Latest Results from T2K

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What is T2K trying to measure?

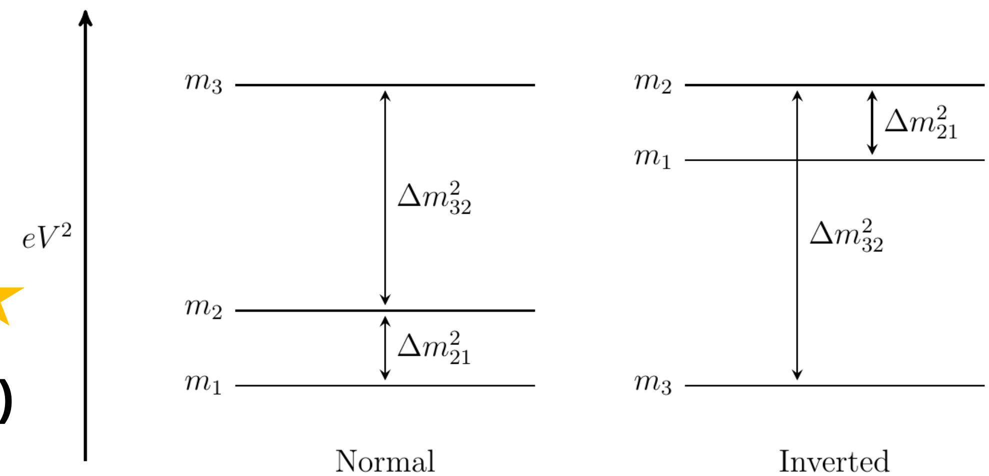
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12}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

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

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

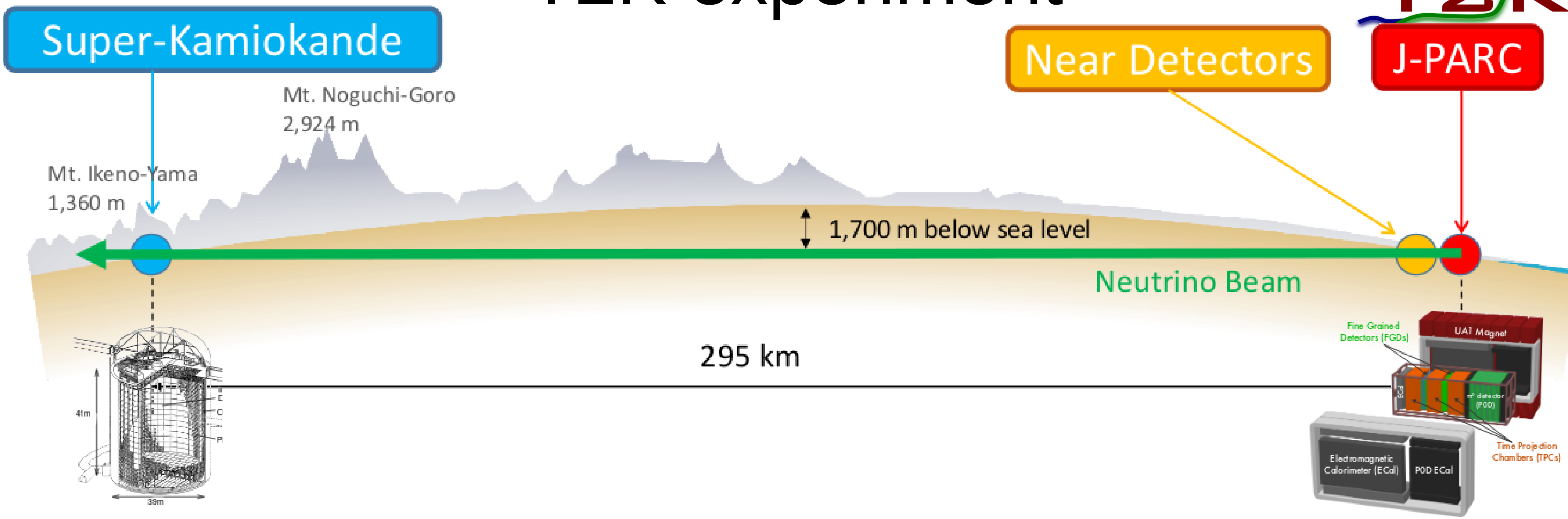
Key questions to answer:

- **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 δ_{CP}, θ_{23}, Δm^2_{32}** ★



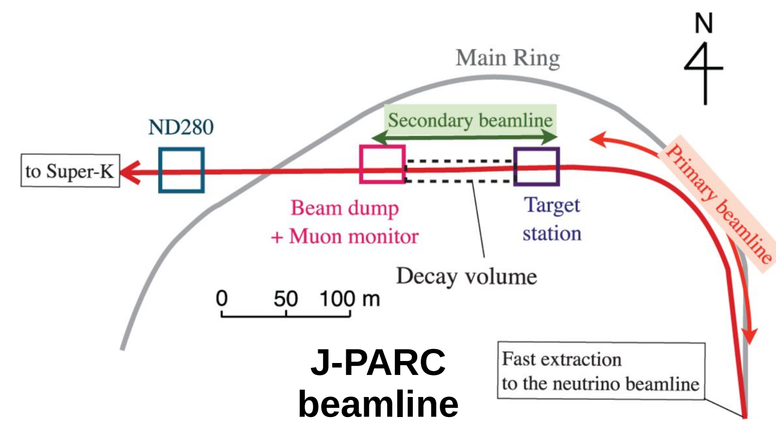
★ **T2K can measure these!**

T2K experiment



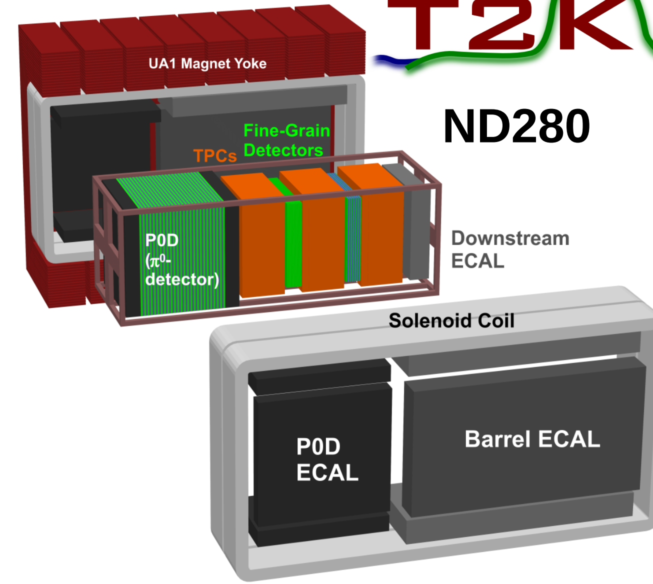
- ~500 kW neutrino beam produced at J-PARC
  - Proton beam collides with graphite target
  - Mesons produced are focused by magnetic horns
  - Mesons decay to produce neutrino beam

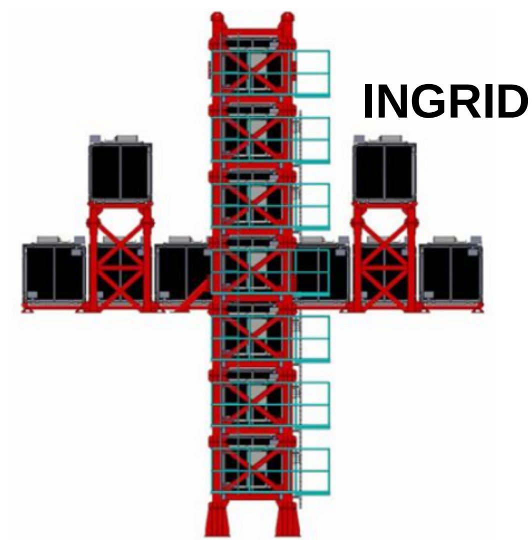
- Near detectors on the east coast of Japan
- Far detector Super-Kamiokande on the west coast
- Measure neutrino oscillations across a baseline of 295km



Near Detectors

- **Near Detector at 280m (ND280)** is situated 280m downstream of neutrino production point
  - Fine Grain Detectors (FGDs) - Plastic scintillator based detectors
  - Time Projection Chambers (TPCs) – measures momentum and gives excellent PID
  - All inside UA1 magnet which allows the charge of particles to be determined with 0.2 T field
- **Interactive Neutrino Grid (INGRID)** monitors neutrino beam position and direction. Made from 14 scintillator modules
- Other near detectors:
  - **WAGASCI –** water and plastic scintillator
  - **BabyMIND** – muon range detector made of iron and scintillator
  - These detectors are used in tandem e.g. https://doi.org/10.22323/1.369.0119
- **Near detectors used to measure systematics in oscillation analysis**
- **Very active cross-section measurement program at T2K utilises Near Detectors**

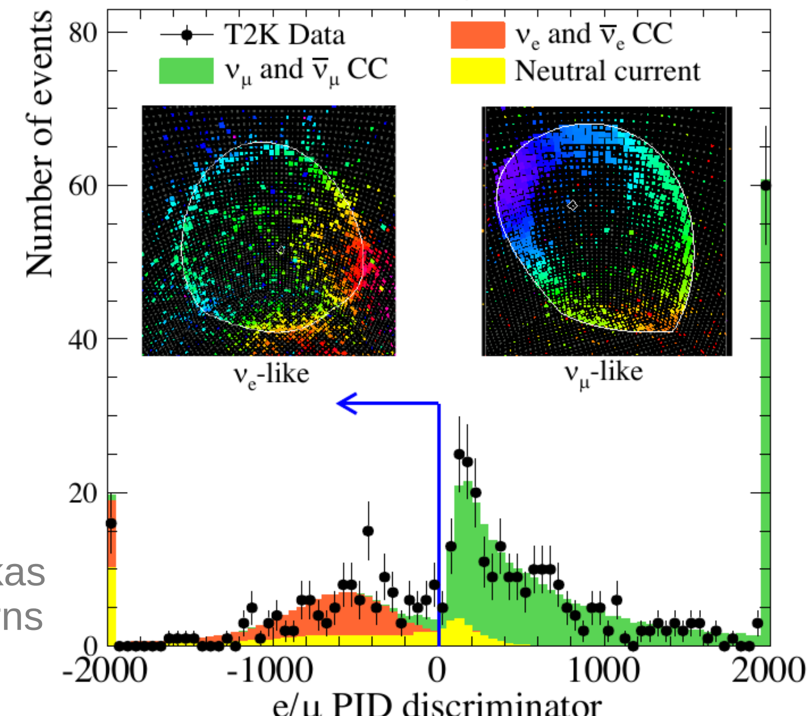




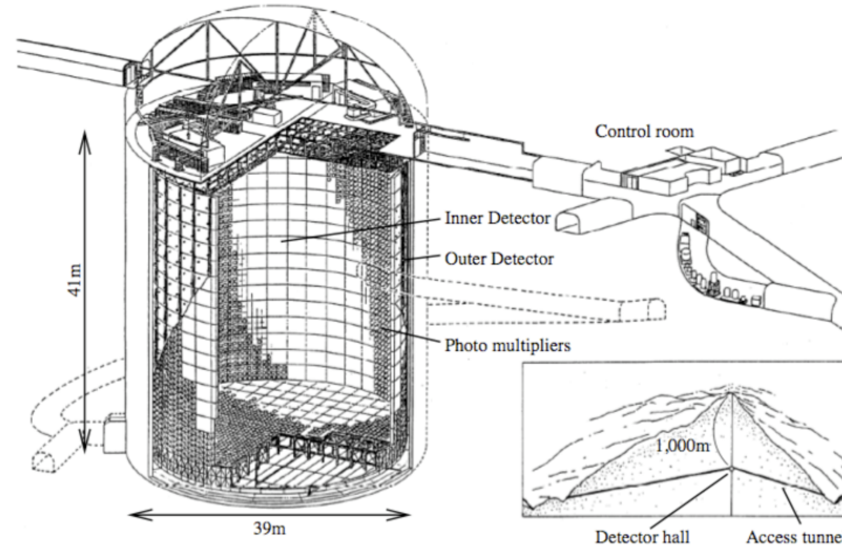
Super-Kamiokande

- **50 kt water-Cherenkov detector**
- Split into two regions:
  - Outer detector – rejects background events
  - Inner detector – events selected for use in an analyses
- Instrumented with PMTs

