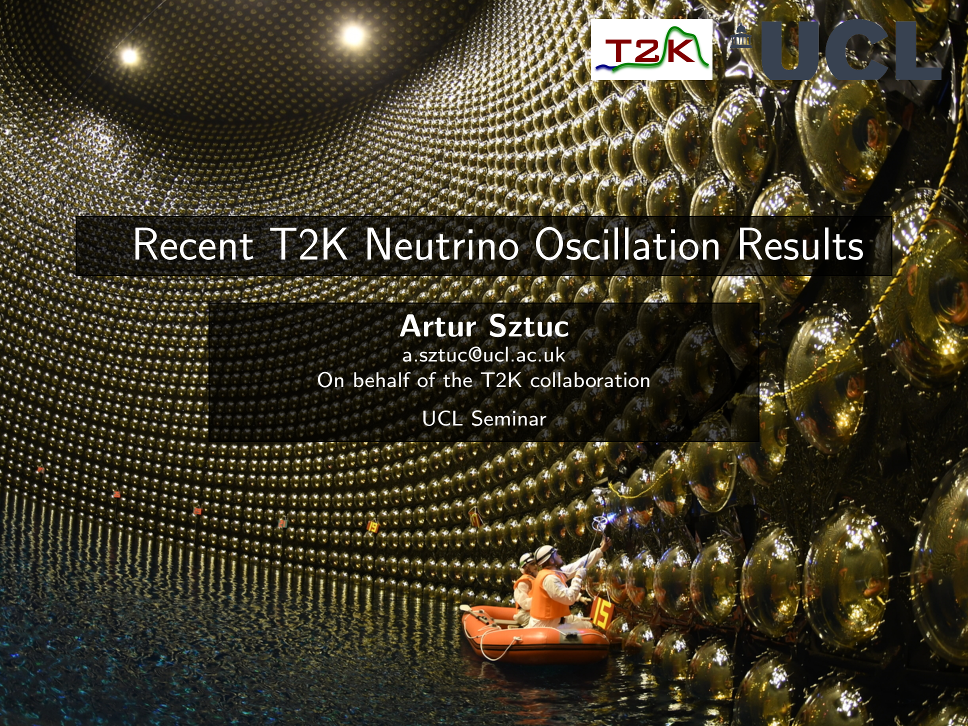

Recent T2K Neutrino Oscillation Results

Artur Sztuc

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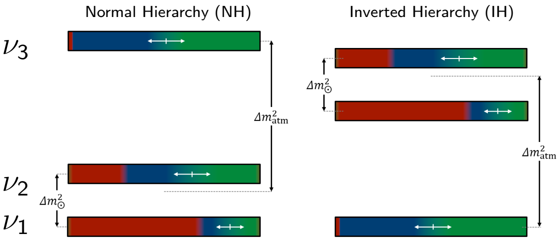
On behalf of the T2K collaboration

UCL Seminar

Outline

1. Neutrino mixing
2. T2K experimental setup
3. T2K Data and model
4. Oscillation analysis results
5. Future prospects

Neutrino Mass Mixing



- Flavour eigenstates; ν_e, ν_μ and ν_τ (interact)
- Mass eigenstates; ν_1, ν_2 and ν_3 (propagate)

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

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

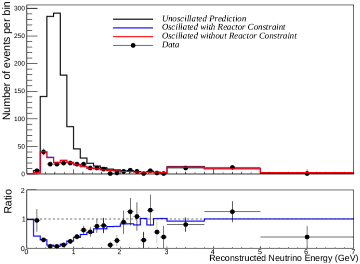
atmospheric, beam	reactor, beam	solar, reactor
Super-K, IceCube, T2K, NOvA, Opera	T2K, NOvA, Double Chooz, Daya Bay, RENO	Super-K, KamLAND, SNO

The T2K experiment

- Around 500 people from 68 institutions, 12 countries
- ~0.6 GeV narrow beam from J-PARC (ν and $\bar{\nu}$ mode)
- Near detector; ND280, 280 m from beam target, measures unoscillated spectrum
- Far detector; Super-Kamiokande, 295 km from the ν source, measures oscillated spectrum

Long baseline oscillations (@T2K)

ν_μ disappearance



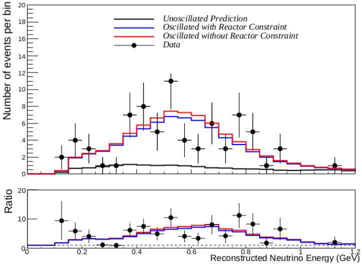
Location of the dip: $|\Delta m^2_{32}|$

(does not depend on the sign)

Depth of the dip: $\sin^2(\theta_{23})$

Difficult to separate $\theta_{23} > 45$ and $\theta_{23} < 45$

ν_e appearance



Magnitude of the peak;

$\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$, δ_{CP}

Small dependence on the sign of Δm^2_{32}

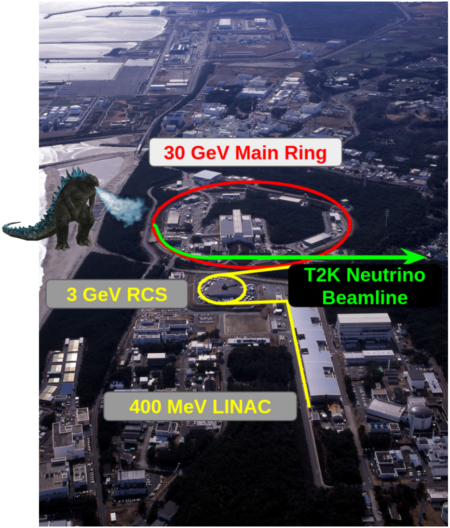
Channel for CP violation detection

First-order sensitivity: $|\Delta m^2_{32}|$, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$

