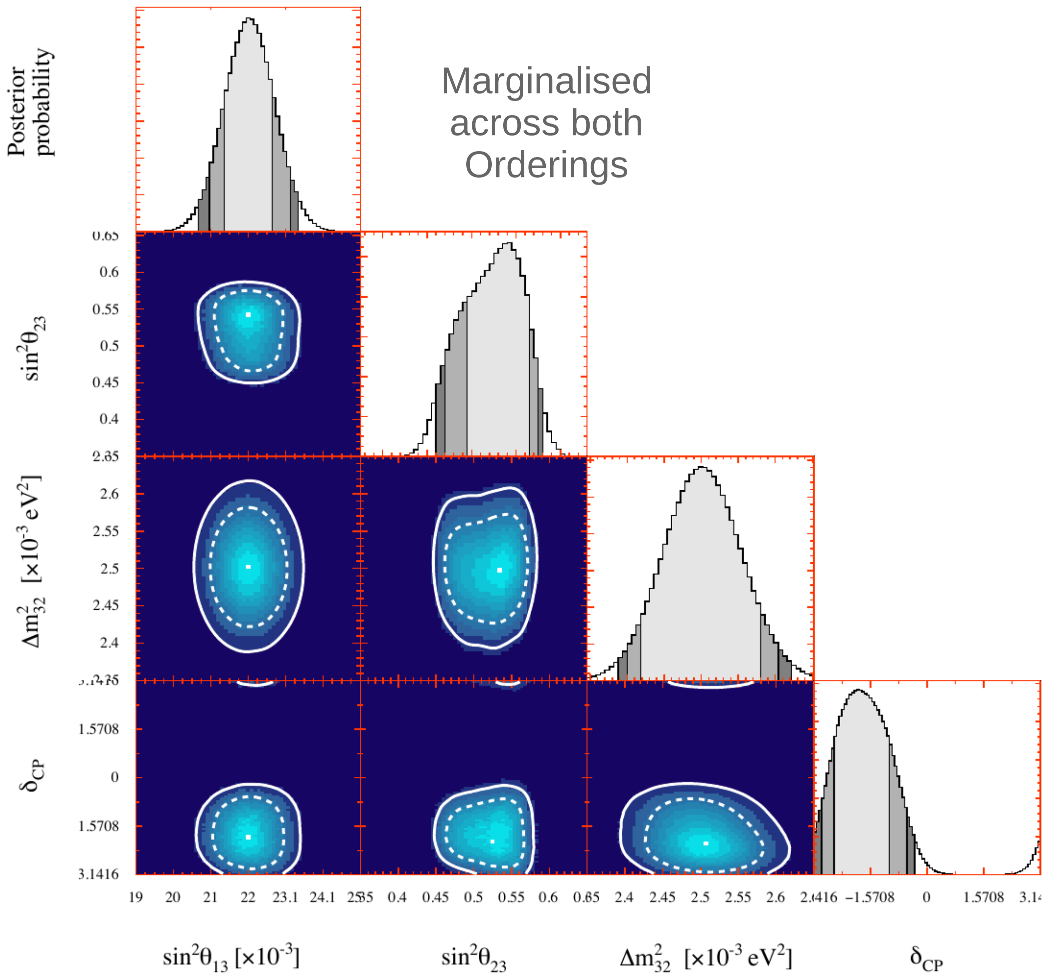
Joint Analysis with NOvA:

- **See Ryan Patterson’s talk!**





Summary



- The T2K experiment has made world-leading measurements of neutrino oscillation parameters
  - T2K favours $\delta_{CP} = -\pi / 2$, disfavours 0 and π
  - Slight preference for Normal Ordering and Upper Octant of $\sin^2\theta_{23}$
- T2K will continue taking data and has many new analyses to come!
- Near Detector Upgrade now taking data and will enable better understanding of neutrino interactions!

Thanks for listening!

BACKUPS

Neutrino Oscillations

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

Neutrino mass eigenstates mix with neutrino flavour eigenstates.
This mixing is described by the PMNS matrix a 3x3 Unitary matrix.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Two flavour approximation*

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

Mixing results in Neutrino Oscillations: probability of changing flavour depends on:

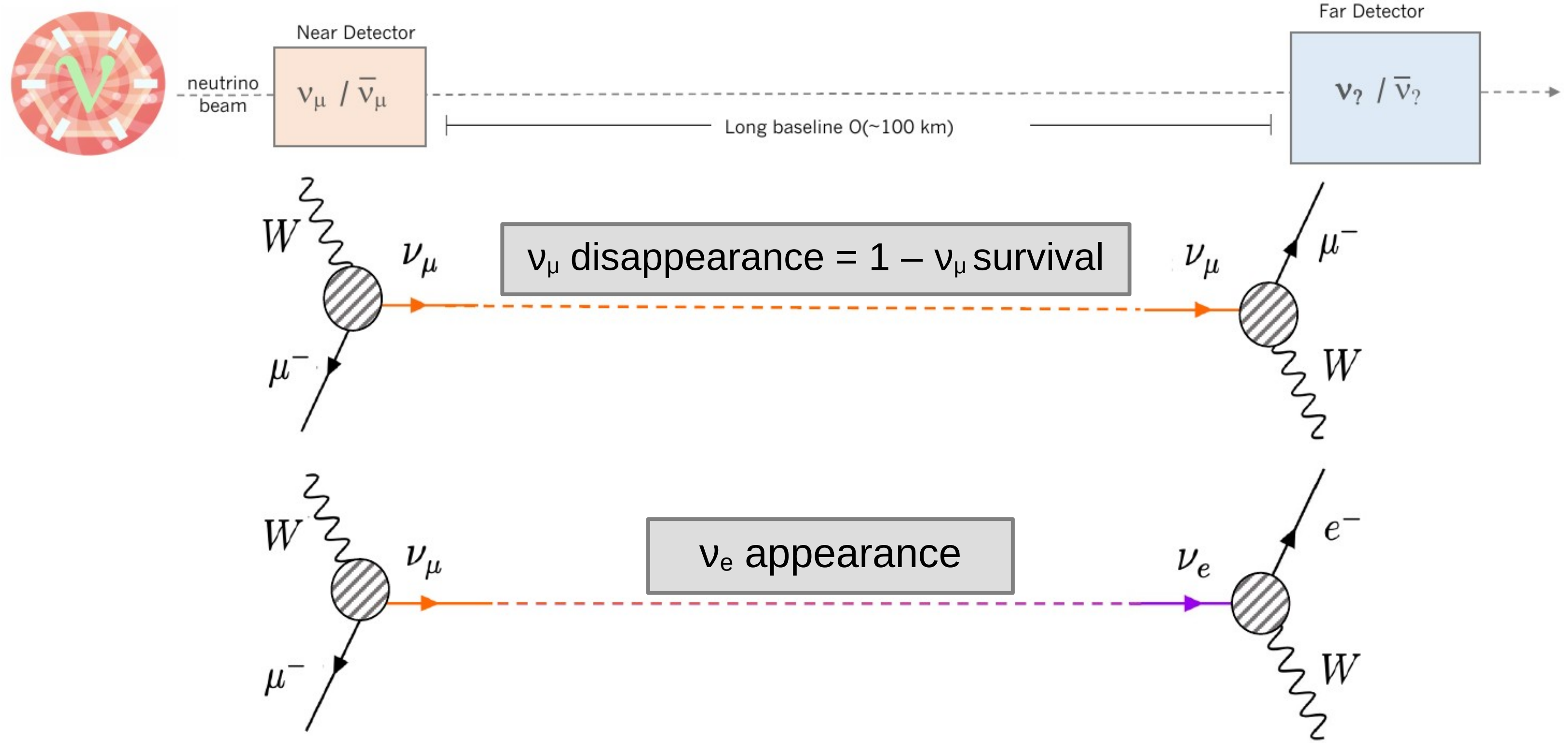
- ➔ Values of the mixing parameters: $\boldsymbol{\delta_{CP}, \theta_{12}, \theta_{13}, \theta_{23}}$
- ➔ Difference in the squares of the neutrino masses: $\boldsymbol{\Delta m^2_{ij} = m^2_i - m^2_j}$
- ➔ Energy of the neutrino: **E**
- ➔ Distance travelled by the neutrino (baseline): **L**

Neutrino Oscillations at Long-Baseline experiments

LBL experiments measure oscillations by firing a neutrino beam across **hundreds of kms.**

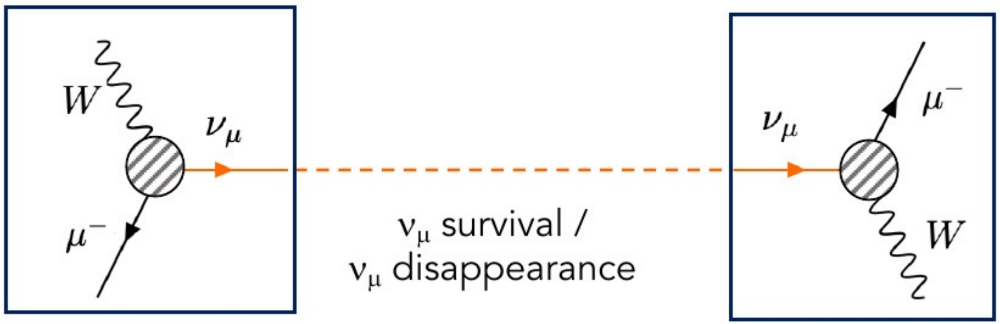
- **Can use a muon neutrino beam: ν_μ**
- **Can use a anti-muon neutrino beam: $\bar{\nu}_\mu$**

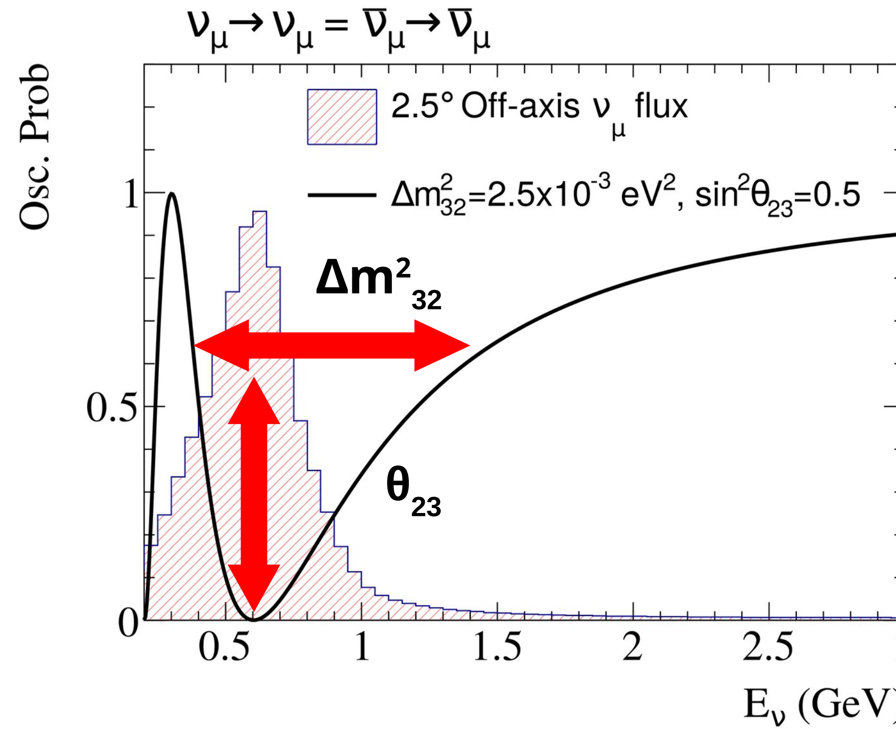
Measure neutrinos **before oscillations** with **Near Detector** and **after** with **Far Detector**.