Adapted from arXiv:1910.03887v2



Lukas Berns



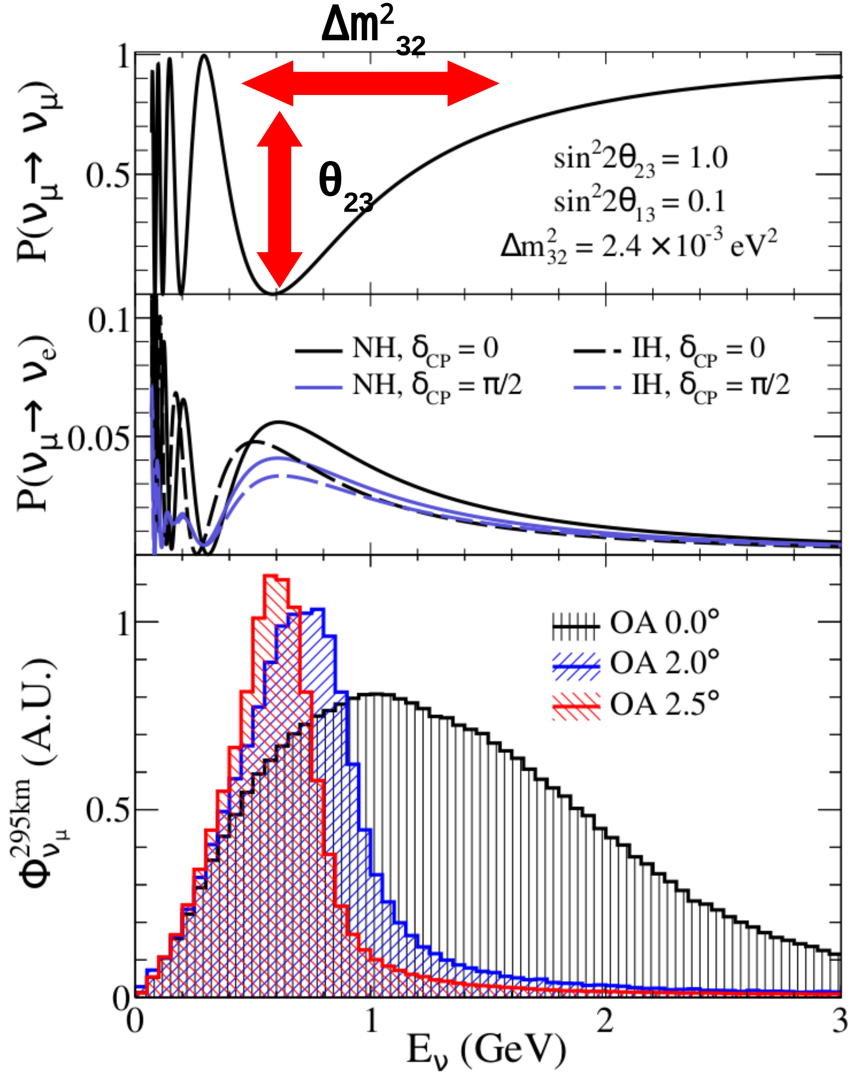
- Particles are identified by their Cherenkov rings
  - **Muons** produce **sharp** Cherenkov rings in the detector
  - **Electrons** scatter more so produce **“fuzzier”** rings
- Pions below Cherenkov threshold possible by looking for **Michel electrons**
- No charge discrimination

Neutrino Oscillations at T2K

- Measure neutrino oscillation using **muon neutrino and anti-neutrino beam**
- ND280 and Super-K are both placed 2.5˚ away from neutrino beam axis
- This gives maximal muon-neutrino disappearance probability for a neutrino energy of **~0.6 GeV**

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

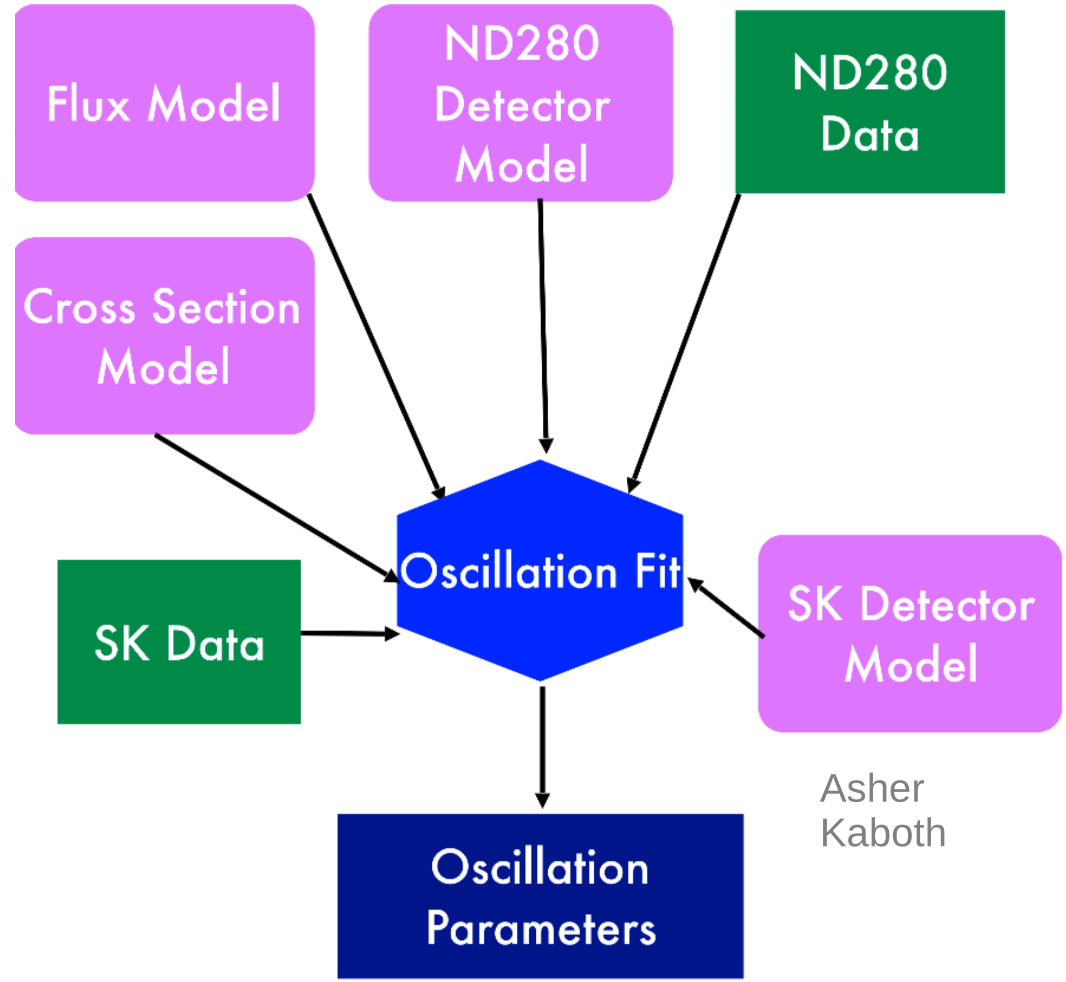
- Electron (anti-)neutrino **appearance**:
  - Leading terms depend on $\sin^2\theta_{13}$, Δm^2_{32} and $\sin^2\theta_{23}$
  - Can use **reactor constraints** for θ_{13} to improve sensitivity
  - Dependence on $\boldsymbol{\delta_{CP}}$
    - If $\delta_{CP} = \pi/2$ fewer neutrinos than anti-neutrinos
    - If $\delta_{CP} = -\pi/2$ more neutrinos than anti-neutrinos



Neutrino Oscillation Analysis

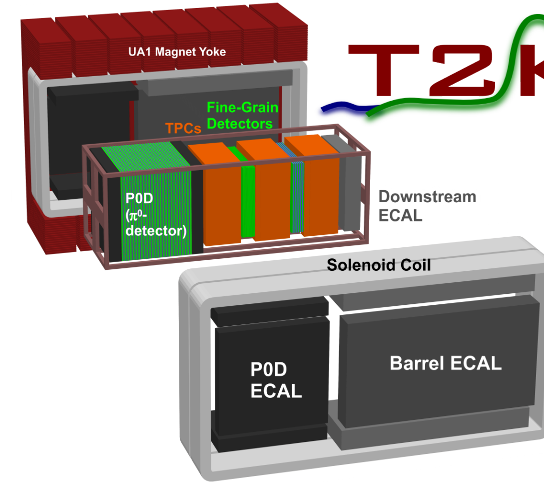
- Analysis strategy defines models for the Near Detector response, SK detector response, neutrino interactions, neutrino flux
- These base simulations then get constrained by data at both the near detector and SK

- Several fitter groups exist within T2K which have slightly differing techniques:
  - Frequentist vs. Bayesian
  - Sequential ND, SK fit vs. simultaneous ND+SK fit
  - Sample binning
- Fitters are all cross-checked against each other



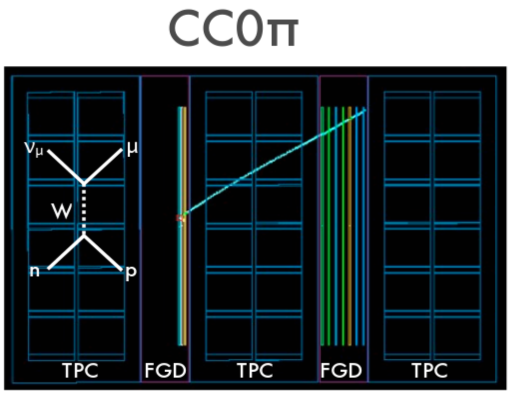
Asher Kaboth

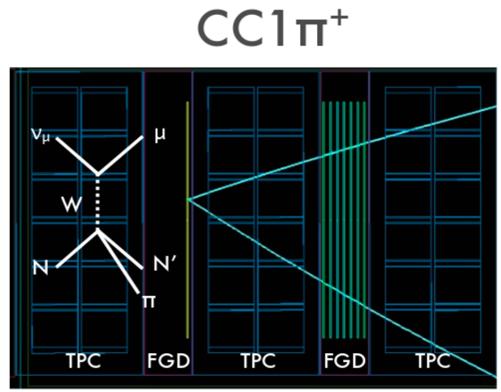
ND280 data samples

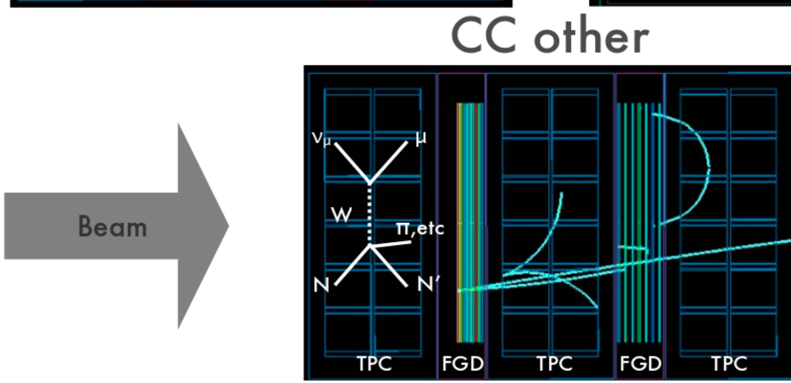


Oscillation analysis uses neutrino events that occur in samples in the upstream (FGD1) and downstream (FGD2) FGDs. FGD1 primarily C-target and FGD2 primarily O-target.