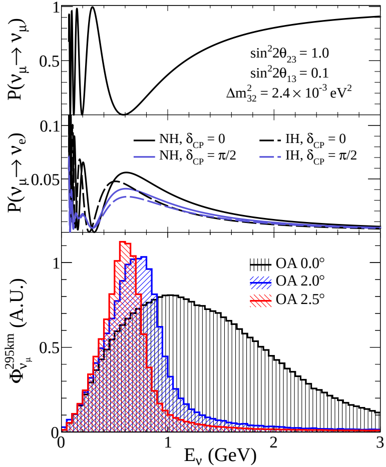
Second-order sensitivity: sign of Δm^2_{32}, $\sin^2\theta_{23}$ octant, δ_{CP}

J-PARC Facility

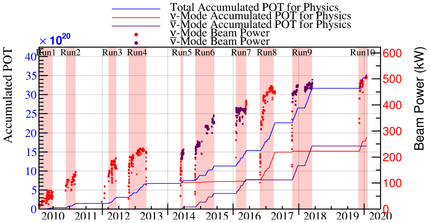
- The Main Ring shared between T2K and other experiments
- Fast extraction from the main ring with pulse every 2.5 s
- Plans to upgrade the power supply allowing 1.3 s pulse



The T2K neutrino beam



Off-axis beam angle tuned for maximal ν_μ disappearance



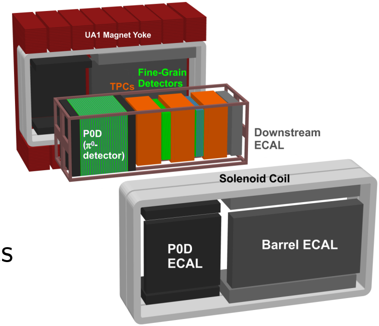
The latest result includes combined run 1–10 data

- ν_μ: 1.97×10^{21} POT
- $\bar{\nu}_\mu$: 1.65×10^{21} POT

(POT; Protons on target)

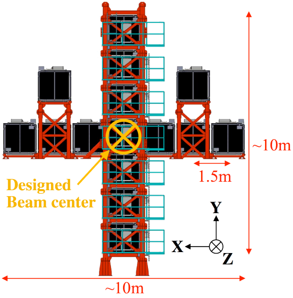
Beam operating over 500kW for the first time

T2K near detectors



ND280

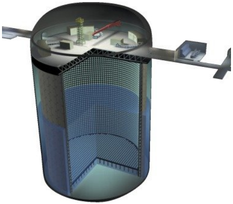
- Off-axis, 280 m from beam target
- Measures unoscillated ν spectrum
- Neutrino cross-section measurements

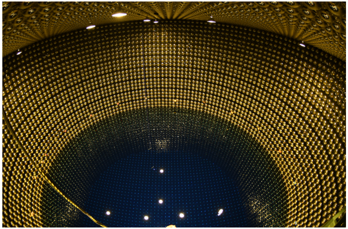


INGRID

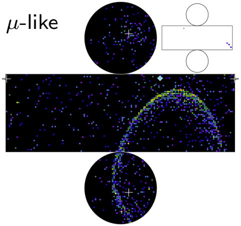
- On-axis, 280 m from beam target
- Measures beam direction and stability
- Also contributes to cross-sections
- Different flux spectrum

Super-Kamiokande detector

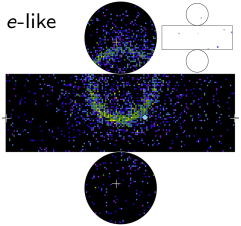




μ-like

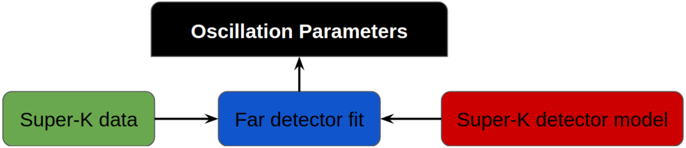


e-like



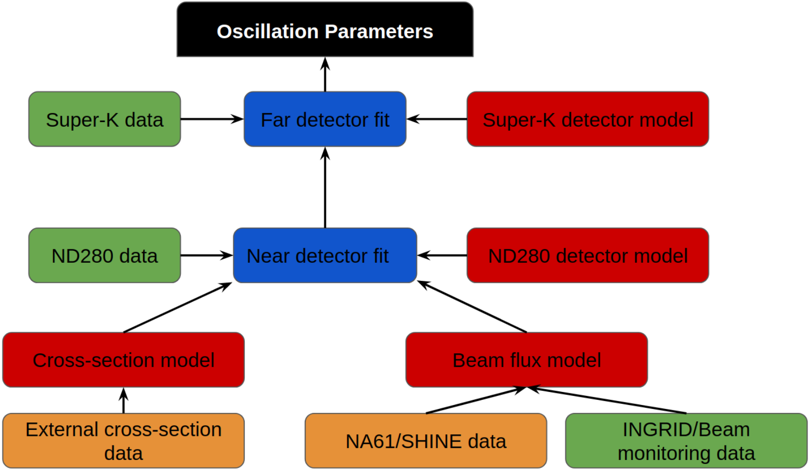
- 1000 m overburden
- 50 kton of water, 22.5 kton fiducial
- 11,000 PMTs in Inner Detector
  - 40% photo-coverage
- 2,000 PMTs in Outer Detector
  - Cosmic veto/outgoing particles