T2K IMPERIAL

Muon-Neutrino Disappearance

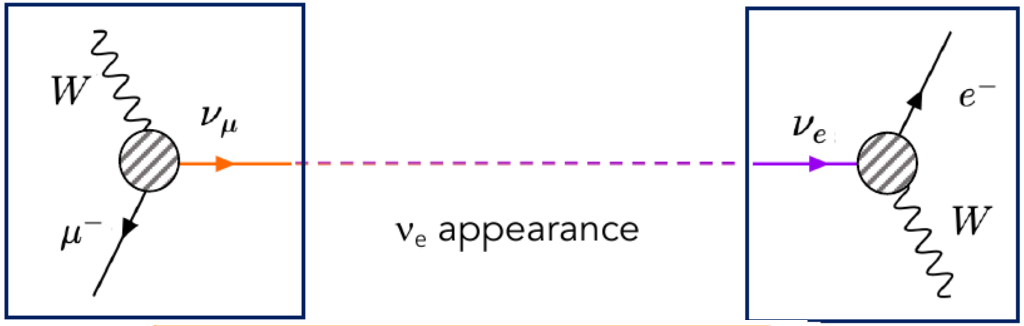


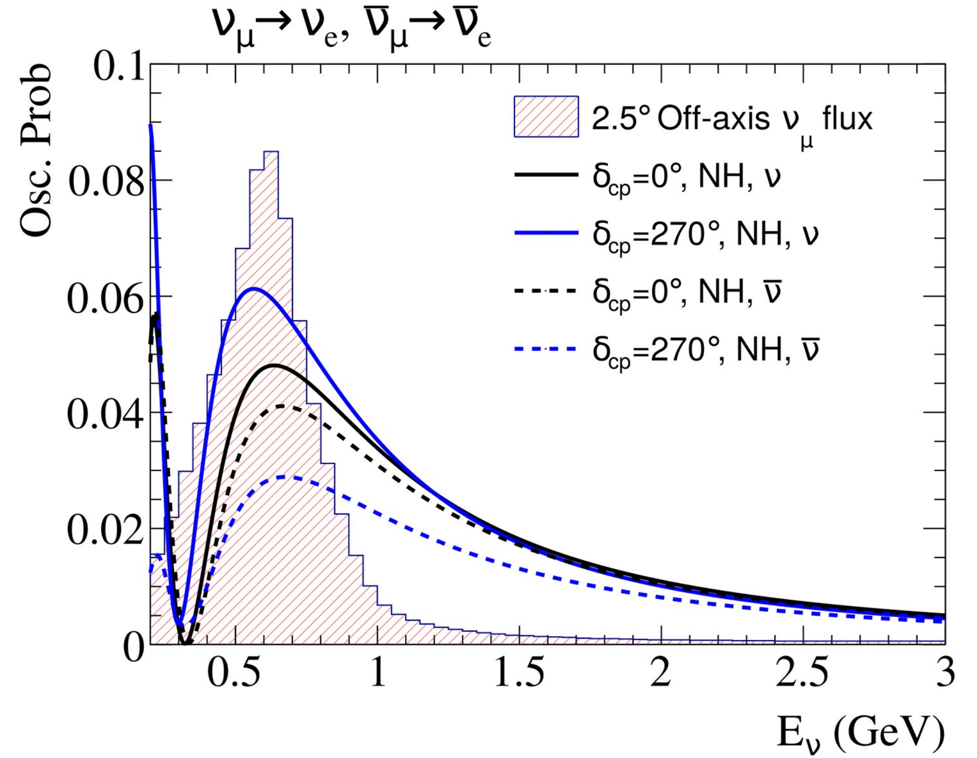


$$P_{\mu \rightarrow x} \approx 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)$$

- Leading Order dependence on **$\sin^2 2\theta_{23}$ and Δm^2_{32}** as well as **L/E**
- If $\sin^2 2\theta_{23}=1$ then maximal muon neutrino disappearance

Electron-Neutrino Appearance





$$P_{\mu\rightarrow e} \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

+ [CP violating terms]

- [CP conserving terms]

+ [other terms]

