T2K results and plans
ICPPA 2018

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for the T2K Collaboration

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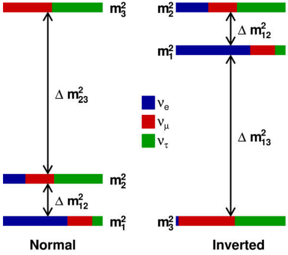
3-flavour neutrino oscillations

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

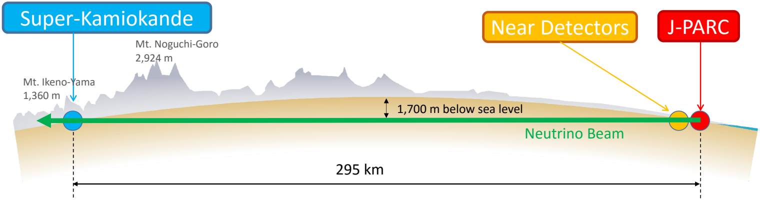
$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

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



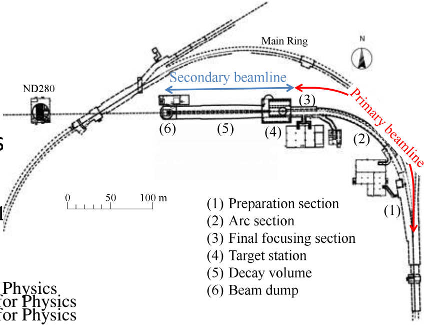
The T2K experiment

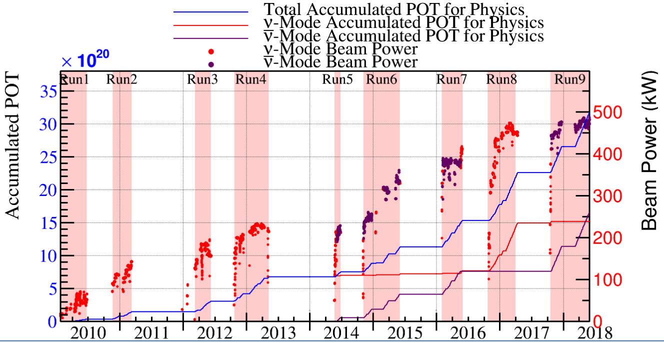
- Long baseline neutrino oscillation experiment in Japan
  - ν_μ beam produced at J-PARC, Tokai
  - Near detectors at J-PARC, 280m downstream of target
  - Super-Kamiokande (SK) far detector, 295km downstream of target in Kamioka
  - Off-axis beam produces energy spectrum peaked at 0.6 GeV
- Precision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



Neutrino beamline

- Three horn magnets focus π to produce ν-mode or $\bar{\nu}$-mode beam
- Stable beam running at 485kW
- Delivered 3.16×10^{21} total protons on target (POT)
- Analysis presented uses 2.65×10^{21} POT



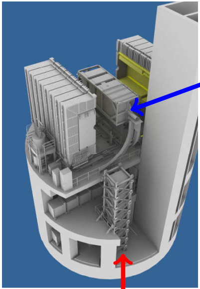


Analysis approach

- 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

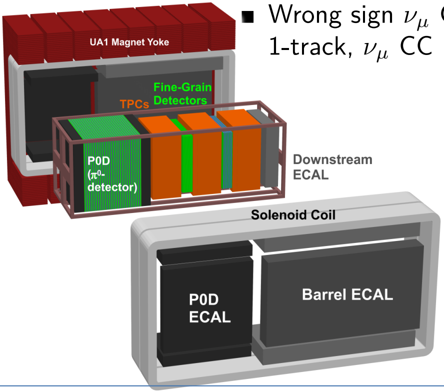
ND280 data fit

ND280 (2.5° off-axis)



INGRID (on-axis)

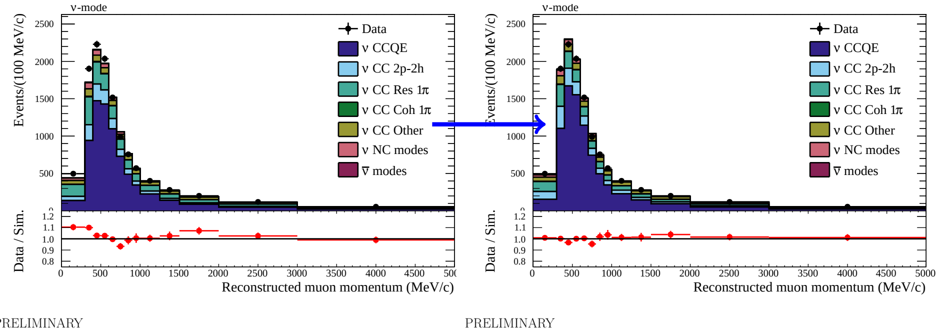
- Fit reduces flux and interaction model uncertainties at SK
- Also use ND280 to measure ν-nucleus cross-sections