Analysis strategy



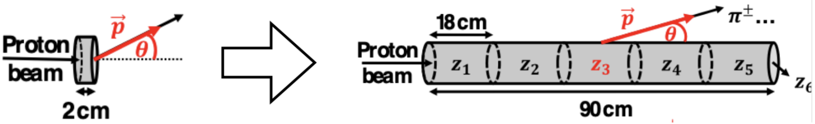
- Constraining the T2K model with Super-K data to extract oscillation parameters
- Super-K does not have enough statistics to constrain the cross-section and flux systematics well

Analysis strategy



Flux uncertainties

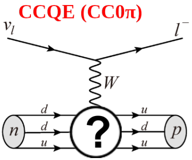
- The proton interactions on target simulated with FLUKA
- Simulation reweighted to NA61/SHINE data
- Update: thin graphite target replaced with T2K replica

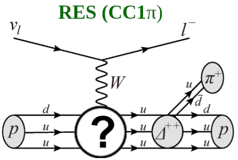


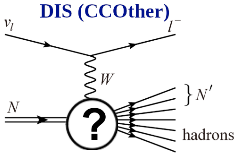
- Flux uncertainties reduced from $\sim 8\%$ to $\sim 5\%$

Cross-section model

- Three dominant scattering modes at T2K: CCQE, RES and DIS
- Moved from Relativistic Fermi Gas +RPA (2018) to a tuned Benhar spectral function
- Removal energy treated as a shift in lepton momentum, tuned to electron scattering data
- Correlated pion FSI uncertainties between ND and FD detectors
- Improved DIS treatment







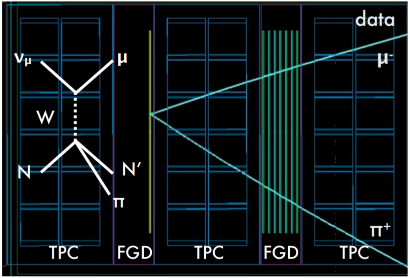
ND280 Data selection

ND280 data constrains the neutrino flux and cross-section systematics at Super-K

Data samples for two FGD targets (CH and H_2O);

- 3×2 samples for ν beam mode
  - ν_μCC0π (primary in the analysis)
  - ν_μCC1π (shown on right)
  - CCOther
- 4×2 samples for $\bar{\nu}$ beam mode
  - $\bar{\nu}_\mu$CC1Track
  - $\bar{\nu}_\mu$CCNTrack
  - ν_μCC1Track
  - ν_μCCNTrack

H_2O samples constrain water interactions at Super-K

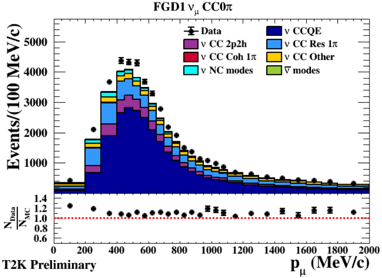


Two Fine Grid Detectors (FGD), event display shows FGD1 producing μ^+ and π^-

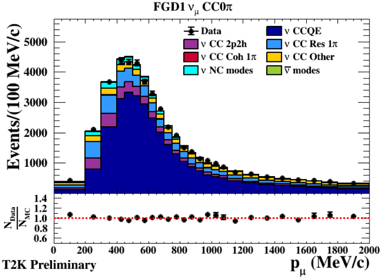
Data are binned in outgoing μ momentum and angle

ND280 data fit effect

Prefit CC0π



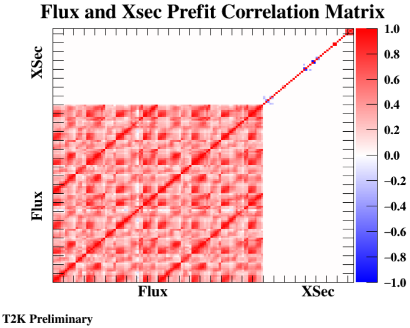
Postfit CC0π



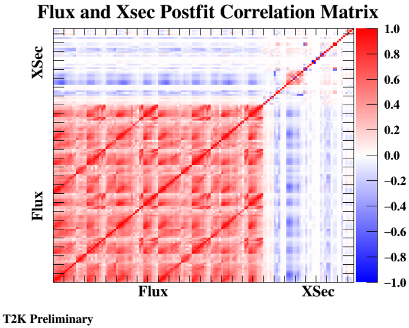
- The prediction agrees much better with the data after the ND280 fit (p-value of 74%)
- This is true for all the data samples

ND280 data fit effect

Before ND fit



After ND fit



- By constraining the predicted number of events, the ND fit introduces anti-correlations between cross-section and flux systematics