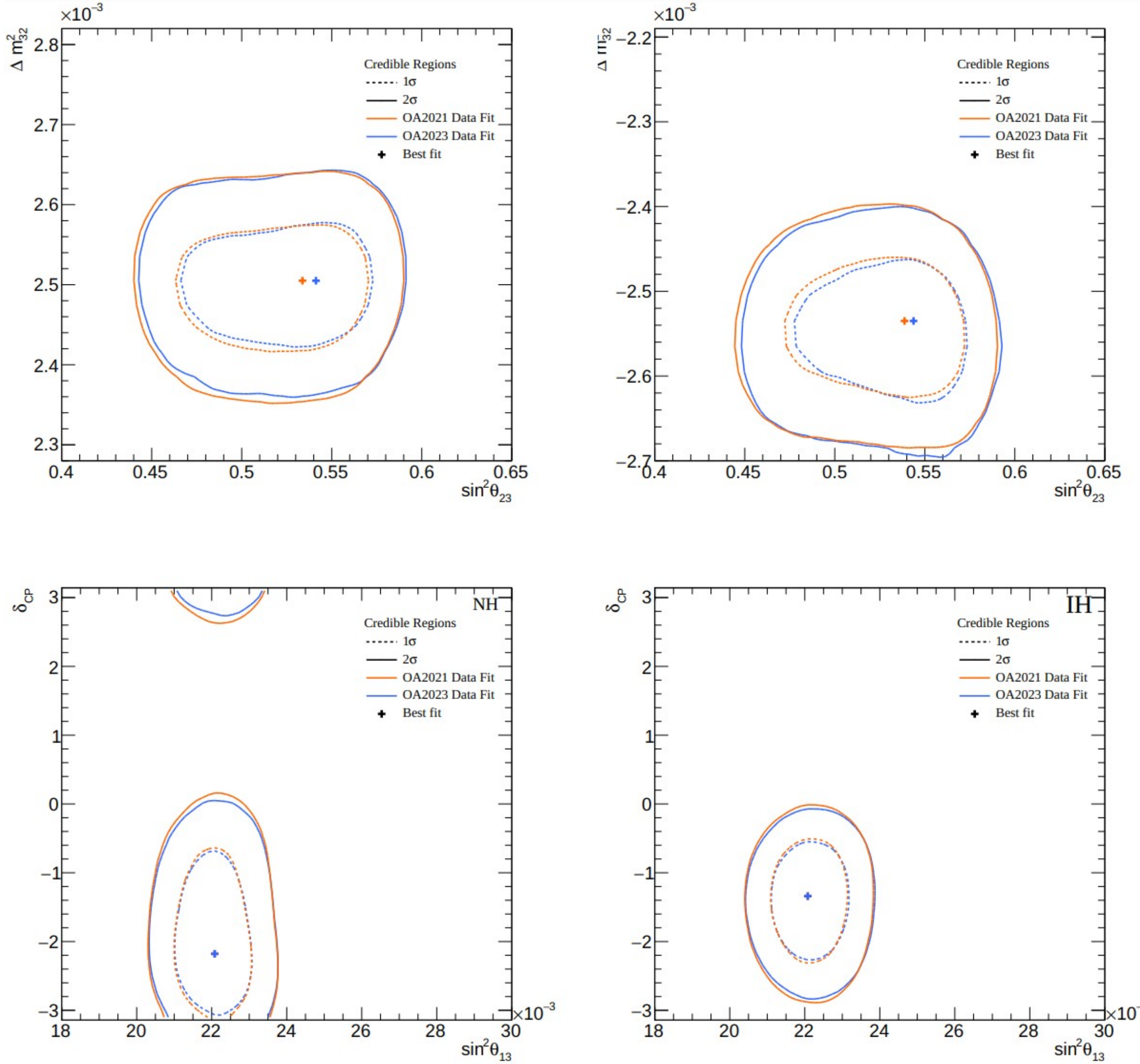
* Approximation only holds in vacuum

***Matter Effects** modify oscillation probability

- Sensitive to **$\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP}, magnitude and sign of Δm^2_{32}**
- Opposite impact of matter effects and δ_{CP} for neutrinos and anti-neutrinos:
  - $\delta_{CP} = \pi/2$ (90°) → fewer neutrinos, more anti-neutrinos
  - **$\delta_{CP} = -\pi/2$ (270°) → more neutrinos, fewer anti-neutrinos**

Important to study neutrinos and anti-neutrinos!