Lepton always has to be reconstructed as a muon
Three topologies defined based on number of pions.







Asher Kaboth

CC0π – no π in the final state

CC1π$^{+(-)}$ – a charged pion in the final state

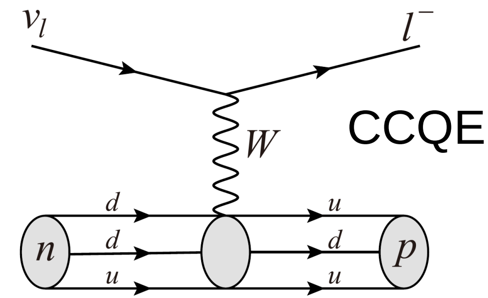
CC-Other – everything else! Multiple πs, gammas, π^0…

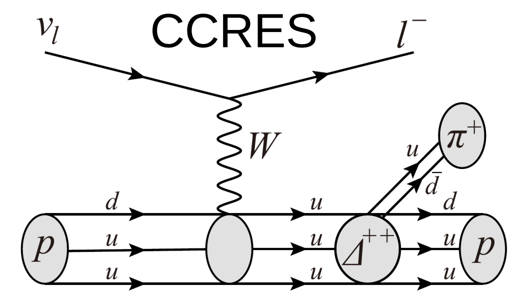
Have these samples for neutrino mode and anti-neutrino mode.
For anti-neutrino mode also look for μ^- to constrain neutrino background.

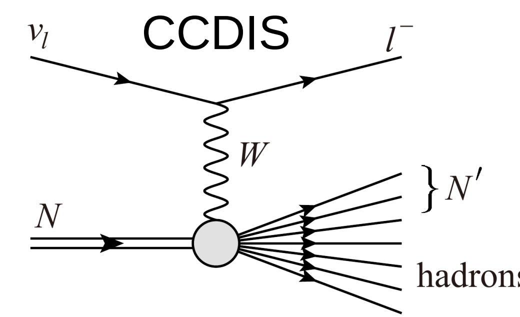
Total of 18 data samples at ND280.

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

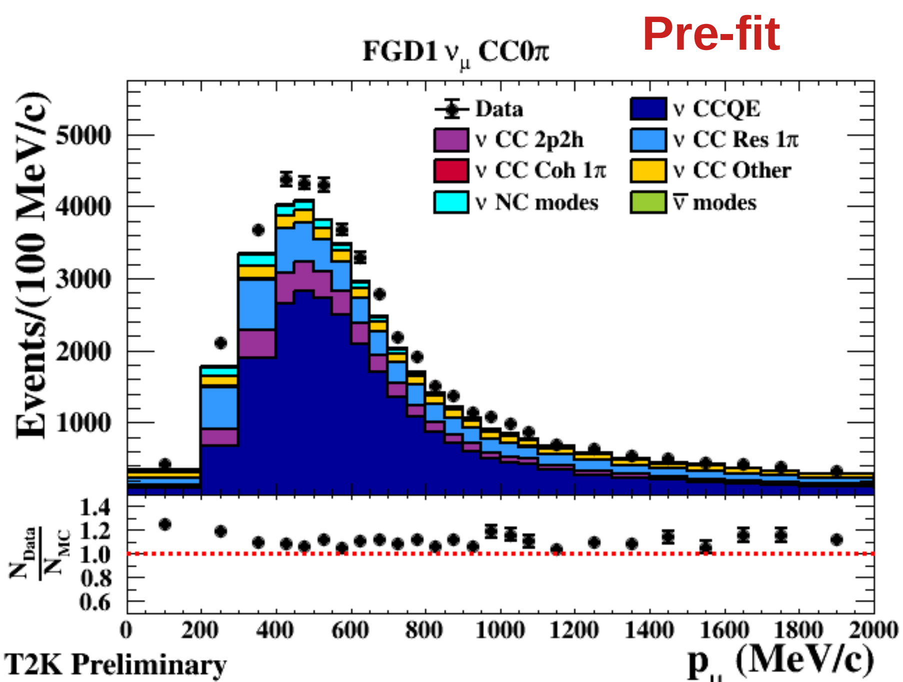


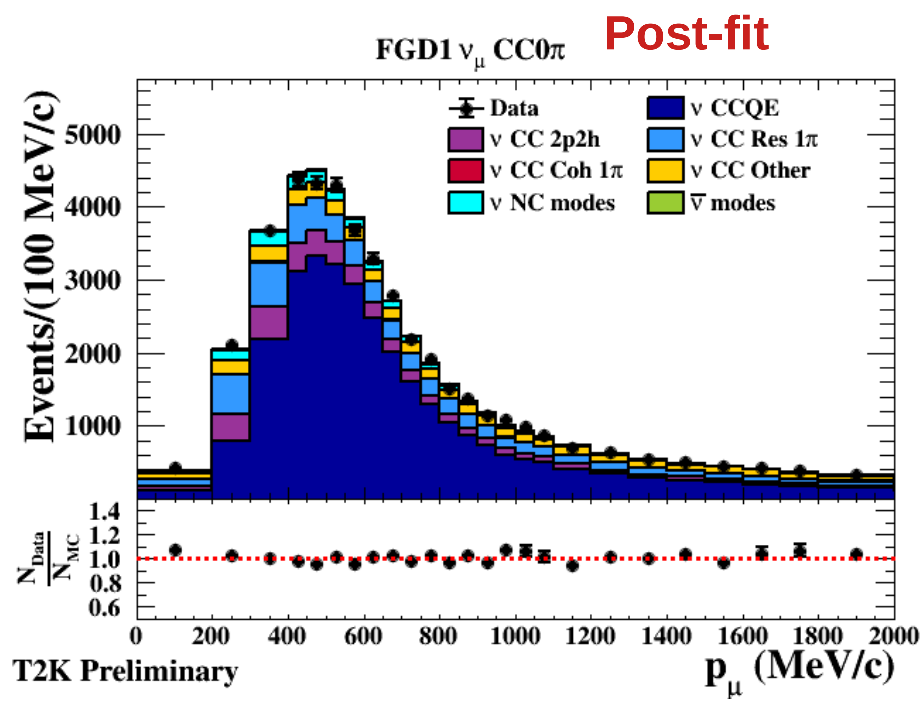




ND280 fit results

- ND280 data constraints uncertainties on neutrino interactions and neutrino flux before oscillations have occurred
- Significantly reduces uncertainty on prediction at SK
- The ND280 fit matches our data well (prior model p-value of 74%)





SK data fit results

Currently 5 samples at SK

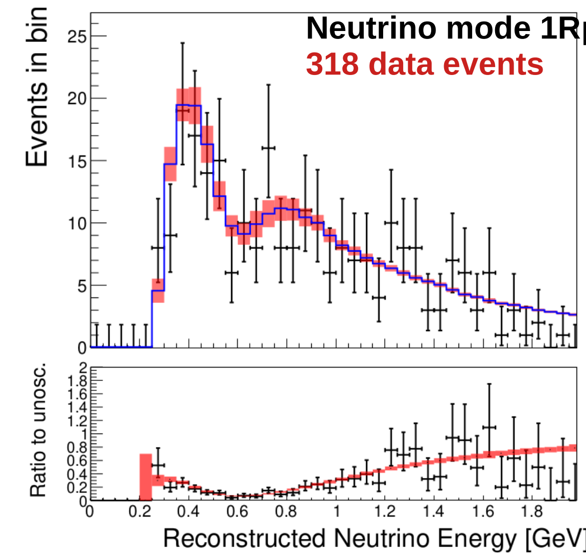
- 1 muon-like ring; **neutrino mode** and **anti-neutrino mode** samples
- 1 e-like ring; **neutrino mode** and **anti-neutrino mode** samples
- 1 e-like ring and 1 michel electron; only neutrino mode

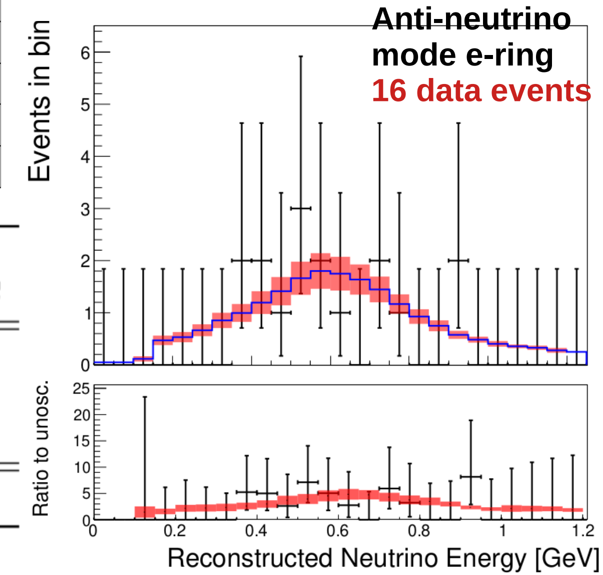
Good agreement between data and post-fit predictions.