- 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

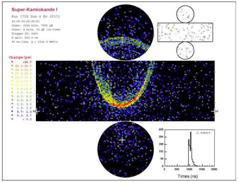
ν_μ CC0π data fit



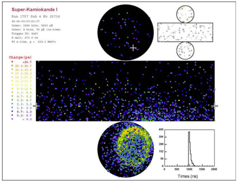
Group	Pre-fit Error (%)	Post-fit error (%)
ν_μ sample	14.05	2.88
$\bar{\nu}_\mu$ sample	11.46	2.68
ν_e sample	14.92	3.02
$\bar{\nu}_e$ sample	12.00	2.86
ν_e sample with decay electron	12.02	3.82

Super-Kamiokande far detector

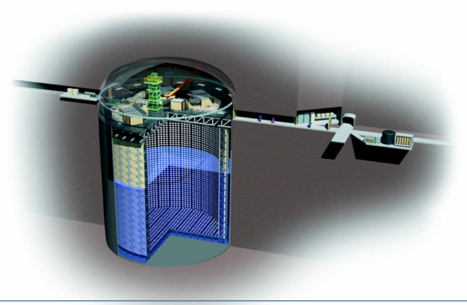
- 50kt water Cherenkov detector
- Inner detector instrumented with 11000 PMTs for 40% photo coverage
- Excellent ν_e/ν_μ separation and good reconstruction at T2K energy

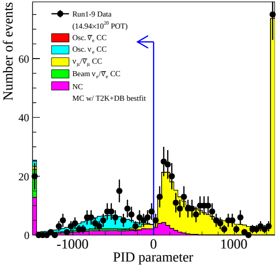


(a) μ-like ring

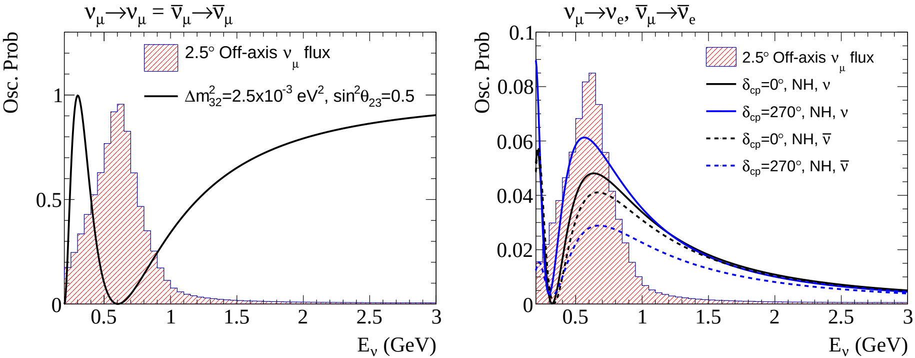


(b) e-like ring





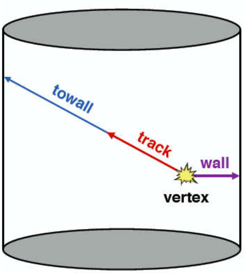
Neutrino oscillation at SK



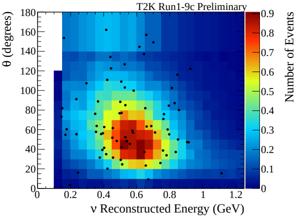
- 2.5° off-axis beam produces flux peak in the region of the oscillation maximum

Recent analysis improvements

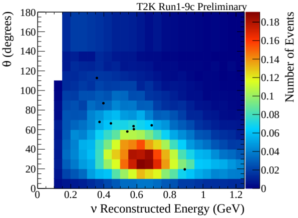
- Additional neutrino-nucleus effects in cross-section model
- Addition of ν_e CC1π sample adds $\sim$ 10% to ν_e sample
- Increase in SK fiducial volume:
  - Used to cut all vertices $<$ 2m from detector wall
  - Now consider particle trajectory to define `towall`
  - Variables tuned to each sample, but now have `towall` $\sim$ 2m, `wall` $\sim$ 50cm
  - Increases statistics by 15-20%
- Total increase in statistics of $\sim$ 30%