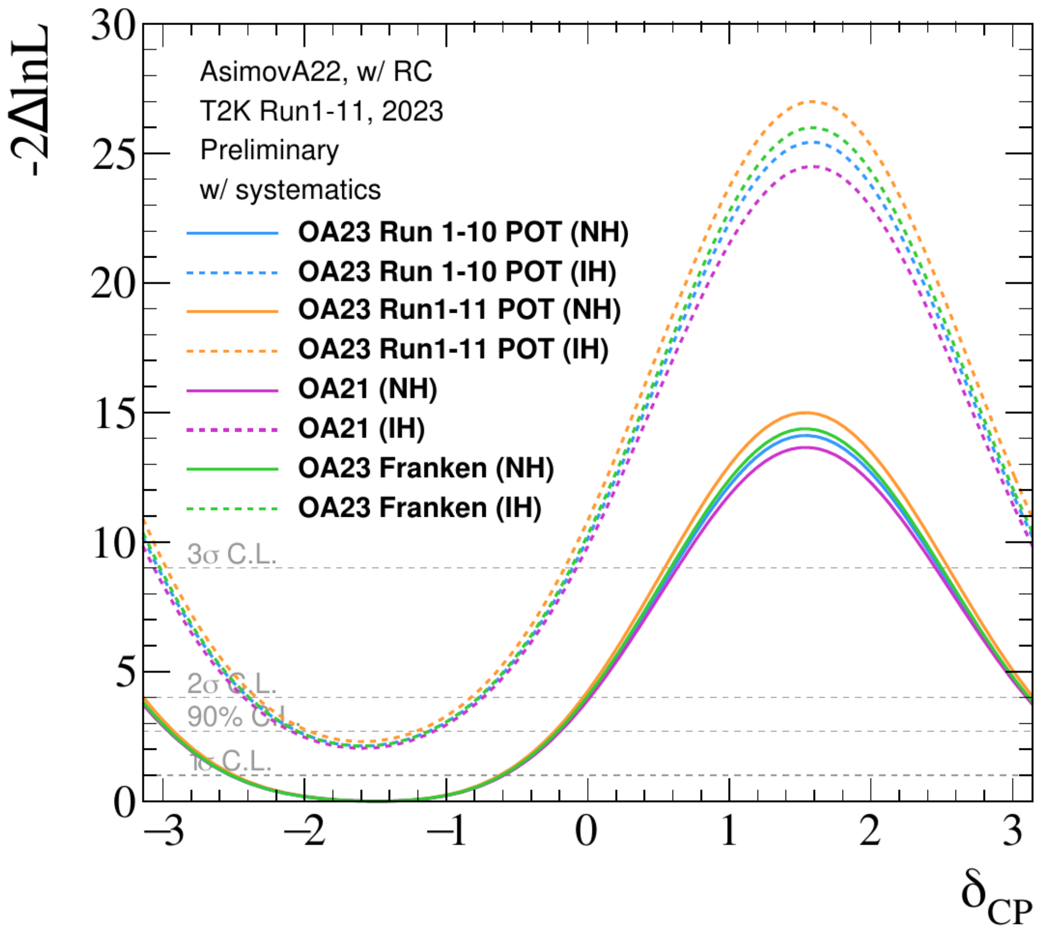
Comparison to previous results



Comparison to previous results

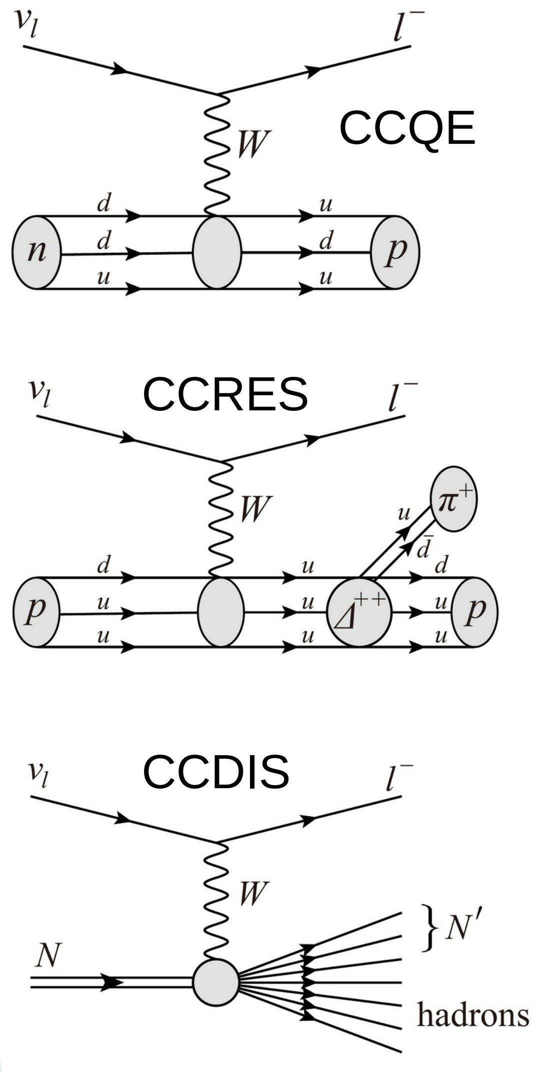
Can see impact of different changes to the analysis.

Impact of new data and new SK detector matrix are similar.



Neutrino interaction modelling

- Important to understand how neutrino interact otherwise we can't accurately reconstruct neutrino energy
- Interactions occur within a nucleus, propagation of particles through nucleus also needs to be modelled. Commonly referred to as Final State Interactions (FSI)
- At T2K energies, Charged Current (CC) Quasi-Elastic (QE) interactions are most dominant type, significant number of multi-nucleon interactions (2p-2h) and resonant pion production (RES). Some Deep Inelastic Scattering (DIS)
- T2K uses the NEUT (5.4.0) neutrino event generator for simulations
- Prior uncertainties motivated by external data sets (e.g. bubble chamber data) and theory



Goodness of Fit checks

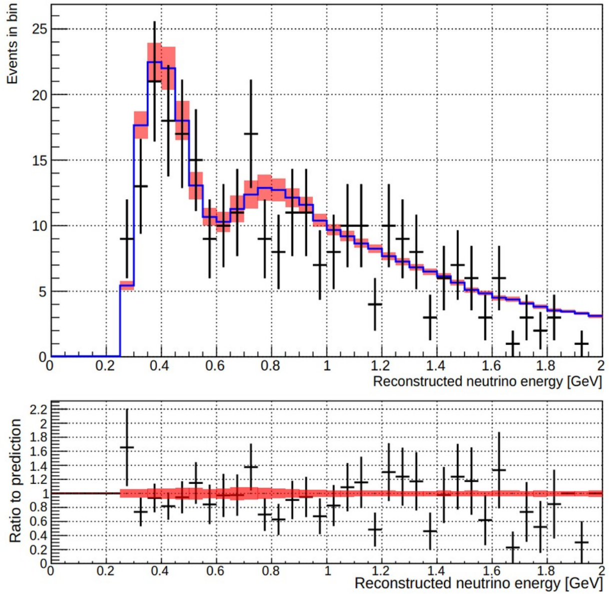
Use posterior predictive p-values (PPP)

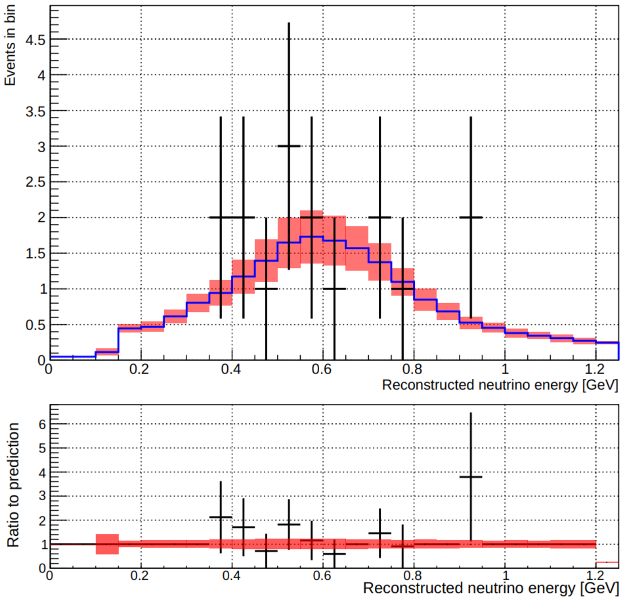
Compare likelihood best fit to data and fluctuated predictions

A good PPP is around 0.5

Good PPPs for total and individual samples

SK Sample	p-value
FHC 1Rmu	0.33
RHC 1Rmu	0.83
FHC ν_μCC1π	0.43
FHC 1Re	0.12
RHC 1Re	0.64
FHC 1Re 1de	0.73
Total	0.51