Systematic Uncertainty					
	Neutrino Mode			Anti-neutrino Mode	
	1 ring μ-like	1 ring e-like	1 ring e-like 1 d.e.	1 ring μ-like	1 ring e-like
Before ND280 fit	11.1%	13.0%	18.7%	11.3%	12.1%
After ND280 fit	3.0%	4.7%	14.3%	4.0%	5.9%

Sources of uncertainty before ND280 fit

Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	5.1	4.7	4.8	4.7	4.9	2.7
Cross-section (all)	10.1	10.1	11.9	10.3	12.0	10.4
SK+SI+PN	2.9	2.5	3.3	4.4	13.4	1.4
Total	11.1	11.3	13.0	12.1	18.7	10.7





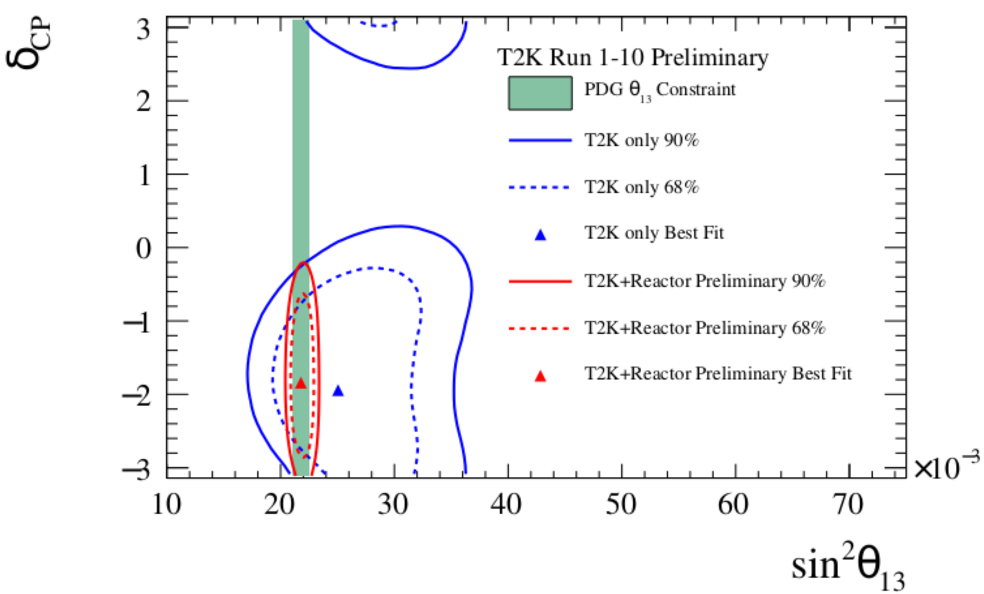
ν_e appearance results

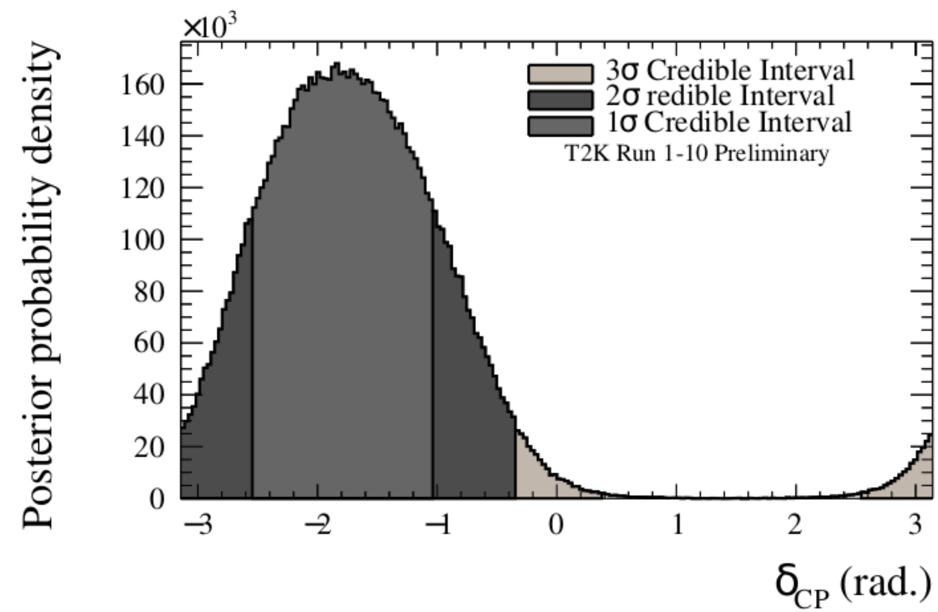
Two sets of results:

- Only using T2K data to provide sensitivity
- Using a PDG 2019 constraint on θ_{13} (so-called "reactor constraint") and T2K data

Using reactor constraint allows more precise measurement of dCP.

T2K prefers value of $\delta_{CP} \approx -\pi/2$. This maximises difference between neutrino and anti-neutrino oscillations.
Disfavour CP conserving values of 0 and π at **90%** confidence (and not quite 2σ).





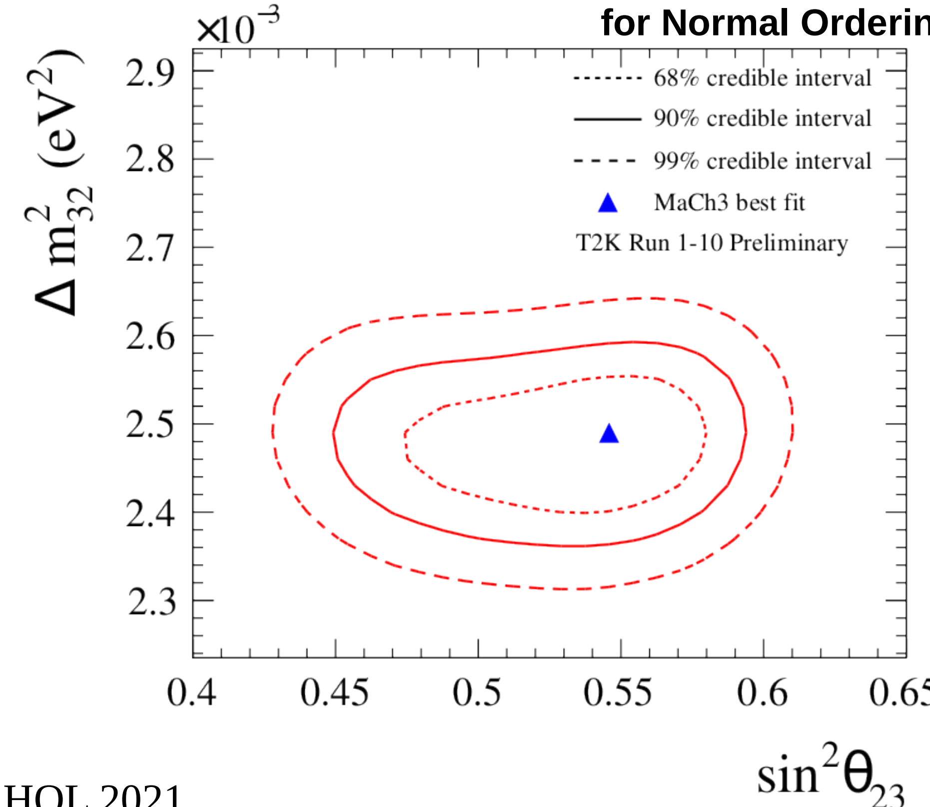
ν_μ disappearance results

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

T2K prefers Normal Ordering.
T2K prefers **Upper octant** of $\sin^2\theta_{23}$ and slight preference for **non-maximal $\sin^2\theta_{23}$**.

	$\sin^2\theta_{23}$	$\Delta m^2_{32} (\times 10^{-3})\mathrm{eV}^2$
2D best fit	0.546	2.49
68% C.I. (1σ) range	0.50 – 0.57	2.408 – 2.548
90% C.I. range	0.460 – 0.587	−2.596 – −2.452 & 2.368 – 2.592

2D credible intervals for Normal Ordering

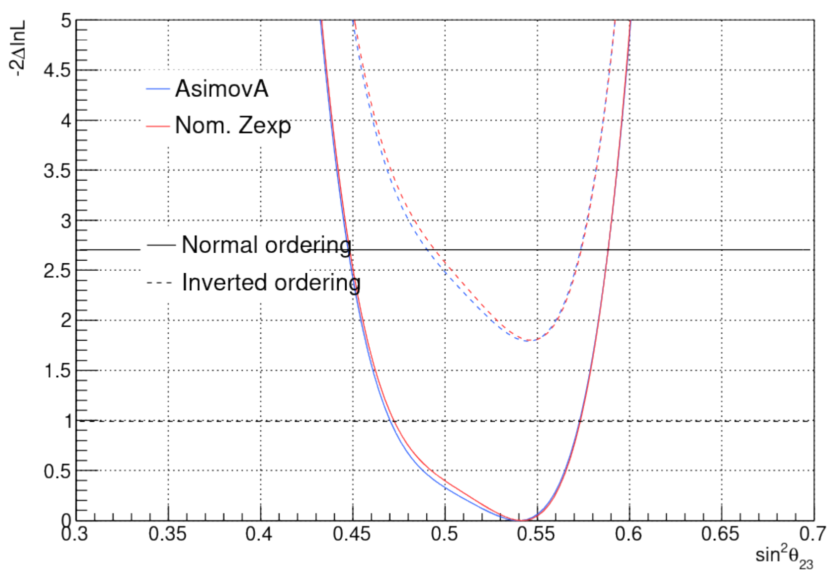


Posterior probabilities:

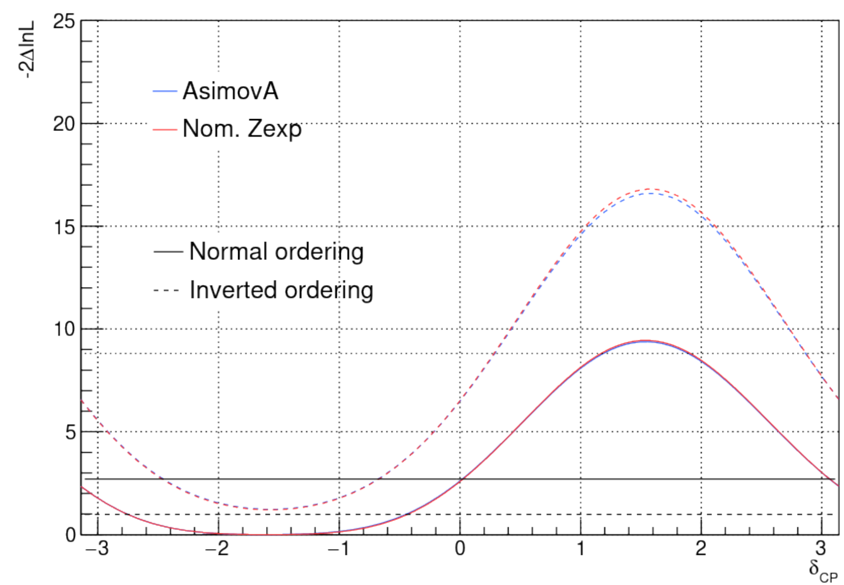
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IH ($\Delta m^2_{32} < 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

Robustness Studies

- Want to be sure that our results are not subject to the choice of base simulation and uncertainties
- Simulate data using alternative models and fit e.g. alternate form factors for CCQE, change in pion production model, data-driven changes to the model
- No significant bias seen on θ_{23}, θ_{13} or δ_{CP}: shows our base model and uncertainties are robust
- Robustness studies show small changes in δ_{CP} limits. Largest bias causes left (right) edge of 90% interval to move by 0.073 (0.080)
- Apply smearing to Δm^2_{32} contours of 8.65 x 10^{-6} eV^2/c^4 from largest bias seen.