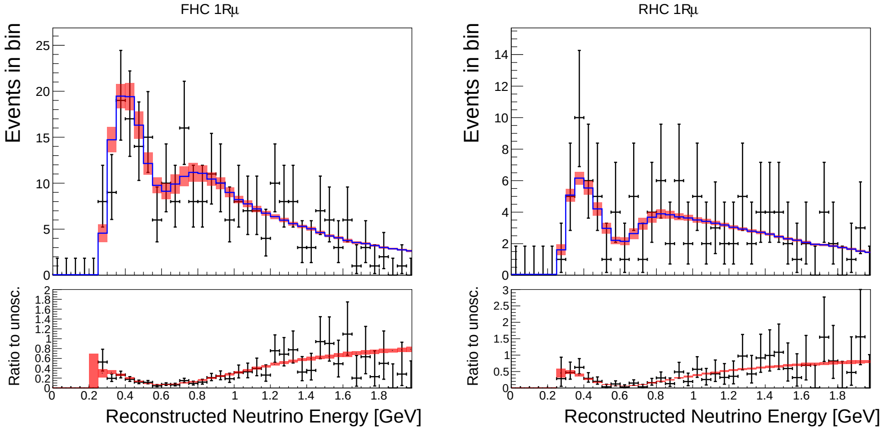
ND280 data fit effect

Super-K event rates systematic errors

Super-K sample	Without ND280	With ND280
ν-beam 1-Ring-μ	11.1 %	3.0%
ν-beam 1-Ring-e	13.0%	4.7%
$\bar{\nu}$-beam 1-Ring-μ	11.3%	4.0%
$\bar{\nu}$-beam 1-Ring-e	12.1%	5.9%

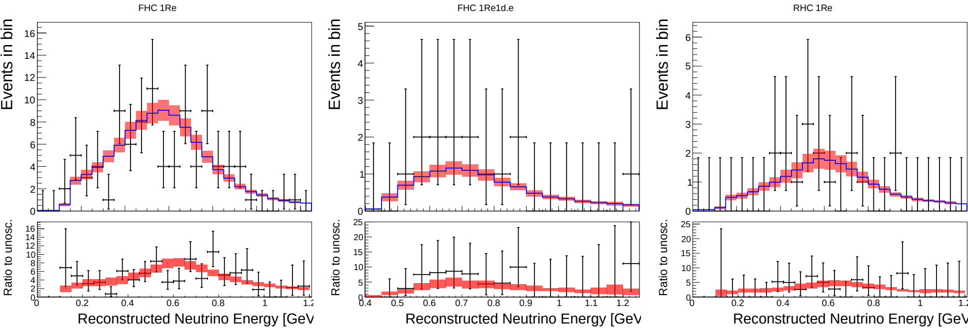
- The effect of the ND fit on the SK samples is large
- Systematic errors on Super-K event rates reduced from $\sim$ 13% to $\sim$ 4%

Super-K Data



- Two μ-like ring samples at Super-K
- One in ν-beam mode and one for $\bar{\nu}$-beam mode
- Systematic uncertainty shown in red

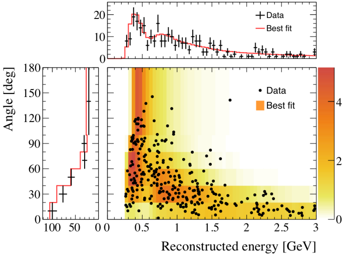
Super-K Data

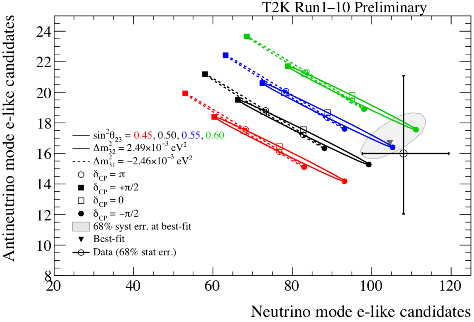


- Three *e*-like ring samples at Super-K
- One for each beam mode (ν, $\bar{\nu}$), and one targeting CC1π events with Michel electron
- Systematic uncertainty shown in red

Super-K Data

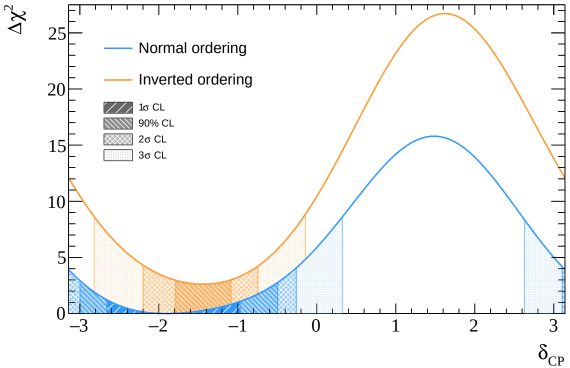
ν-beam 1-Ring-e





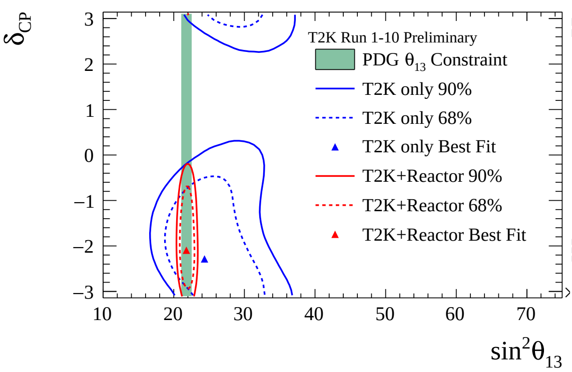
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Data
FHC 1Rμ	346.61	345.90	346.57	347.38	318
RHC 1Rμ	135.80	135.45	135.81	136.19	137
FHC 1Re	96.55	81.59	66.89	81.85	94
RHC 1Re	16.56	18.81	20.75	18.49	16
FHC 1R ν_e CC1π^+	9.30	8.10	6.59	7.79	14