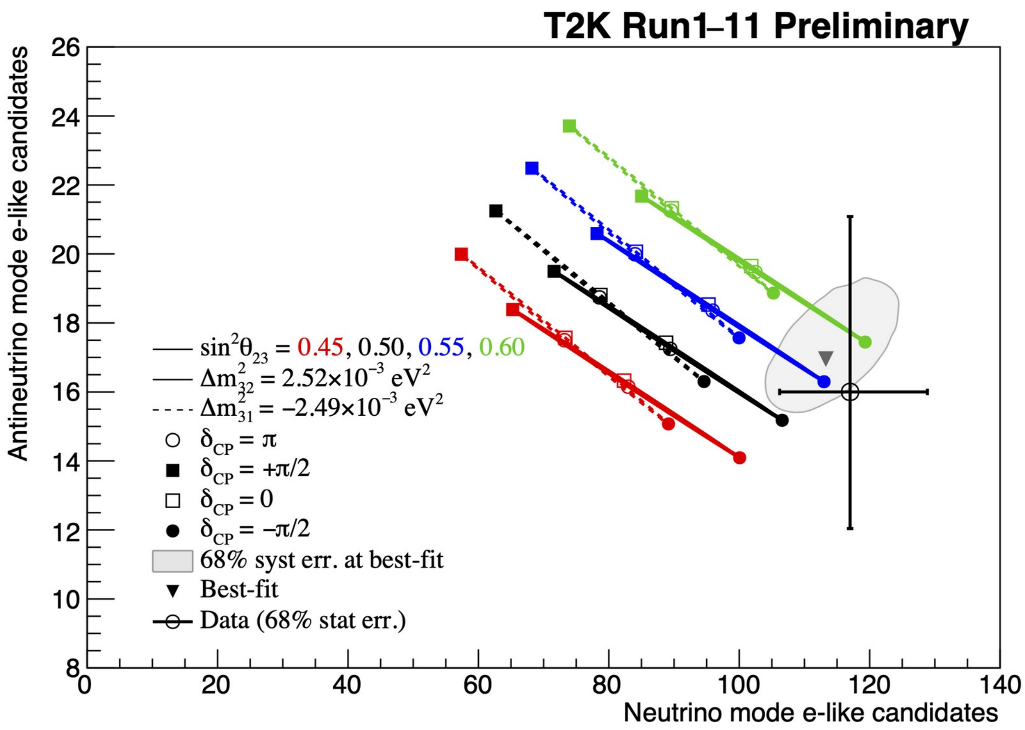
New decay electron cut

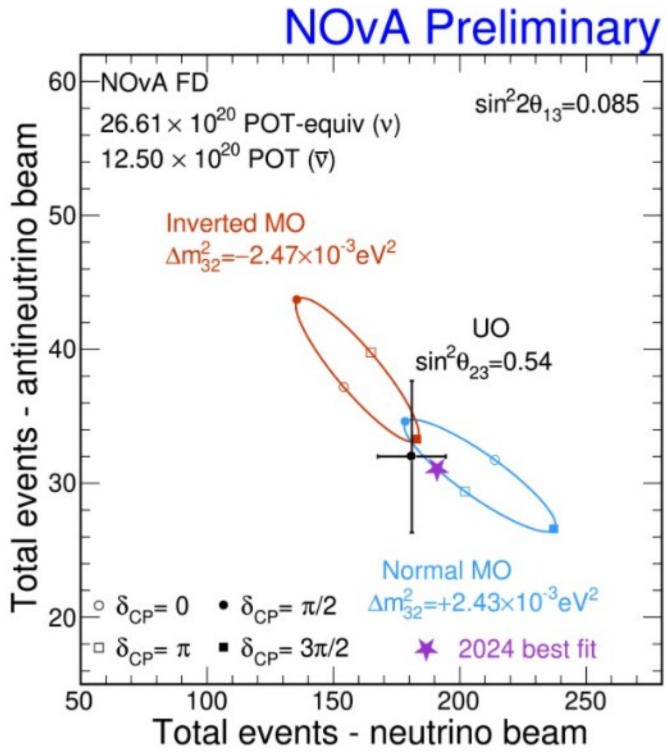
- Also small impact on the data collected with pure water due to n-capture on Hydrogen

Samples	Run 1-10 (Pure water)			Run 11 (0.01% Gd)		
	Old cut	New cut	Δ	Old cut	New cut	Δ
FHC1Re	99	99	0	5	7	40%
RHC 1Re	20	20	0	-		
FHC 1Re1de	14	14	0	2	1	50%
FHC1RMu	335	337	-1%	35	35	0
RHC1Rmu	140	140	0	-		
NumuCC1pi	62	62	0	5	5	
	73	70	-4%	6	4	-33%

Bi-Event T2K and NOvA

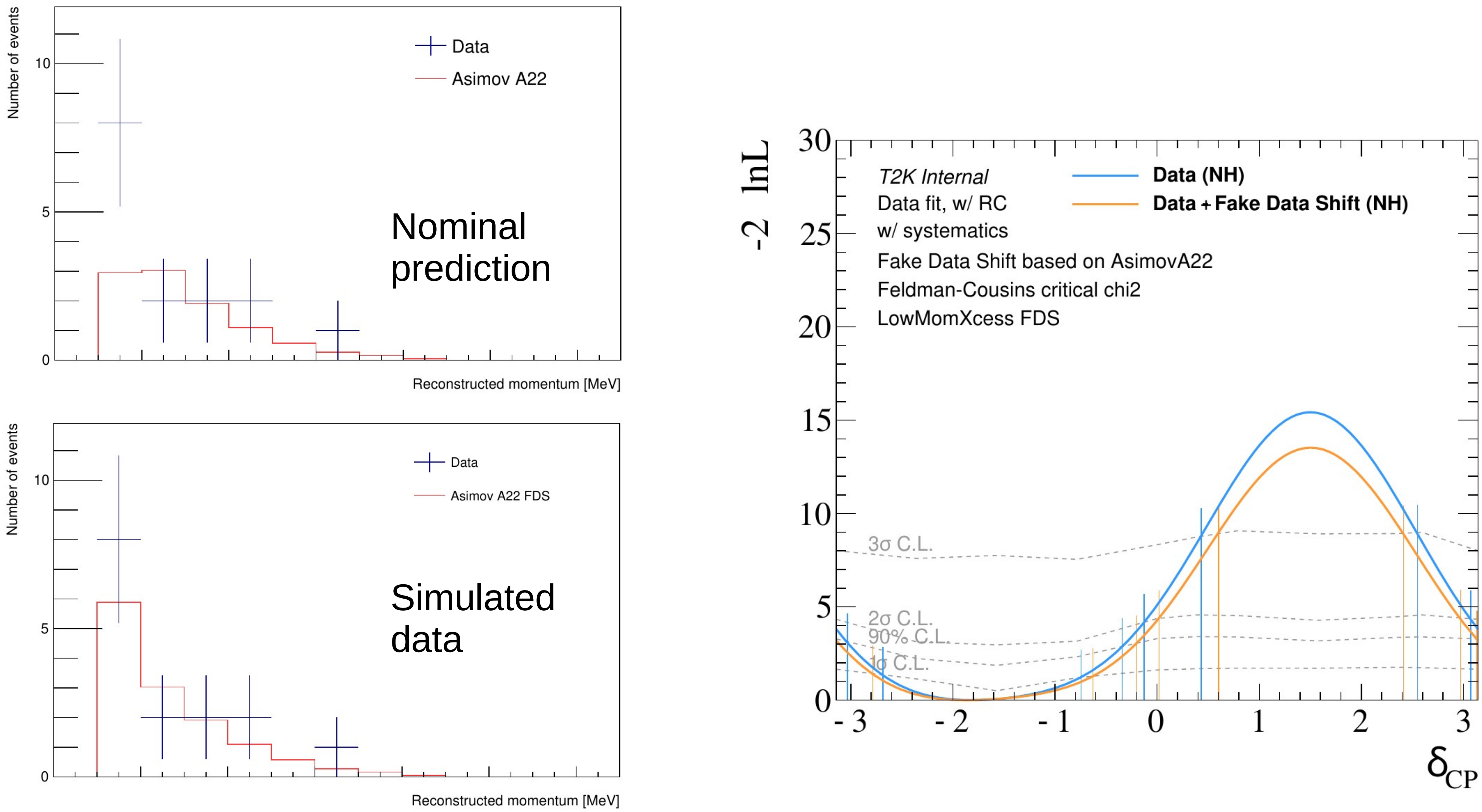
- T2K and NOvA have different baselines and energies so have different sensitivities to oscillation parameters