$\sin^2\theta_{23}$ with reactor constraint

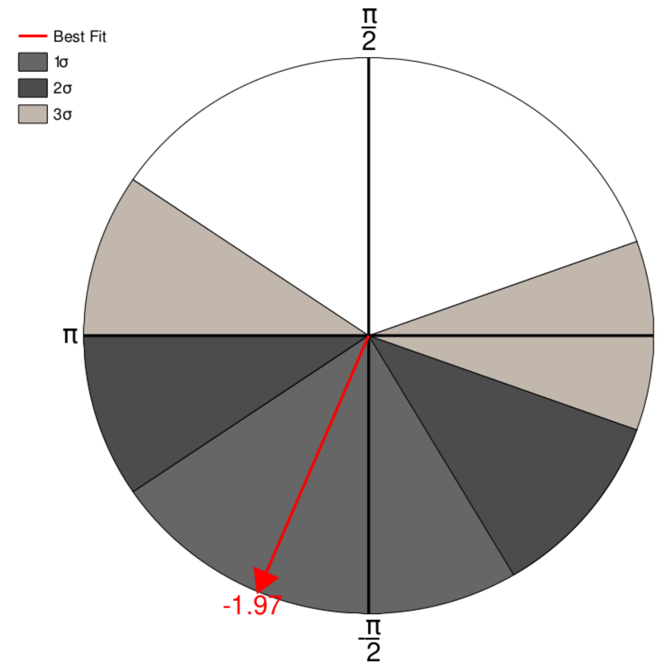


δ_{CP} with reactor constraint

Summary

- The T2K experiment has made world-leading measurements of neutrino oscillation parameters
  - T2K favours $\delta_{CP} = -\pi / 2$, disfavours 0 and π at 90%
  - Preference for Normal Ordering and upper octant of $\sin^2\theta_{23}$

- Many exciting analyses coming from T2K!
  - Updated oscillation analysis with more data samples
  - Joint-fit with SK atmospheric neutrinos
  - Joint-fit with NovA collaboration
  - Cross-section analyses using many off-axis angles



- T2K phase II is fast approaching!
  - Upgraded ND280
  - More precise measurements to come!

Future plans at T2K

T2K

- More data samples at ND280 and SK; **muon-like sample with pion** at SK, ND280 samples using **proton and photon tagging**
- Improved systematics; **new neutrino flux tuning and neutrino interaction model**
- Cross-section measurements with multiple Near Detectors

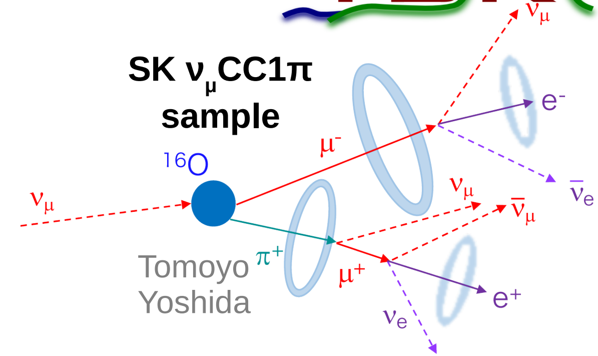
T2K phase-II

- **Upgraded ND280** – high angular coverage, 3D scintillator readout, better hadron tagging and reconstruction
- **SK being doped with Gd** – neutron tagged samples for oscillation analysis
- J-PARC beam upgrade to reach **0.75 MW**

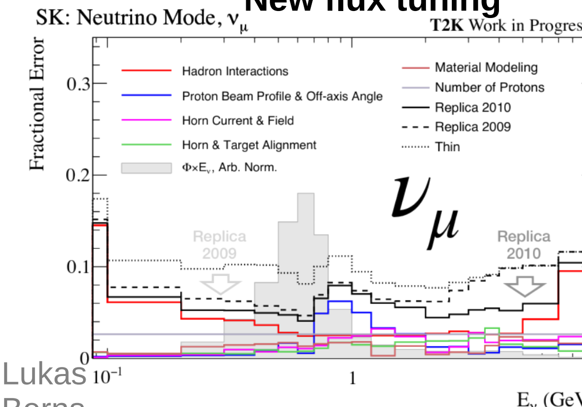
Joint-fits

- Joint-fits between T2K and **SK atmospherics** as well as T2K and **NOvA**
- These joint-fits should allow some of the **most precise constraints** on neutrino oscillation parameters.

SK ν_μCC1π sample



New flux tuning



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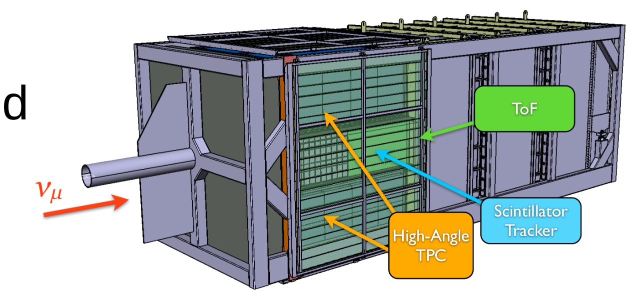


ND280 Upgrade

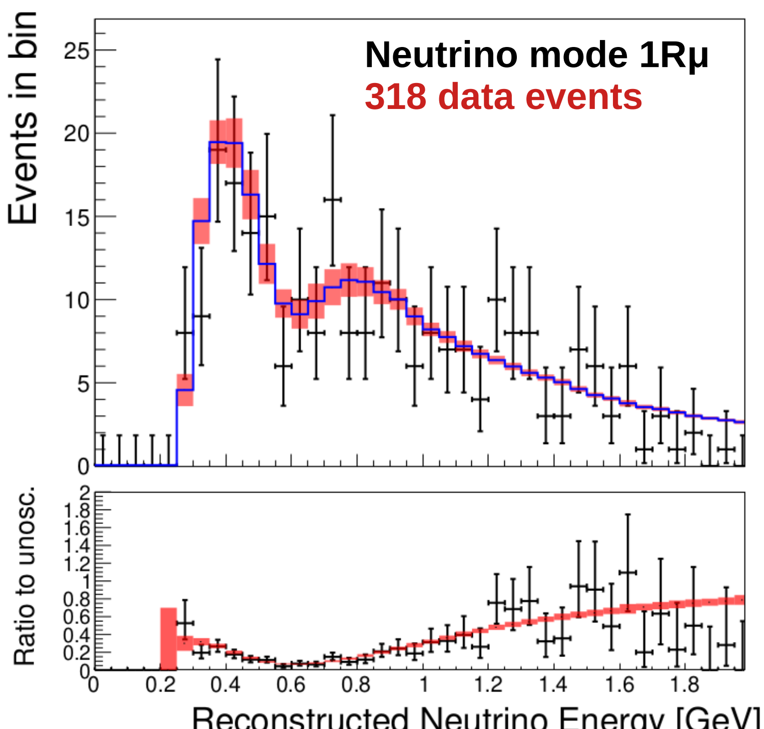
BACKUPS

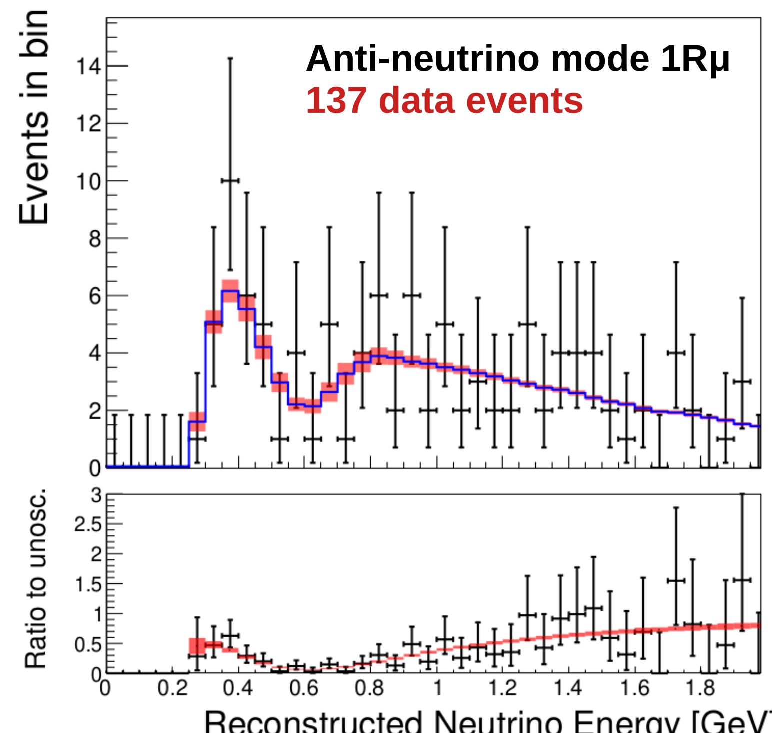
SK data fit results

Two samples with 1 muon-like cherenkov ring: neutrino mode and anti-neutrino mode.

Systematic uncertainty band is given by red band and statistical uncertainty on data given by error bars.

Systematic uncertainty on rate is 3% for neutrino mode and 4% for anti-neutrino mode.





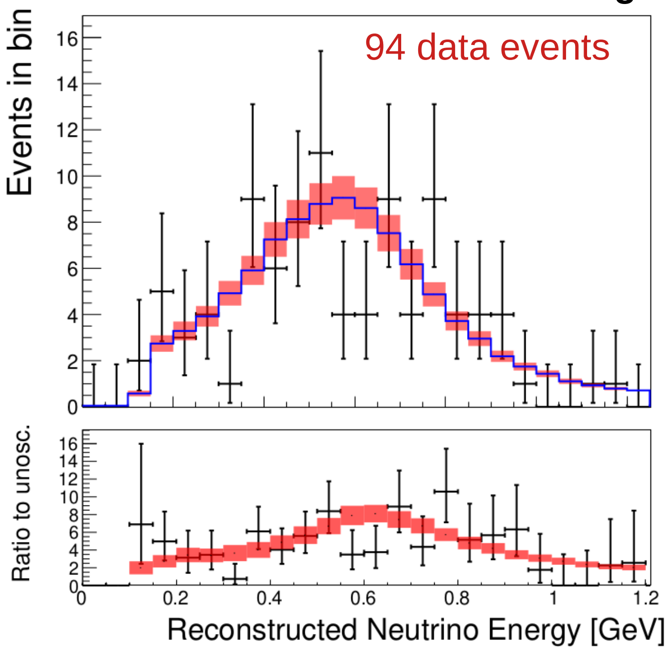
SK data fit results

Three samples with e-like cherenov rings:

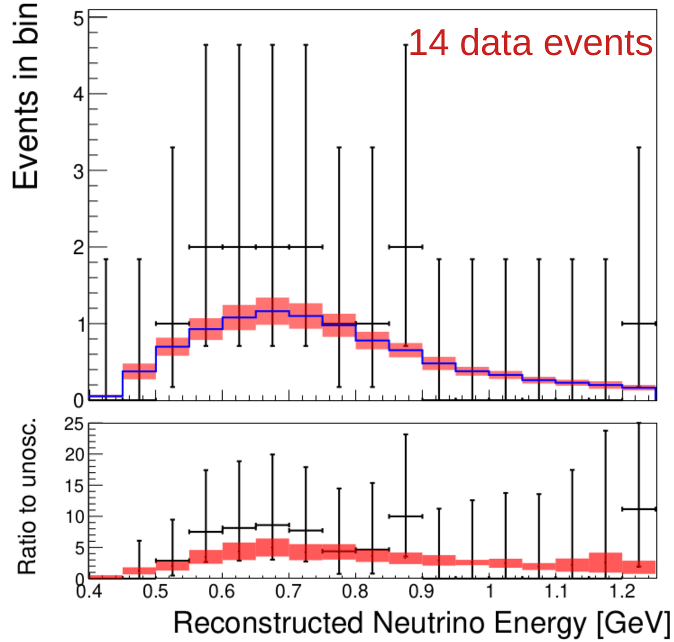
- Two samples with one e-like ring; one in neutrino mode and one in anti-neutrino mode
- One sample with one e-like ring and Michel electron from pion below cherenkov threshold

Uncertainty on rate is 4.7%-5.9% for single ring e-like samples and 14.3% for Michel electron sample.

