Measuring the neutrino CP phase and mass ordering

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Outline

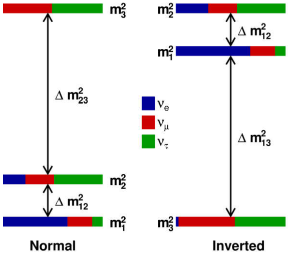
- Introduction to the T2K experiment
- CP phase:
  - T2K measurement
  - Comparison to expected sensitivity
  - Feldman-Cousins critical value behaviour
- Mass ordering:
  - Frequentist properties of the mass ordering posterior probability
  - Mass ordering sensitivity

3-flavour neutrino oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{accelerator/atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{accelerator/reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{solar}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

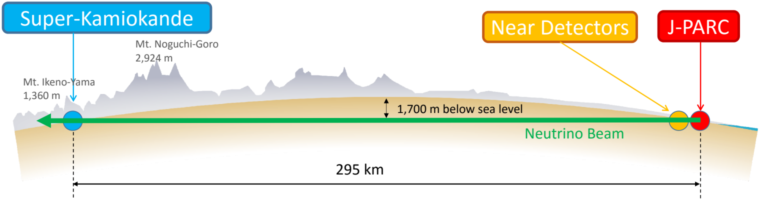
$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

- Long baseline experiments can measure:
  - θ_{23} and Δm^2_{32} via disappearance channel
  - θ_{13} and δ_{CP} via appearance channel
  - Mass ordering



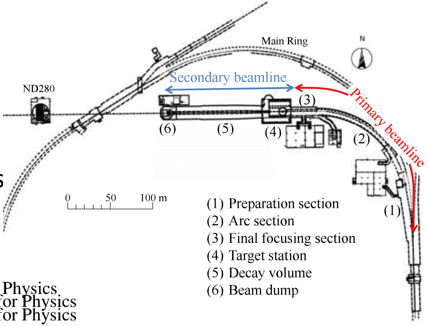
The T2K experiment

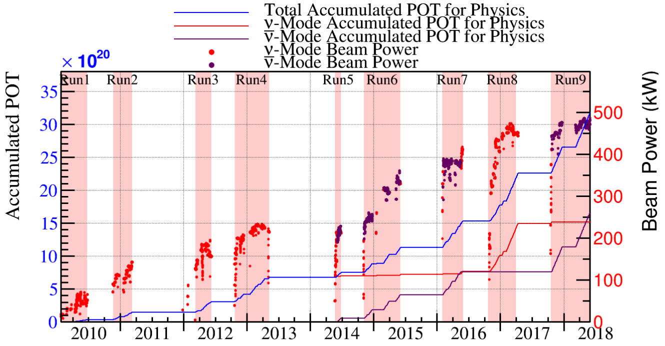
- Long baseline neutrino oscillation experiment in Japan
  - ν_μ beam produced at J-PARC, Tokai
  - Near detectors at J-PARC, 280m downstream of target
  - Super-Kamiokande (SK) far detector, 295km downstream of target in Kamioka
  - Off-axis beam produces energy spectrum peaked at 0.6 GeV
- Precision measurements of ν_μ disappearance
- Originally designed to discover ν_e appearance
- Currently searching for CP-violation



Neutrino beamline

- Stable beam running at 485kW
- Three horn magnets focus π to produce ν-mode or $\bar{\nu}$-mode beam
- Delivered 3.16×10^{21} total protons on target (POT)

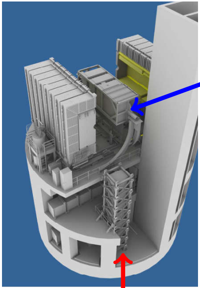




Analysis approach

- Neutrino flux model
  - Simulation and NA61 and T2K replica target data on π and K yields
- Neutrino cross-section model
  - Simulation and external data on $\nu/e/h$ interactions
- Detector model
  - Simulation and calibration and test beam data
- Make predictions at ND280 and SK
  - Parametrise cross-section and flux model
  - Constrain cross-section and flux by tuning ND280 prediction to observation
- Extract oscillation physics
  - Perform simultaneous fits of the 5 SK samples to measure oscillation parameters