From Erika Catano-Mur's recent [Wine and Cheese](#)

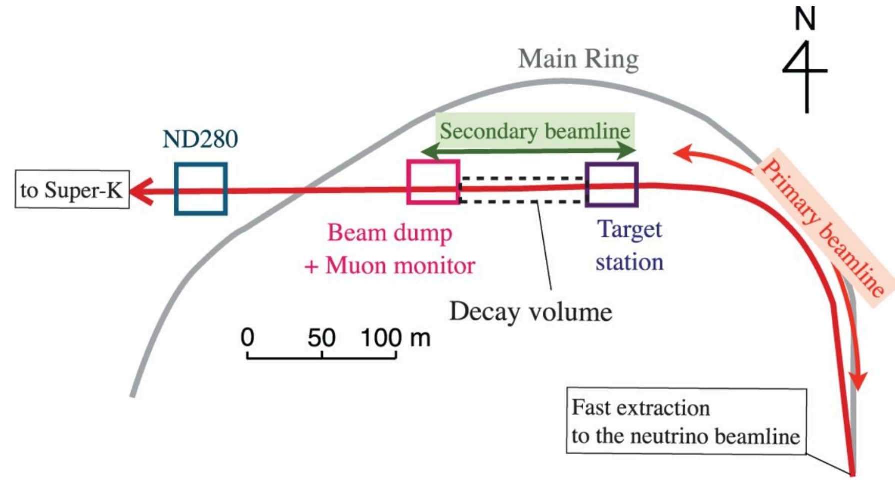
Low momentum FHC 1Re1de simulated data

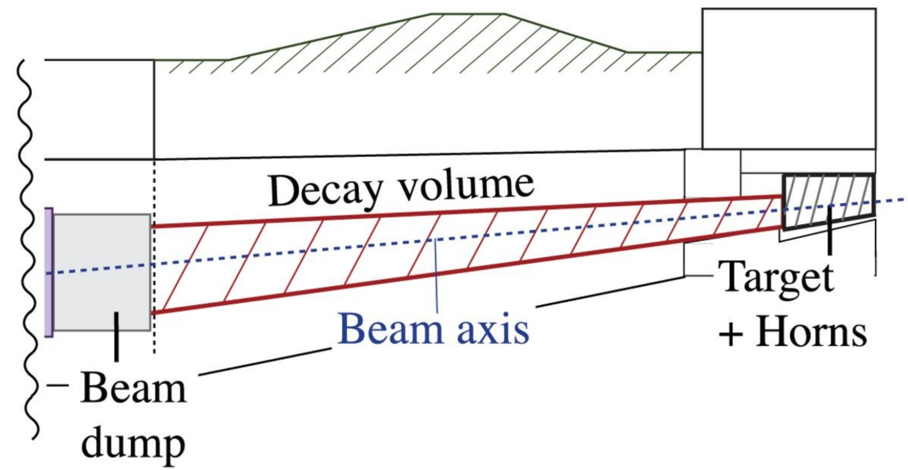


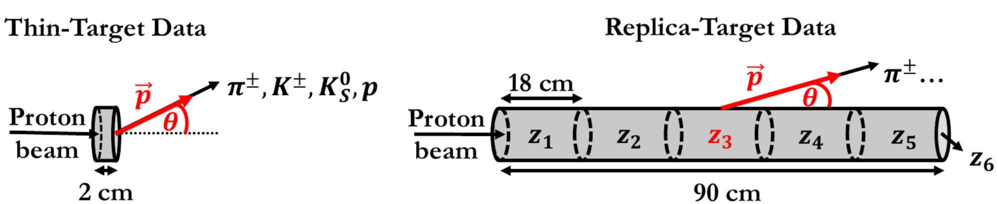
Neutrino Flux

- Beam produced by colliding protons from J-PARC facility with graphite target
- Many hadrons are produced in collision
- Hadrons focussed by series of **magnetic horns**
- These hadrons (mainly π, K) **decay** to produce neutrinos
- Ideally we would like a pure muon (anti-)neutrino beam
- Can run in **neutrino mode** and **anti-neutrino** mode by changing direction of field in horns
- Proton beam and neutrino beam are measured by a series of **beamline monitors**

- **External constraints** on production of hadrons on/in target used from **NA61 experiment**