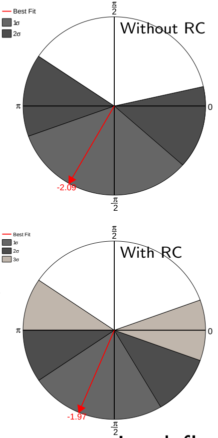
1D δ_{CP}



- T2K rejects $\sim$ 35% area of δ_{CP} values at $3\,\sigma$
- Preference for the CP-violating values of δ_{CP}
- CP-conserving values excluded at 90% CL, but not quite at $2\,\sigma$

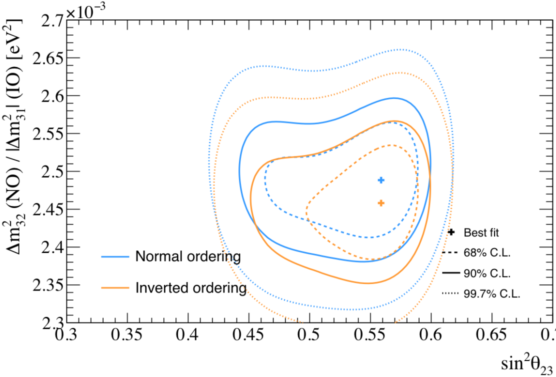
Reactor results, θ_{13} and δ_{CP}





- There are no tensions between Reactor-constrained fits and T2K-data-only
- T2K-only results for $\sin^2\theta_{13}$ agree well with PDG 2019

Disappearance results



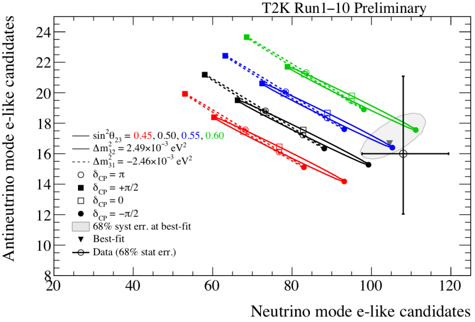
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Normal ordering	0.19	0.65	0.83
Inverted ordering	0.03	0.14	0.17
Column total	0.21	0.79	1.00

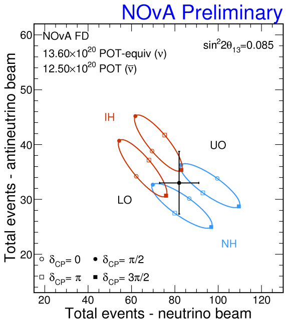
- Normal ordering and higher octant of $\sin^2\theta_{23}$ preferred
- Sensitivity to the $\sin^2\theta_{23}$ enhanced with the reactor constraint on $\sin^2\theta_{13}$

Future prospects

NOvA-T2K joined fits

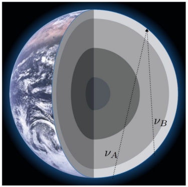
- Both experiments operate at different ν energies and oscillation baselines, with different systematic uncertainties
- Joint fit will help breaking degeneracies and maximising the impact of data

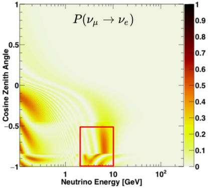


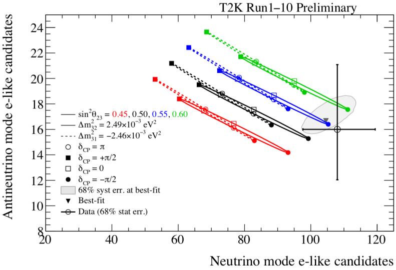


T2K-SuperK joined fits

- Also operate at very different energies and "baselines"
- Atmospheric samples will help constraining the Super-K detector uncertainties and contribute to δ_{CP} and the mass ordering

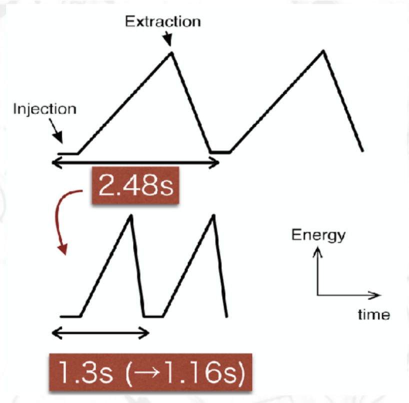






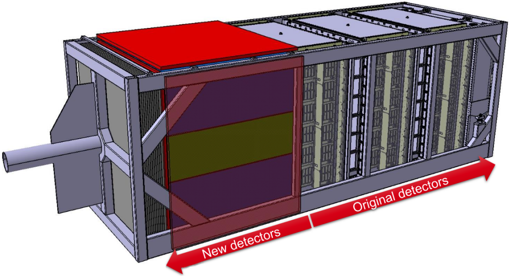
Beam upgrade

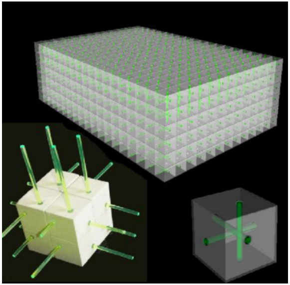
- Increase from 515kW in 2020, through 800kW in 2023 to over 1MW by 2027
- The main ring power supply upgrade completed
- Reduce the beam cycle from 2.48 s to 1.3 s (down to 1.16 s)



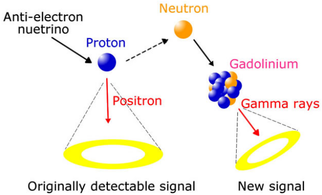
Near detector upgrade

- To be upgraded by $\sim$ 2022 after a decade of operation
- New TPC with a higher angular coverage and better point resolution
- 3D SuperFGD made of 2M cubes
- Better hadron detection and more similar phase-space coverage to SuperK