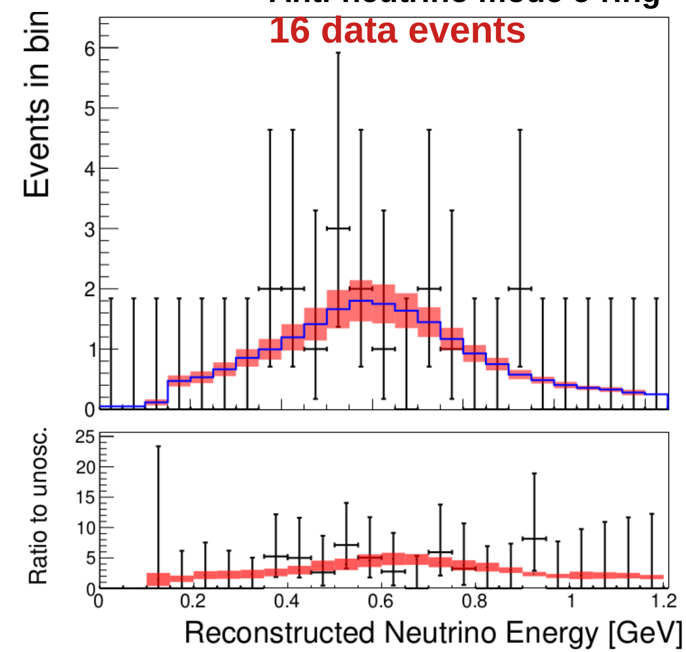
Neutrino mode e-ring



Neutrino mode e-ring and michel electron

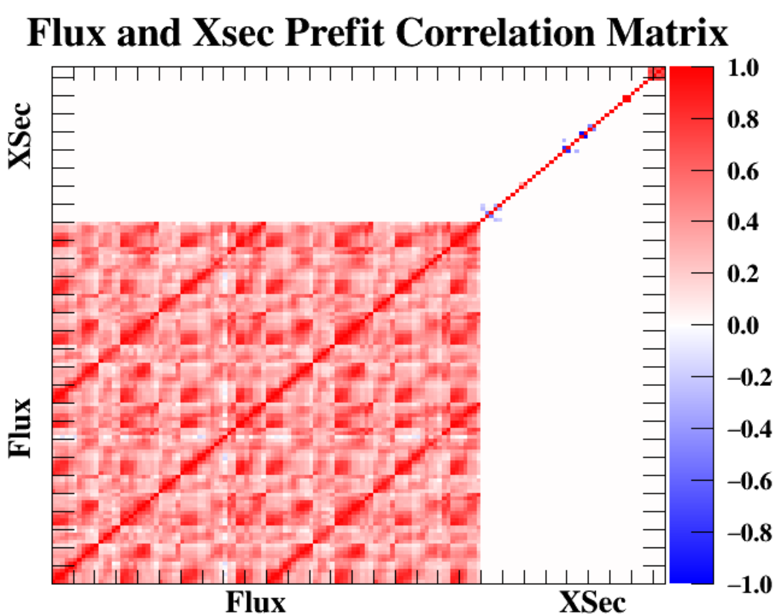


Anti-neutrino mode e-ring

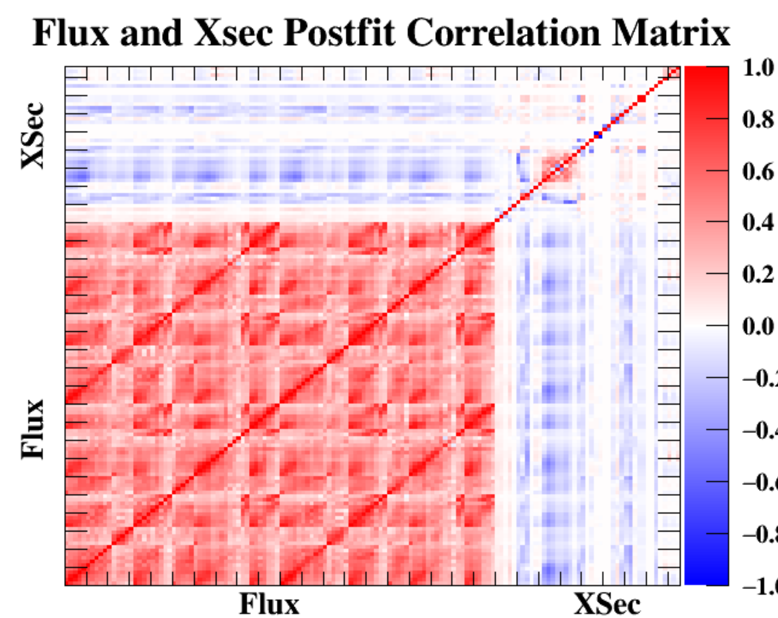


ND280 fit results

- ND280 data constraints uncertainties on neutrino interactions and neutrino flux before oscillations have occurred
- Significantly reduces uncertainty on prediction at SK
- ND280 constrains systematics to the ~3% level
- The ND280 fit matches our data well (prior model p-value of 74%)



T2K Preliminary



T2K Preliminary

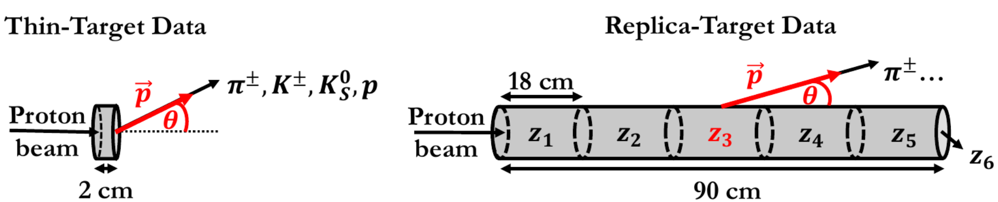
Summary of Data

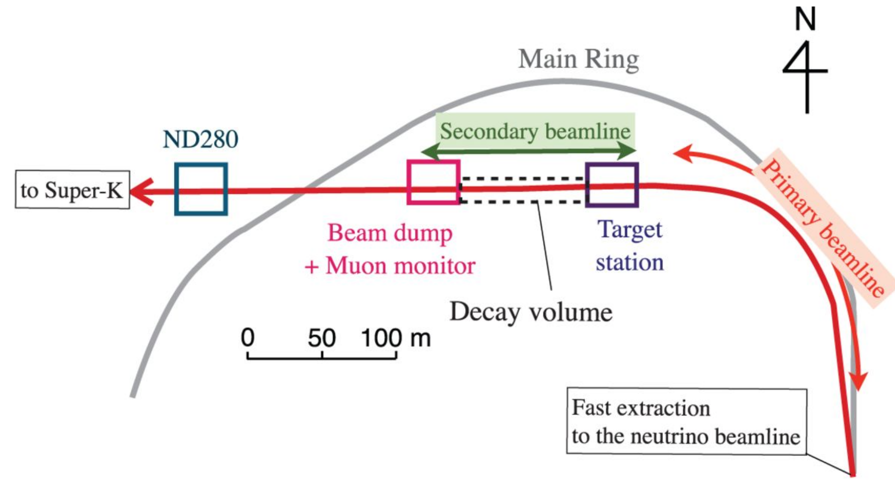
Selection	Run 1-10 POT	Events in Data
FHC 1Rμ	19.644×10^{20}	318
FHC 1Re		94
FHC 1Re1d.e		14
RHC 1Rμ	16.34556×10^{20}	137
RHC 1Re		16

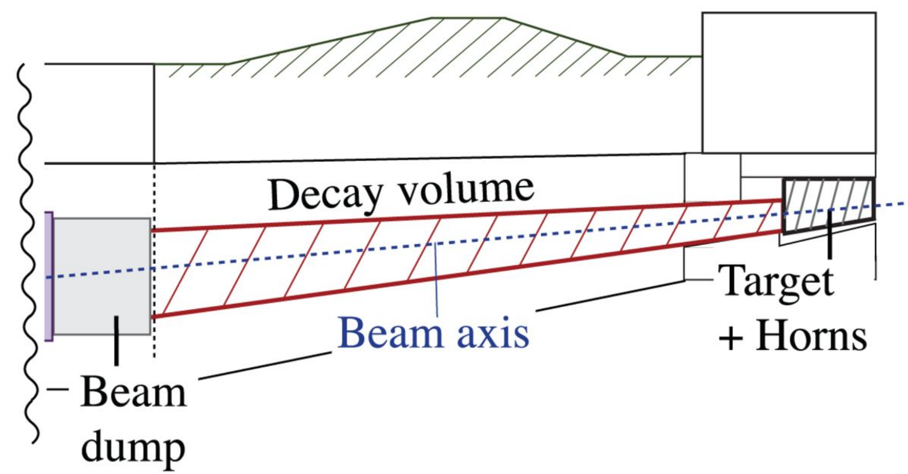
Neutrino Flux

- Neutrino beam is produced by colliding protons from J-PARC facility with graphite target
- Many hadrons are produced in collision
- Hadrons are focussed by a 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**