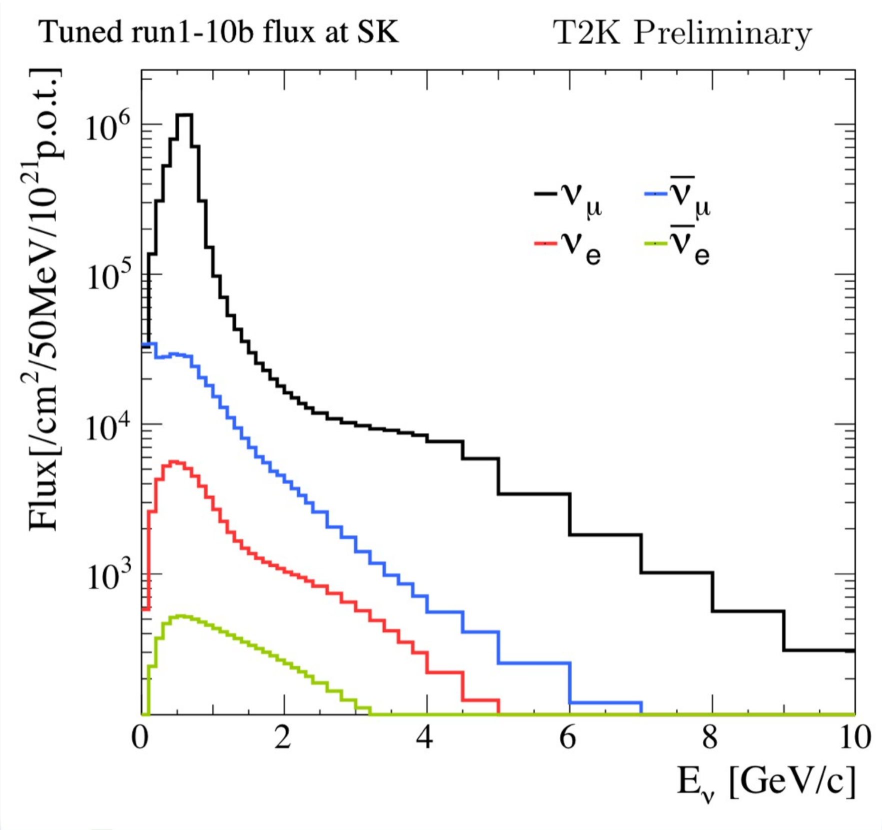


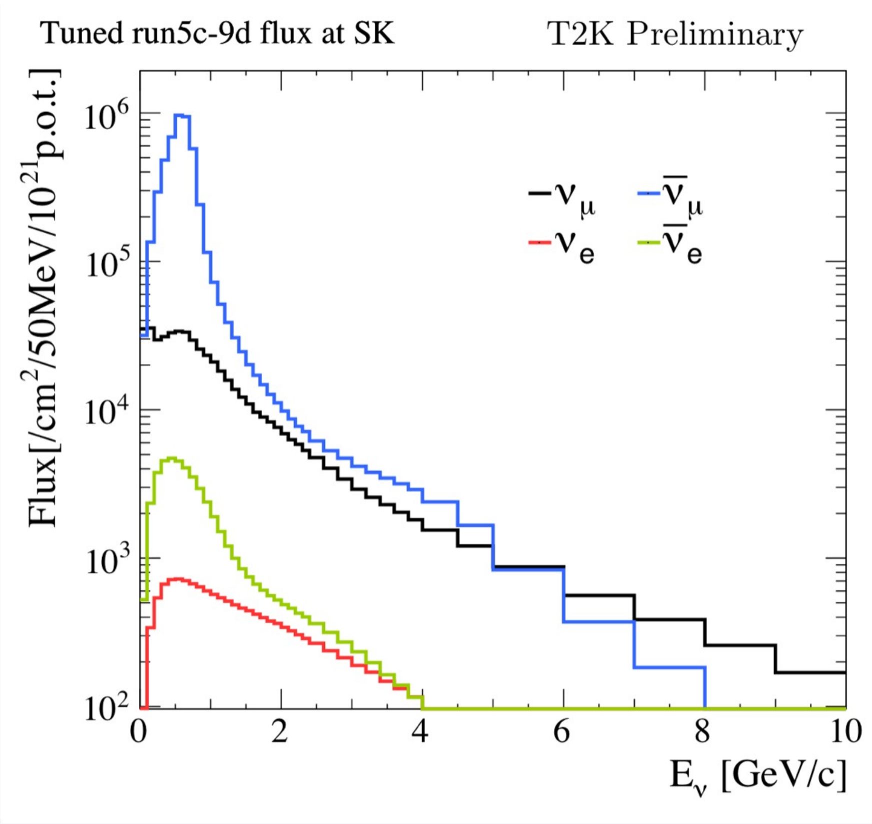




SK flux prediction

Flux predictions at SK for different flavour components for neutrino mode (left) and anti-neutrino mode (right).





T2K Analysis

- After all of this you end up with a likely hood to evaluate, here θ are your model parameters and D is data

$$
\begin{aligned}
-\ln(P(\vec{\theta}|D)) = &\sum_{i}^{ND280bins} N_i^{ND,p}(\vec{f},\vec{x},\vec{d}) - N_i^{ND,d} + N_i^{ND,d} ln[N_i^{ND,d}/N_i^{ND,p}(\vec{f},\vec{x},\vec{d})] \\
&+ \sum_{i}^{SKbins} N_i^{SK,p}(\vec{f},\vec{x},s\vec{kd},\vec{o}) - N_i^{SK,d} + N_i^{SK,d} ln[N_i^{SK,d}/N_i^{SK,p}(\vec{f},\vec{x},s\vec{kd},\vec{o})] \\
&+ \frac{1}{2}\sum_{i}^{osc}\sum_{j}^{osc} \Delta o_i (V_o^{-1})_{i,j} \Delta o_j \\
&+ \frac{1}{2}\sum_{i}^{flux}\sum_{j}^{flux} \Delta f_i (V_f^{-1})_{i,j} \Delta f_j = \\
&+ \frac{1}{2}\sum_{i}^{xsec}\sum_{j}^{xsec} \Delta x_i (V_x^{-1})_{i,j} \Delta x_j \\
&+ \frac{1}{2}\sum_{i}^{nd280det}\sum_{j}^{nd280det} \Delta d_i (V_d^{-1})_{i,j} \Delta d_j \\
&+ \frac{1}{2}\sum_{i}^{skdet}\sum_{j}^{skdet} \Delta skd_i (V_{skd}^{-1})_{i,j} \Delta skd_j
\end{aligned}
$$

Data at ND280

Data at SK

What we want!!

Oscillation Parameters

Flux

Interaction Model

ND280

SK Detector

Use priors from various sources