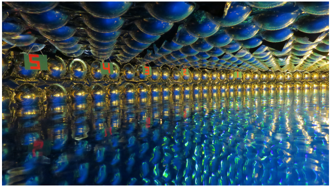


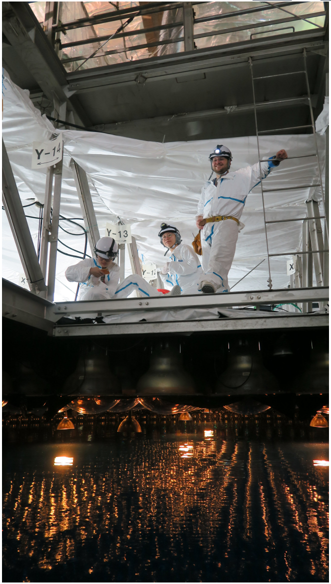


Super-Kamiokande Gadolinium



- 2018–2019 refurbishment to allow Gd doping
- Low-energy $\bar{\nu}_e$ detection via neutron capture



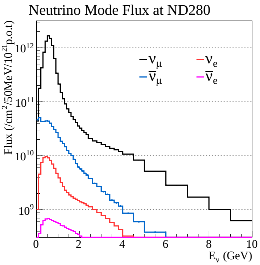


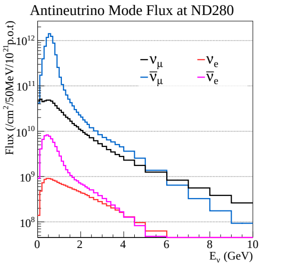
Conclusions

- CP-violating values of δ_{CP} preferred, with 35% of the CP-conserving values rejected at $3\,\sigma$ level
- Data prefers Normal Hierarchy ($\sim$83%)
- Preference for the upper octant of $\sin^2\theta_{23}$ ($\sim$79%)
- Many future upgrades planned:
  - Beam to each 1 MW by 2027
  - ND upgrades
  - Joint fits with Super-Kamiokande and NOvA
  - Super-Kamiokande with Gadollinium

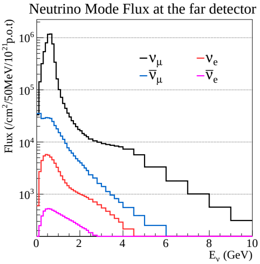
BACKUPS

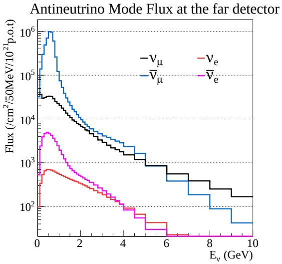
Beam flux





Beam flux composition at ND280

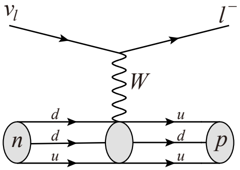




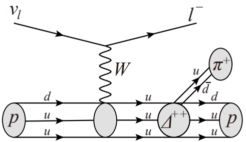
Beam flux composition at Super-K

Neutrino interactions

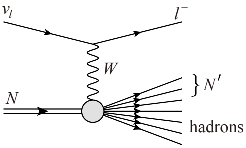
Charged Current Quasi Elastic (CCQE)



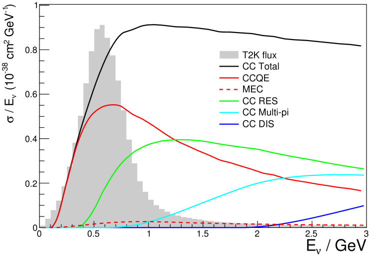
Charged Current Resonant Pion (CCRES)



Charged Current Deep Inelastic Scattering (CCDIS)

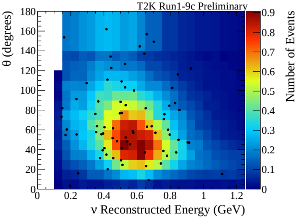


- CCQE dominant interaction mode for T2K
- Interactions with nucleon inside a nucleus
  - Nuclear model dependent
  - Nuclear effects can bias interaction mode and energy reconstruction
- Interaction and Nuclear models tuned to external data