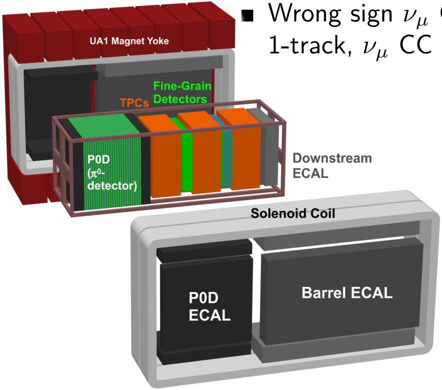
ND280 data fit



ND280 (2.5° off-axis)

INGRID (on-axis)

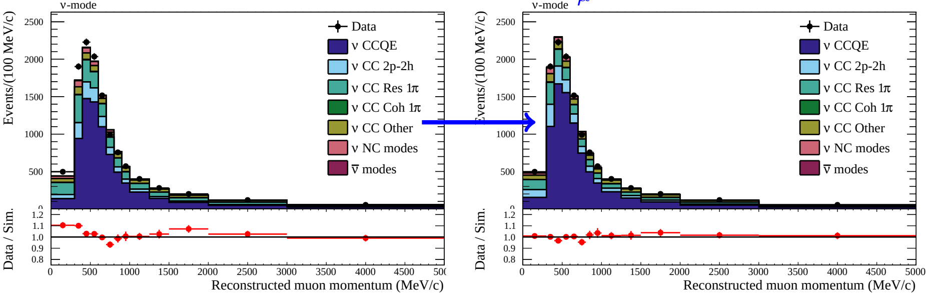
- Fit reduces flux and interaction model uncertainties at SK
- Also use ND280 to measure ν-nucleus cross-sections



- 3 ND280 ν topologies:
  - ν_μ CC0π, ν_μ CC1π^+, ν_μ CC other
- 4 ND280 $\bar{\nu}$ topologies:
  - $\bar{\nu}_\mu$ CC 1-track, $\bar{\nu}_\mu$ CC N-track
  - Wrong sign ν_μ CC 1-track, ν_μ CC N-track

ND280 data fit

ν_μ CC0π data fit



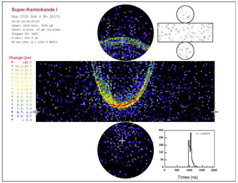
PRELIMINARY

PRELIMINARY

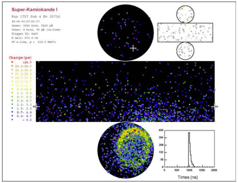
Group	Pre-fit Error (%)	Post-fit error (%)
ν_μ sample	14.66	5.12
$\bar{\nu}_\mu$ sample	12.52	4.45
ν_e sample	16.85	8.81
$\bar{\nu}_e$ sample	14.41	7.13
ν_e sample with decay electron	21.75	18.38

Super-Kamiokande far detector

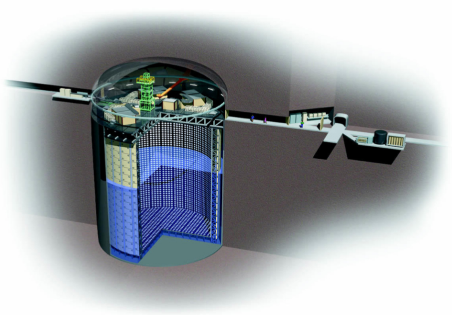
- 50kt water Cherenkov detector
- Inner detector instrumented with 11000 PMTs for 40% photo coverage
- Excellent ν_e/ν_μ separation and good reconstruction at T2K energy