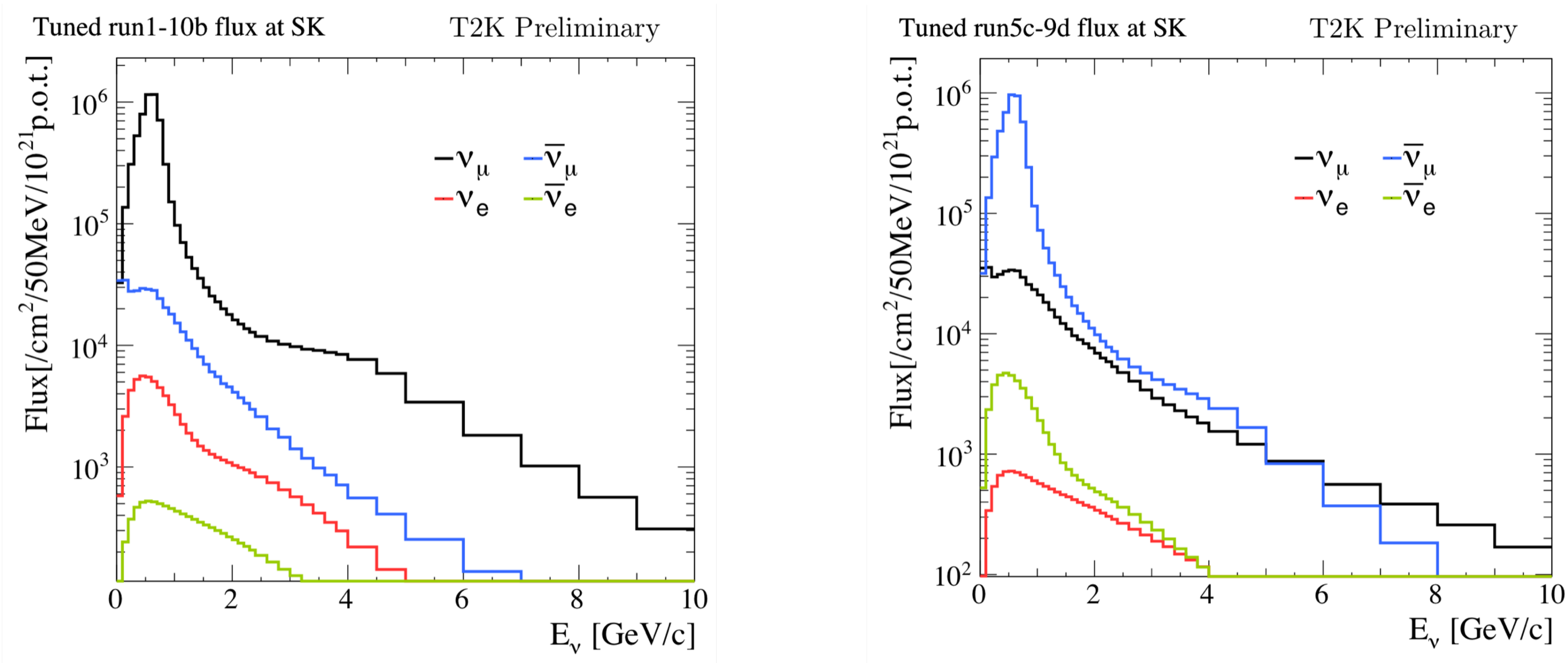






SK flux prediction

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



Neutrino energy reconstruction at SK

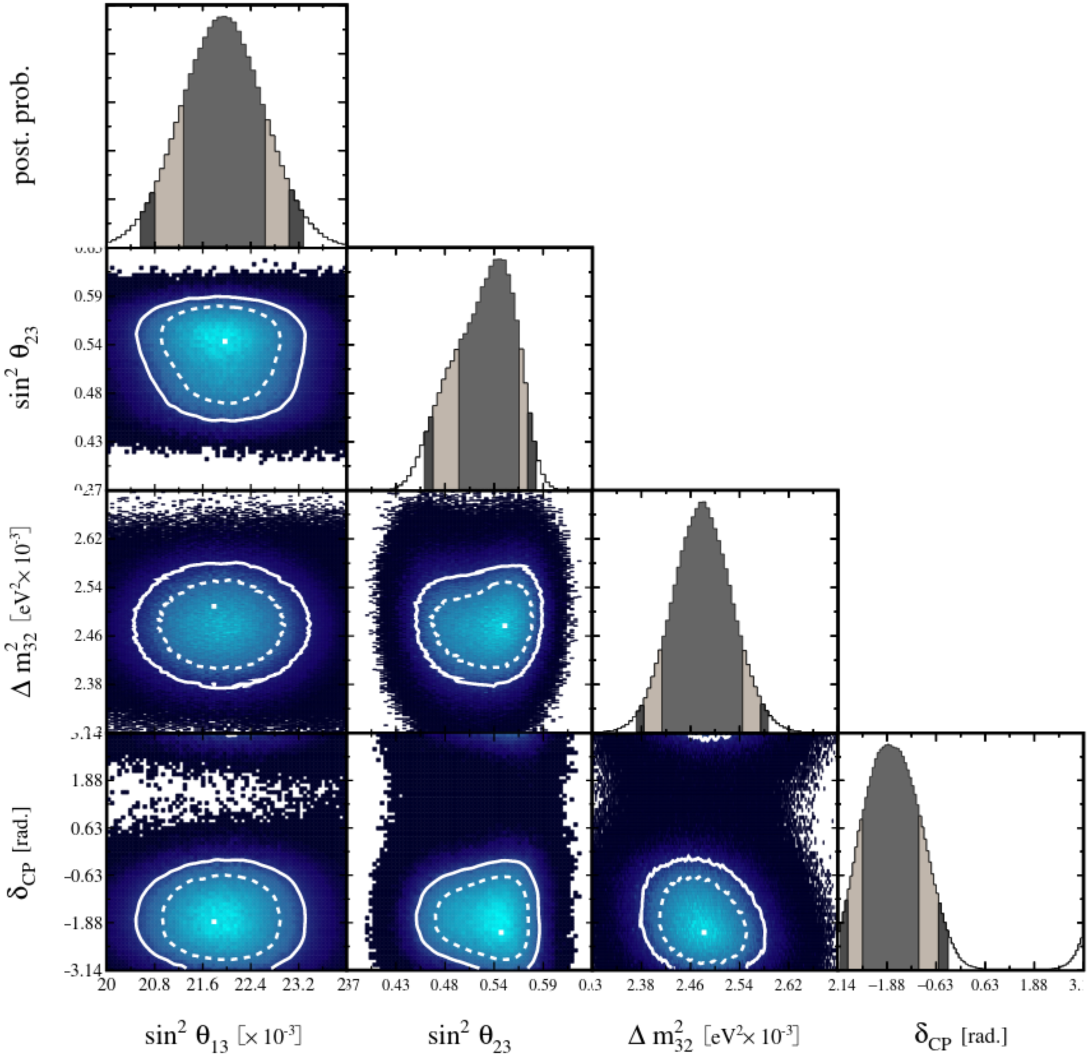
Neutrino energy reconstructed assuming CCQE interaction for single-ring samples.
Only uses lepton kinematics, particle masses and nuclear model.

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

For single-ring with 1 michel electron sample, events assumed to have come from delta++ decay.

$$E_{reco} = \frac{m_{\Delta++}^2 - m_p^2 - m_l^2 + 2m_p E_l}{2\left(m_p - E_l + p_l \cos\theta_{\nu l}\right)}$$

Posterior probabilities



Bayesian "triangle plot" of all oscillation parameters.

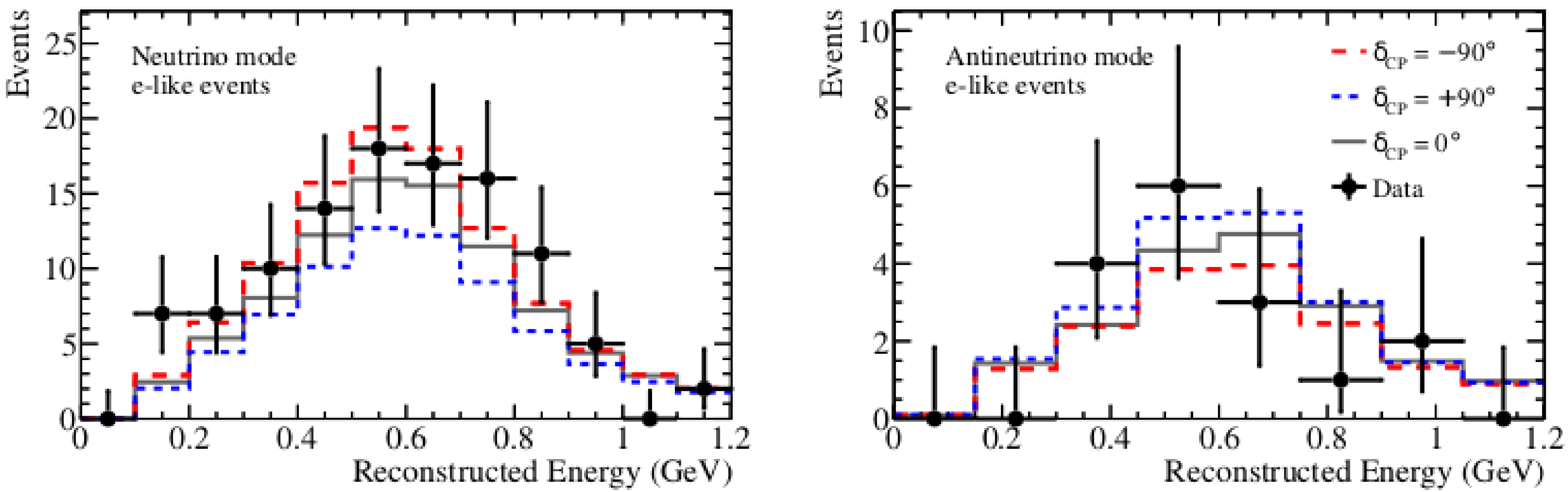
2D posteriors:
- Dashed lines 68% credible interval
- Solid lines 90% credible interval

1D posteriors:
- 68%, 90% and 95.4% (2σ)

Appearance dCP comparison

Comparison of 1 e-like ring samples at SK for different values of dCP

Other oscillation parameters set at best-fit values.



SK p-values

SK p-values using reactor constraint.

Sample / p-value	**Shape-based**	**Total Rate-based**
FHC 1Rμ	0.48	0.18
FHC 1Re	0.19	0.49
RHC 1Rμ	0.85	0.74
RHC 1Re	0.61	0.39
FHC 1Re1d.e.	0.86	0.22
Total	0.73	0.30