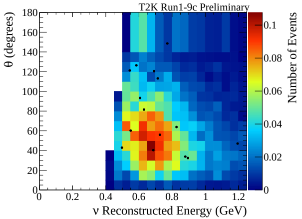


Super-K Data

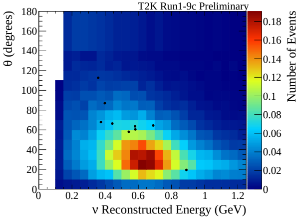
ν-beam 1-Ring-e



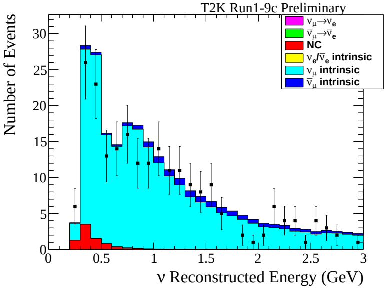
ν-beam 1-Ring-e + π^+



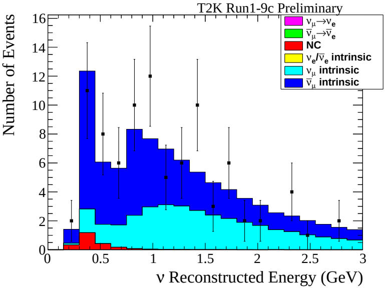
$\bar{\nu}$-beam 1-Ring-e



ν-beam 1-Ring-μ

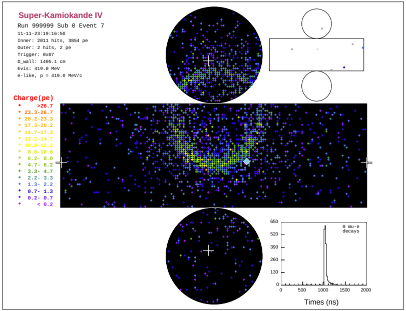


$\bar{\nu}$-beam 1-Ring-μ

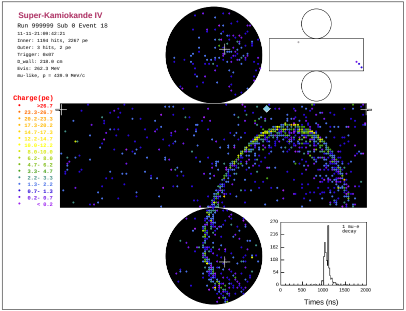


Super-K Event display

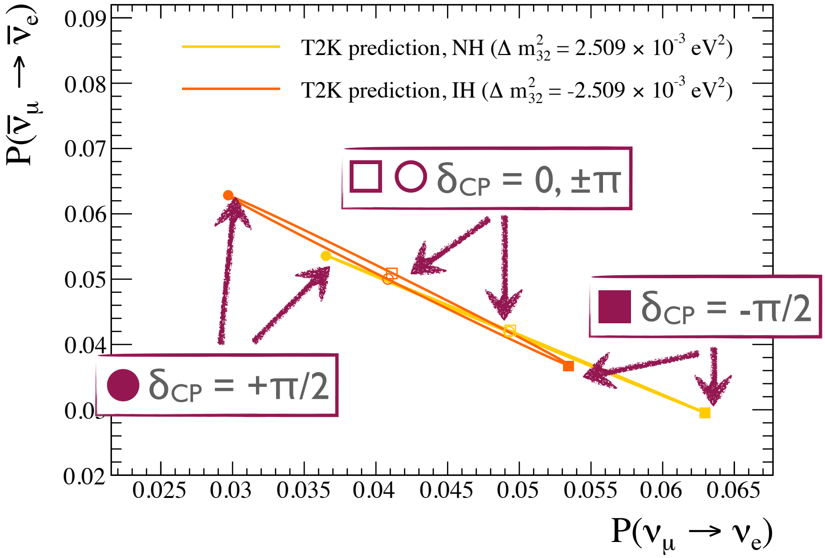
e-like event



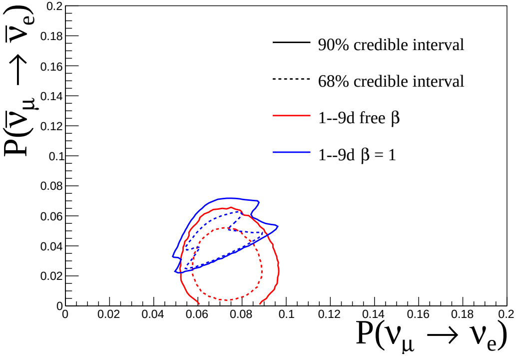
μ-like event

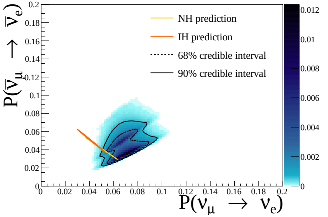


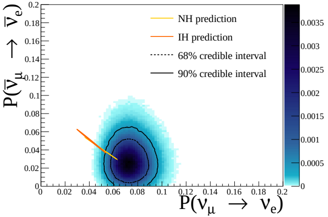
Bi-probability plots: intro



Bi-probability plots

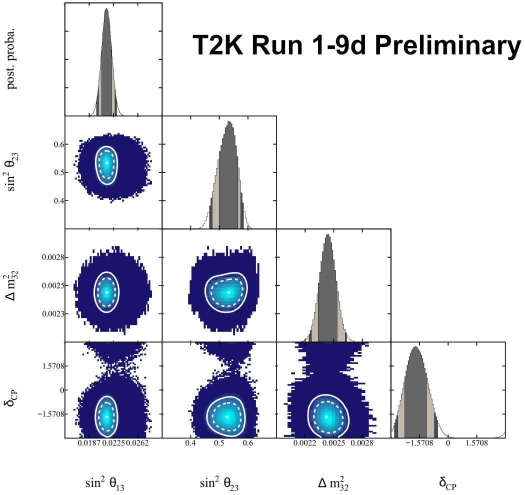




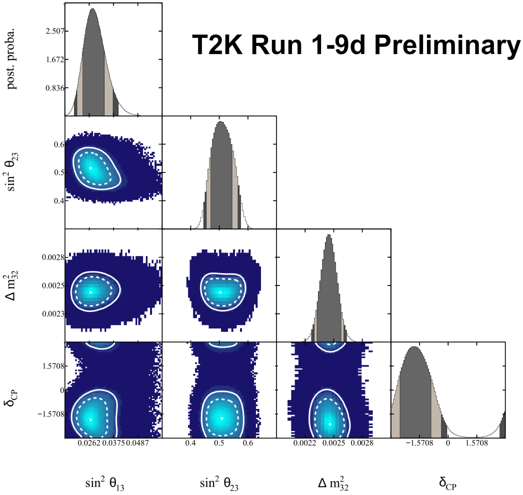


- Free β fit probes non-PMNS space
- $\beta = 1$ fit probes PMNS-only space
- Data consistent with the PMNS model