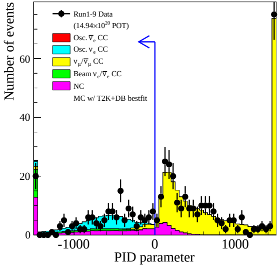


(a) μ-like ring

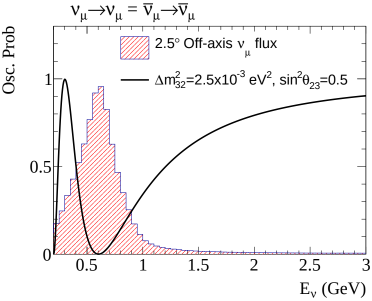


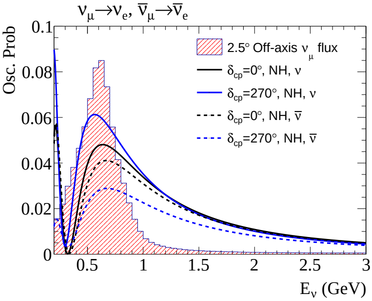
(b) e-like ring

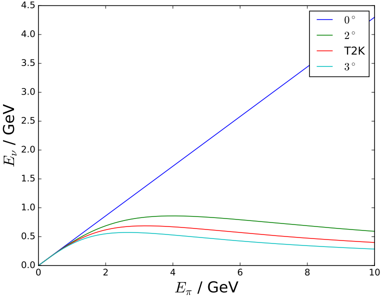




Neutrino oscillation at SK

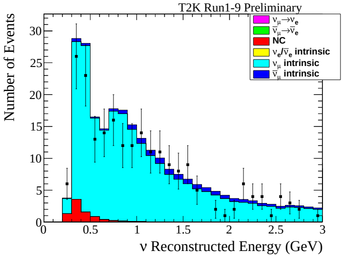




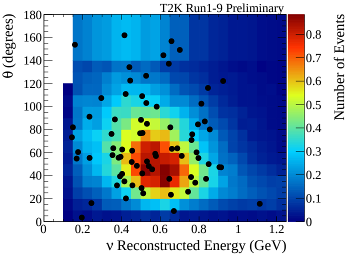


- 2.5° off-axis beam flattens neutrino energy versus parent pion energy
- Results in flux peak in the region of the oscillation maximum

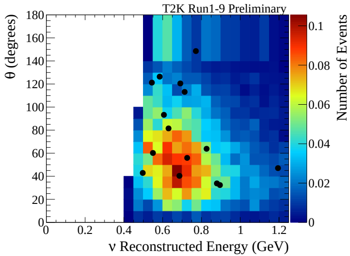
SK data fits - FHC



FHC 1Rμ



FHC 1Re

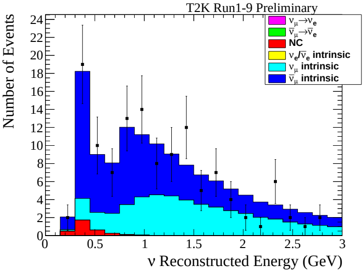


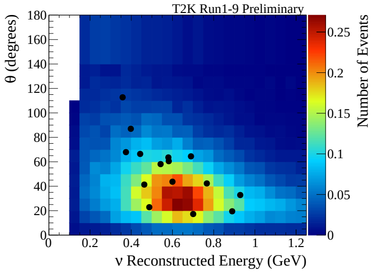
FHC CC1π^+

Sample	Asimov A	Data
μ-like	272.4	243
e-like	72.8	75
CC1π^+-like	6.9	15

Asimov A: $\sin^2\theta_{13} = 0.0212$, $\sin^2\theta_{23} = 0.528$, $\delta_{CP} = -1.601$, $\Delta m^2_{32} = 2.509 \times 10^{-3}\,\text{eV}^2\,\text{c}^{-4}$

SK data fits - RHC





RHC 1Rμ

RHC 1Re

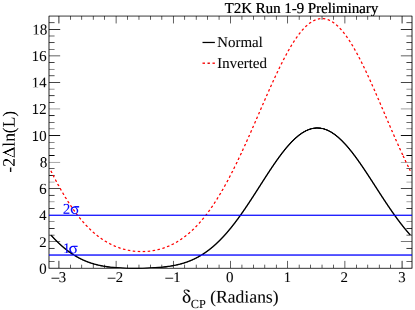
Sample	Asimov A	Data
μ-like	139.5	140
e-like	16.8	15