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

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

Data at ND280

Data at SK

Oscillation Parameters

Flux

Interaction Model

ND280

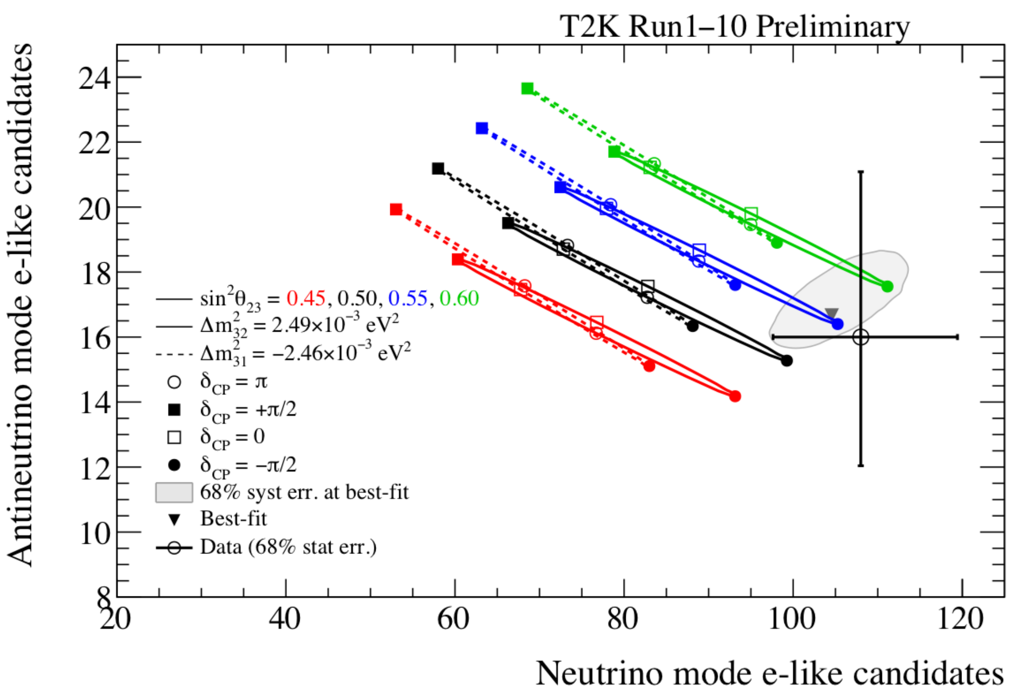
SK Detector

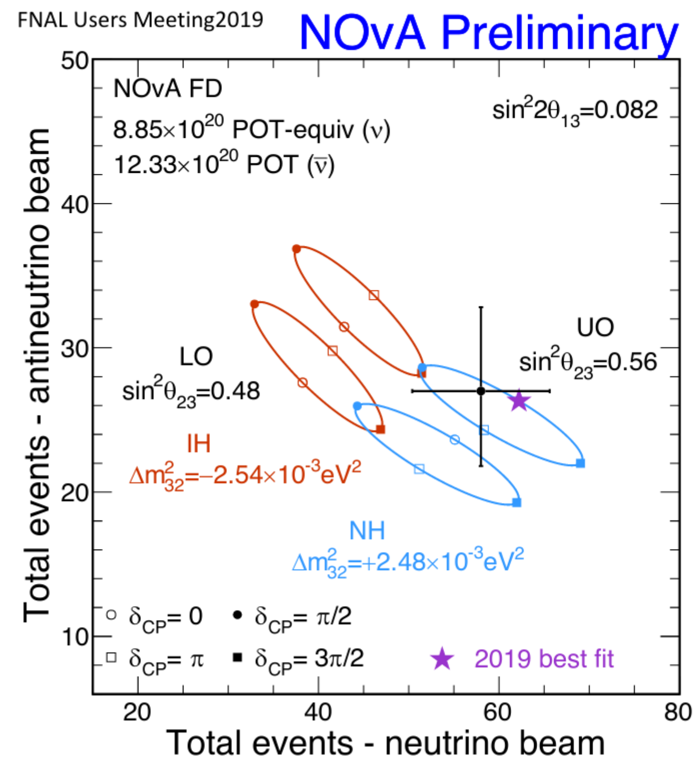
What we want!!

Use priors from various sources

T2K-NOvA joint-fit

- T2K and NOvA have different baselines and energies so have different sensitivities to oscillation parameters
- Joint-fit between the two experiments should lift some degeneracies in oscillation parameters and give more precise measurements

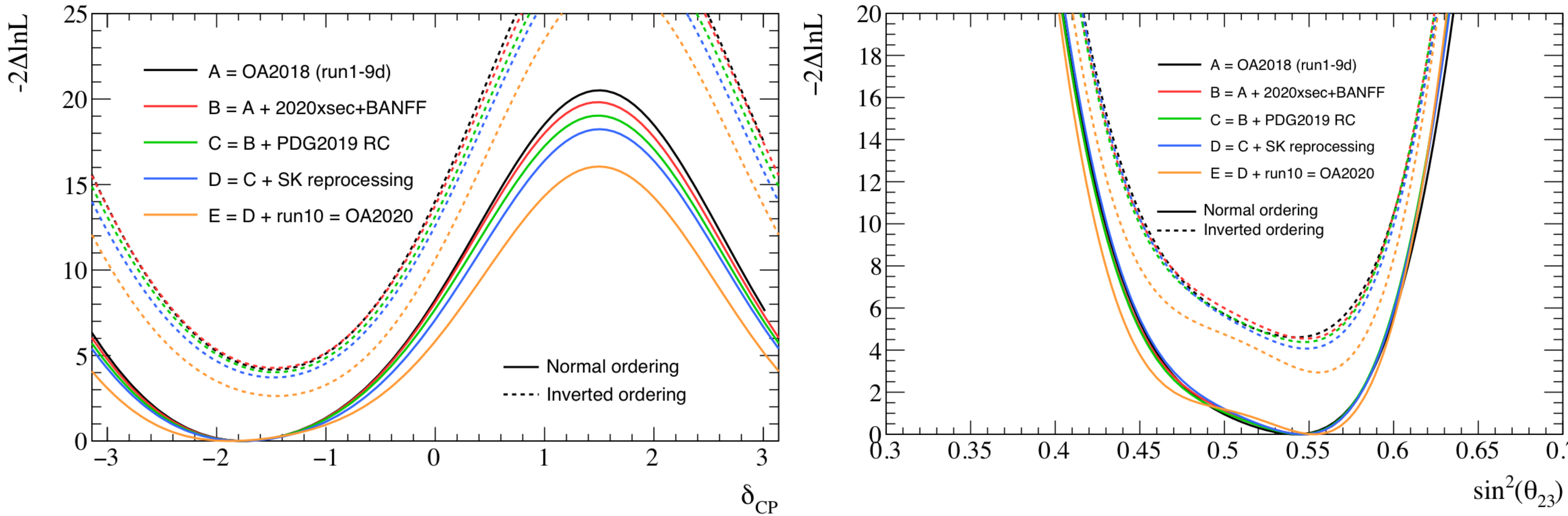




Comparison to previous analyses

Comparison of 2020 analysis with 2018 analysis, showing the impact of different updates in the analysis on the sensitivity.

- BANFF is the ND280 fit
- SK reprocessing migrates some event due to new calibration
- Addition of new data has largest impact



Summary of oscillation results

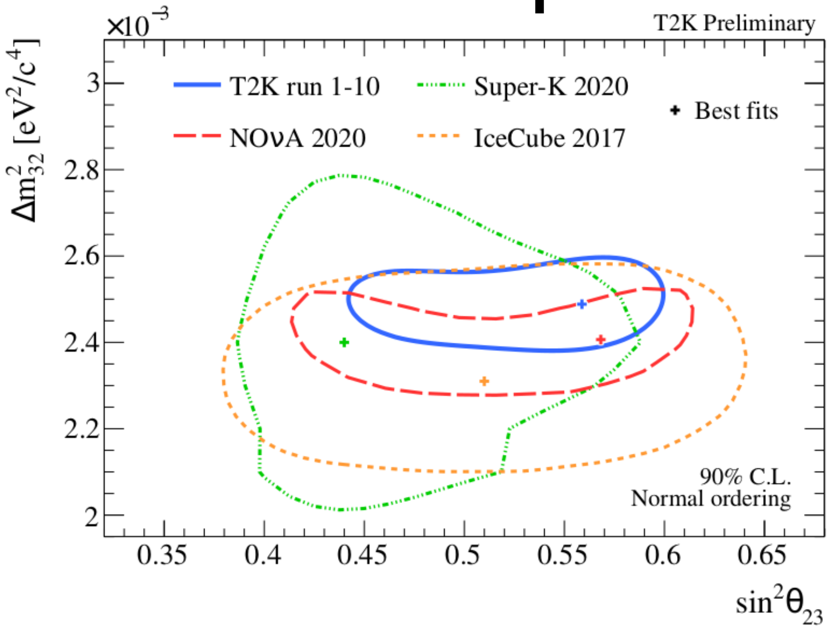
Disappearance best-fit and credible intervals with reactor constraint

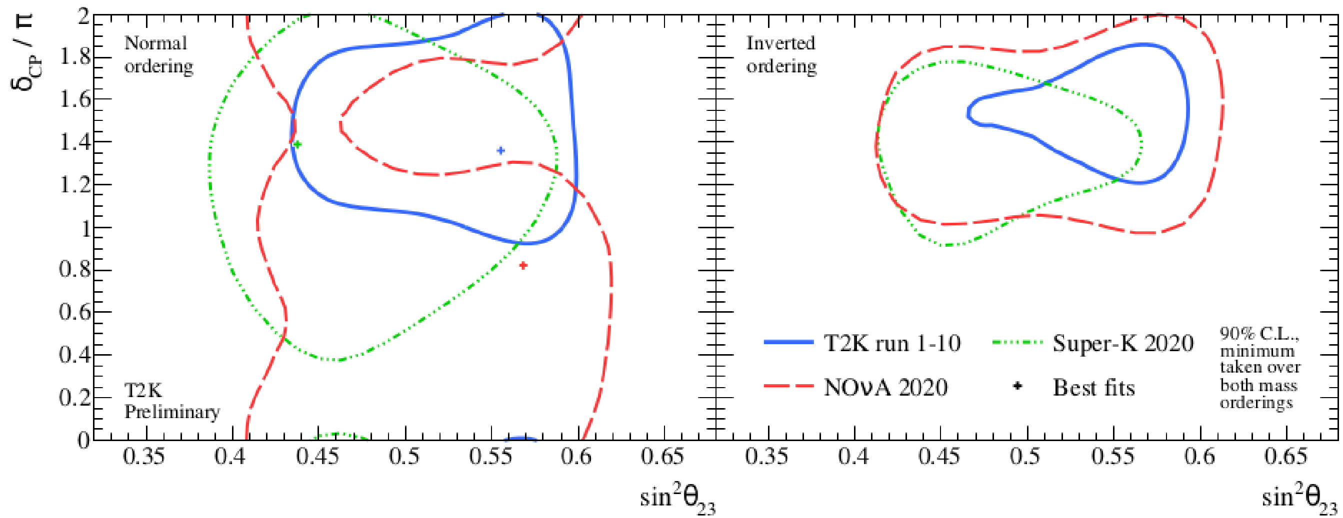
	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})\mathrm{eV}^2$
2D best fit	0.546	2.49
68% C.I. (1σ) range	0.50 – 0.57	2.408 – 2.548
90% C.I. range	0.460 – 0.587	-2.596 – -2.452 & 2.368 – 2.592

Appearance best-fit and credible intervals with reactor constraint

	$\sin^2\theta_{13}$	δ_{CP}
2D best fit	0.0220	-1.967
68% C.I. (1σ) range	0.0212 – 0.0226	-2.545 – -1.037
90% C.I. range	0.0208 – 0.0231	-2.922 – -0.565
95.4% C.I. range	0.0206 – 0.0234	$-\pi$ – -0.346
99% C.I. range	0.0201 – 0.0237	$-\pi$ – 0.063 & 2.827 – π
99.7% C.I. range	0.0198 – 0.0240	$-\pi$ – 0.346 & 2.545 – π

Comparison to other experiments





Different fitters

Summary of the different statistical techniques used by the three fitters at T2K

	Analysis 1	Analysis 2	Analysis 3
Kinematic variables for 1Re sample at SK	Erec-θ	p_e-θ	Erec-θ
Likelihood	Binned Poisson Likelihood Ratio	Binned Poisson Likelihood Ratio	Binned Poisson Likelihood Ratio
Likelihood Optimization	Markov Chain Monte Carlo	Gradient descent and grid scan	Gradient descent and grid scan
Contours/limits produced	Bayesian Credible Intervals	Frequentist Confidence Intervals with Feldman-Cousins (credible intervals supplemental)	Frequentist Confidence Intervals with Feldman-Cousins
Mass Hierarchy Analysis	Bayes factor from fraction of MCMC points in each hierarchy	Bayes factor from likelihood integration	Frequentist p-value from generated PDF
Near Detector Information	Simultaneous joint fit	Constraint Matrix	Constraint Matrix
Systematics Handling	Simultaneous fit then marginalization	Marginalization during fit	Marginalization during fit