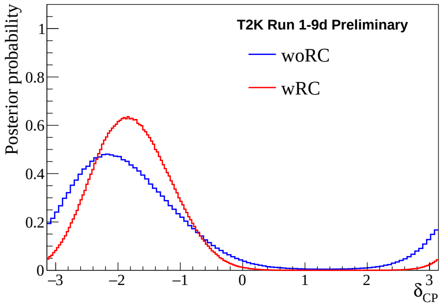
All osc parameters:
with θ_{13} reactor constraint

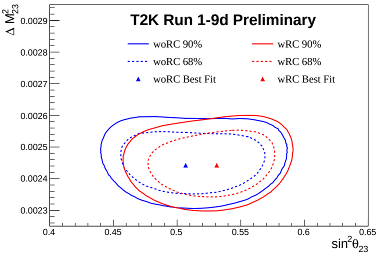


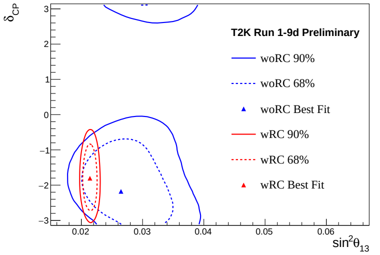
All osc parameters:
without θ_{13} reactor constraint



With/without θ_{13} reactor

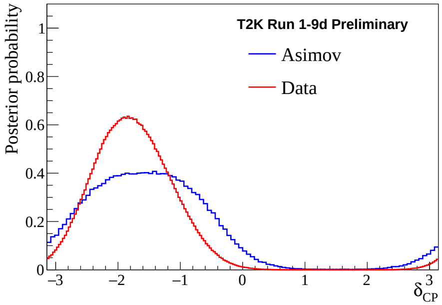


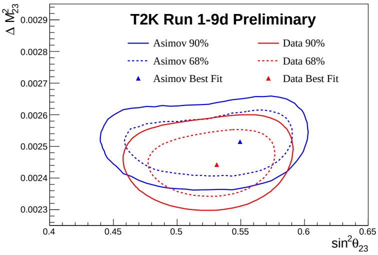


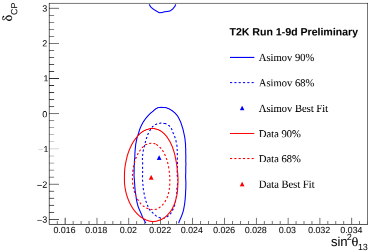


- Normal Hierarchy only
- Reactor constraint in a form of a prior
- Reactor θ_{13} taken from 2018 PDG

Data vs "Asimov" sensitivity

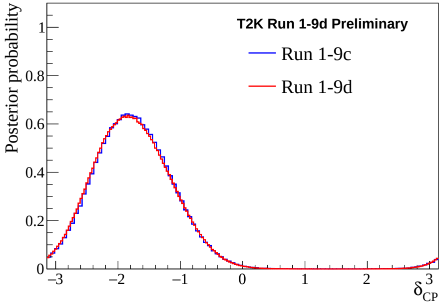


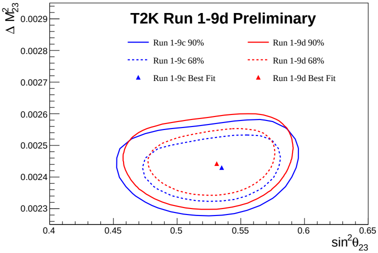


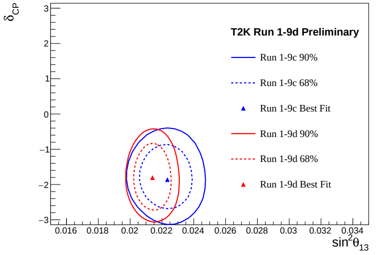


- Normal Hierarchy only
- Higher constraint on δ_{CP} than expected from the sensitivity

New vs old results

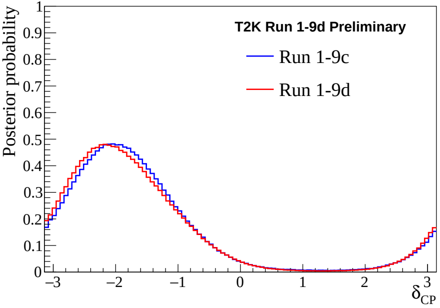


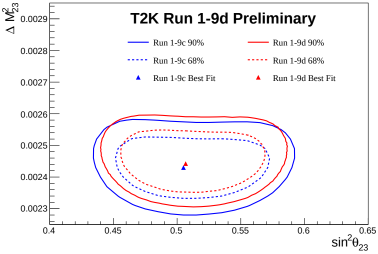


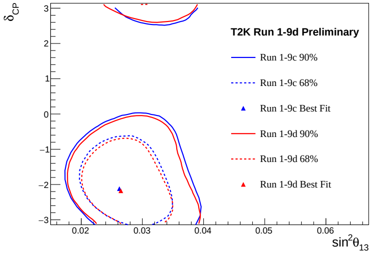


- Normal Hierarchy only
- With reactor θ_{13}
- The reactor θ_{13} updated in new fit

New vs old results







- Normal Hierarchy only
- Without reactor θ_{13}