SK event rates

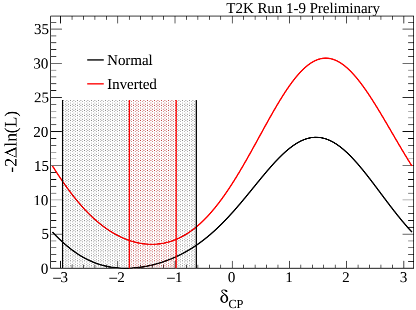
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_μ-like sample	272.4	272.1	272.4	272.8	243
ν_e-like sample	72.8	60.8	49.3	61.3	75
$\bar{\nu}_\mu$-like sample	139.5	139.2	139.5	139.9	140
$\bar{\nu}_e$-like sample	16.8	19.2	21.3	18.9	15
ν_e CC1π^+-like sample	6.9	6.0	4.8	5.7	15

- $\sin^2\theta_{12} = 0.307$
- $\Delta m^2_{21} = 7.530 \times 10^{-5}$ eV^2 c^{-4}
- $\sin^2\theta_{23} = 0.528$
- $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2 c^{-4}
- $\sin^2\theta_{13} = 2.12 \times 10^{-2}$
- Normal ordering

δ_{CP}



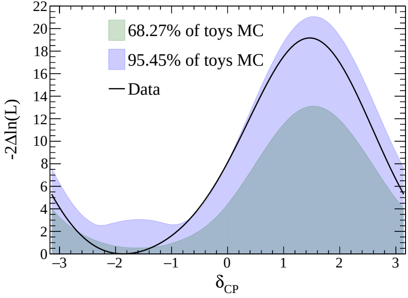
(a) MC



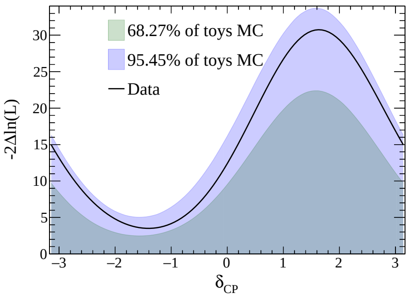
(b) Data

- CP conservation is rejected at 2σ

Comparison of δ v mass ordering with sensitivity



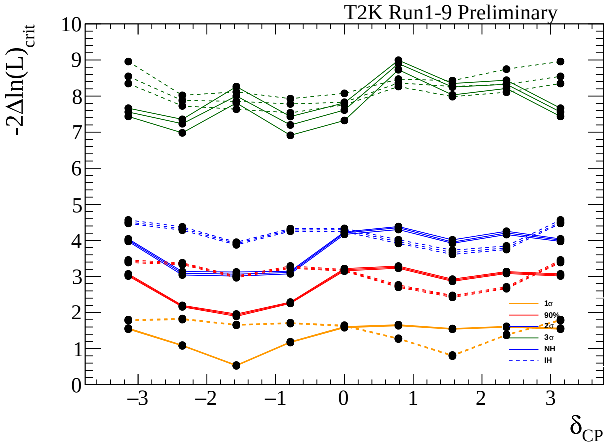
NO



IO

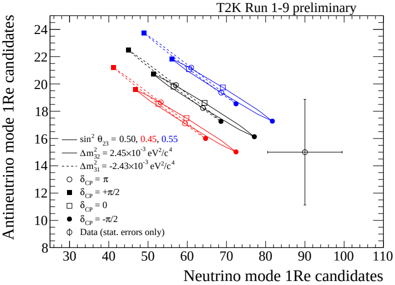
- Approximately 5% of toys are more extreme than our data
- 25% of toys exclude CP conservation at 2σ (both $\delta_{CP} = 0$ and $\delta_{CP} = \pi$)

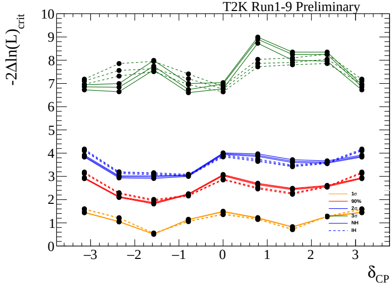
FC critical value variation



- $\Delta\chi^2 = \chi^2_{\text{true}} - \chi^2_{\text{min}}$
- Normal ordering has lower critical values for $\delta < 0$
- Inverted ordering has lower critical values for $\delta > 0$
- Differences between FC and gaussian approx critical values

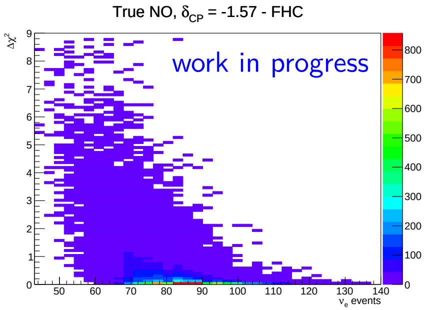
Degeneracy in δ and mass order

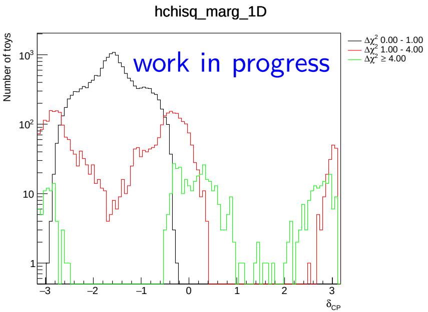




- Bi-event plot clearly shows δ/mass order degeneracy
- $\Delta\chi^2 = \chi^2_{\text{true}} - \chi^2_{\text{min}}$ allows better fits from wrong mass ordering
- This increases $\Delta\chi^2$ values
- Disallowing fits in the wrong ordering (right plot) lowers critical values and causes convergence of critical values in the two true mass orderings

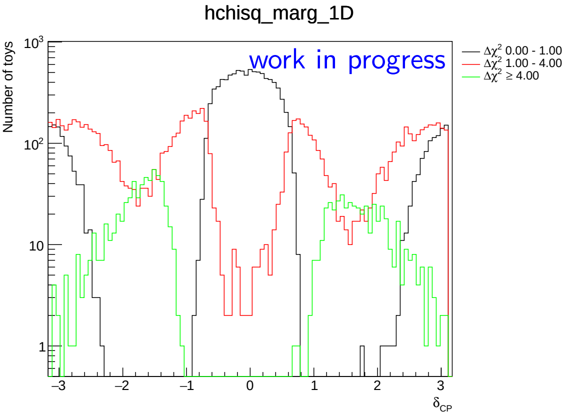
Physical boundary effects





- ν_e ($\bar{\nu}_e$) event rate reaches a maximum (minimum) at $\delta = -\pi/2(+\pi/2)$
- Fluctuations to higher ν_e event rates can't find lower χ^2 beyond physical boundary
- Toys pileup at the physical boundary (right plot)
- This decreases $\Delta\chi^2$ values (left plot)

Degeneracy between $\delta = 0$ and $\delta = \pi$



- Significant degeneracy between $\delta = 0$ and $\delta = \pi$
- Fits around $\pm\pi$ evident at lower confidence levels $\rightarrow$ increases $\Delta\chi^2$
- Lack of sensitivity to separate 0 and π means $\Delta\chi^2 = \chi^2_0 - \chi^2_\pi$ is not large enough to populate the tail of the $\Delta\chi^2$ distribution
- Effect disappears at higher confidence levels

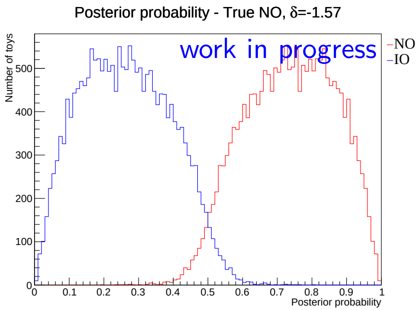
Summary of critical value behaviour

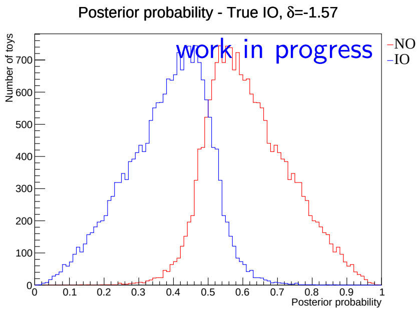
- Mass ordering is discrete, acts like an additional degree of freedom, raising critical values
- Physical boundaries lower critical values below gaussian approximation.

Frequentist properties of mass ordering posterior

- Determine the expected posterior probability distribution for the mass ordering using the Feldman-Cousins toys
- Likelihood for hypothesized hierarchy determined by averaging over the likelihoods for 101 bins of δ_{CP}
- Posterior probability is then $P_{\text{post}} = \frac{L_{NO}}{L_{NO}+L_{IO}}$

Mass ordering posterior - $\delta_{CP} = -\pi/2$

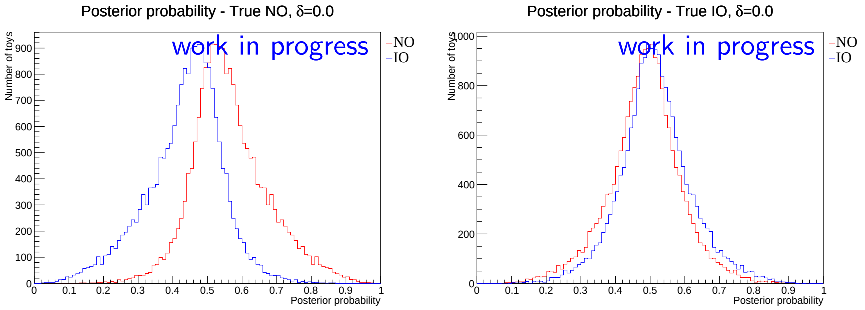




True ordering	Reject false ordering	Reject true ordering
Normal	0.02820	0.00000
Inverted	0.00000	0.00160

- For 95% threshold, rate of true hypothesis rejection $\sim$ 6% of rate of false hypothesis rejection

Mass ordering posterior - $\delta_{CP} = 0$

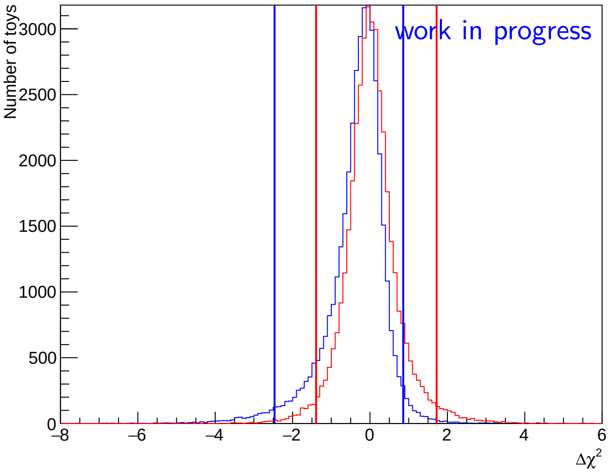


- No sensitivity to determine the mass ordering

FC summary plot

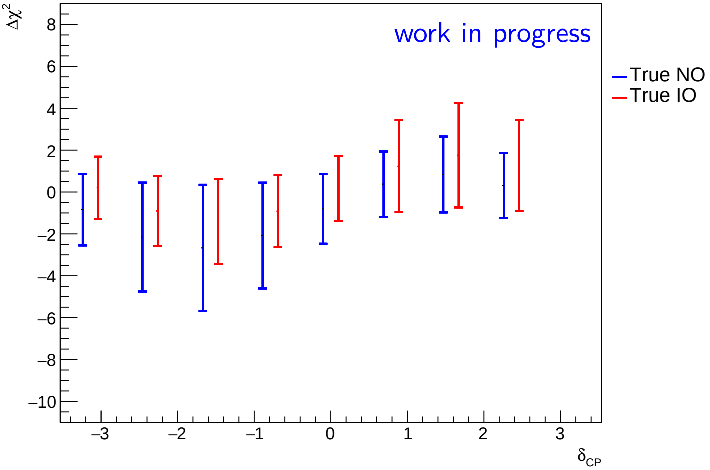
- An alternative means of presenting Feldman-Cousins information; both δ and the mass ordering in a single plot
- Use Feldman-Cousins toys to compute distributions of $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH}$ at each true point of δ and mass ordering

Example distributions for true $\delta = 0$



- Blue and red lines represent 2σ intervals for true NO and true IO respectively

FC summary plot



- 2σ intervals
- Intervals offset in δ_{CP} for readability

Conclusion

- T2K has seen a hint of CP violation, with exclusion of conservation at 2σ and a best-fit near the maximally CP violating value of $-\pi/2$
- While T2K has limited sensitivity to the mass ordering, the best-fit for δ is in the region where the ability to reject the inverted mass ordering is greatest