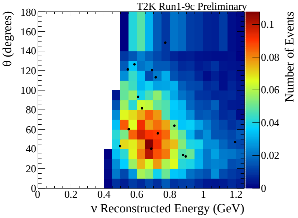
SK data fit



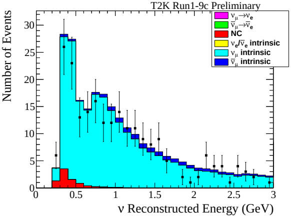
(a) ν-mode e-like



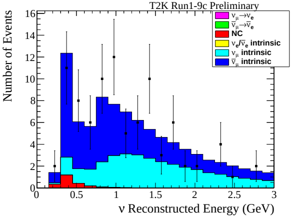
(b) $\bar{\nu}$-mode e-like



(c) ν-mode CC1π^+-like



(d) ν-mode μ-like



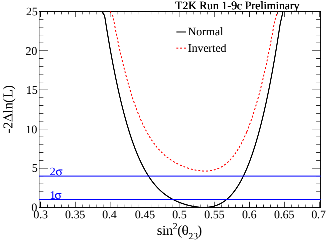
(e) $\bar{\nu}$-mode μ-like

SK event rates

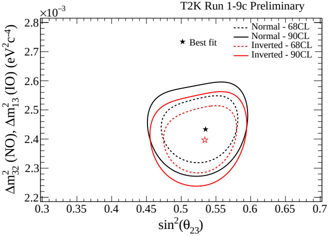
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_μ-like sample	268.525	268.232	268.494	268.880	243
ν_e-like sample	73.780	61.615	50.072	62.238	75
$\bar{\nu}_\mu$-like sample	95.528	95.306	95.529	95.770	102
$\bar{\nu}_e$-like sample	11.753	13.403	14.899	13.250	9
ν_e CC1π^+-like sample	6.928	6.009	4.869	5.788	15

- $\sin^2\theta_{12} = 0.304$
- $\Delta m^2_{21} = 7.530 \times 10^{-5}$ eV^2 c^{-4}
- $\sin^2\theta_{23} = 0.528$
- $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2 c^{-4}
- $\sin^2\theta_{13} = 2.19 \times 10^{-2}$
- Normal ordering

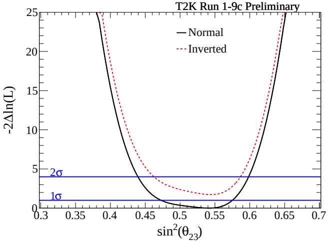
Δm^2 vs $\sin^2\theta_{23}$



(a) Data



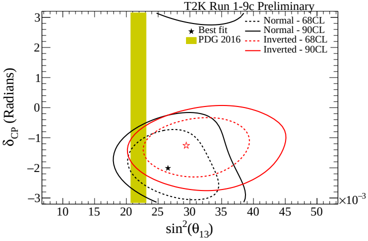
(b) Data



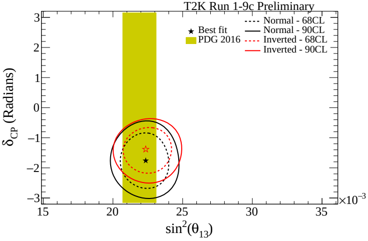
(c) MC

	Normal	Inverted
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$\lvert\Delta m^2\rvert$ (10^{-3} eV^2)	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$

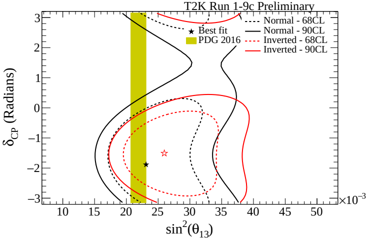
δ_{CP} vs $\sin^2\theta_{13}$



(a) Data (T2K-only)



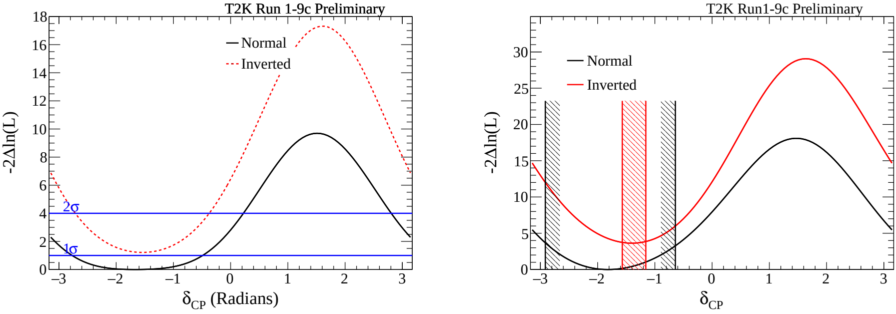
(b) Data (T2K + reactor)



(c) MC (T2K-only)

- Sensitivity assumptions:
  - $\sin^2\theta_{13} = 0.0219$ (PDG 2016)
  - $\sin^2\theta_{23} = 0.528$
  - $\delta_{CP} = -1.601$
- Data constraint stronger than sensitivity

δ_{CP}



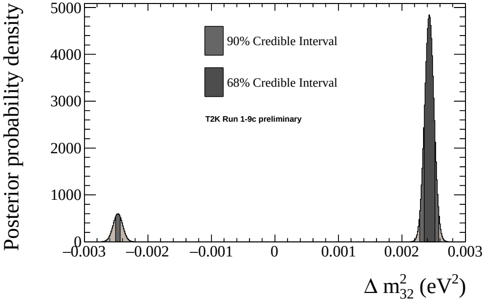
(a) MC (b) Data

- CP conservation is rejected at 2σ
- 19% of toys exclude CP conservation at 2σ (both $\delta_{CP} = 0$ and $\delta_{CP} = \pi$)

Mass ordering and octant

- T2K also performs a Bayesian analysis, used to express our confidence about the mass ordering and octant

	$\sin^2\theta_{23} \leq 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
Normal	0.204	0.684	0.888
Inverted	0.023	0.089	0.112
Sum	0.227	0.773	1

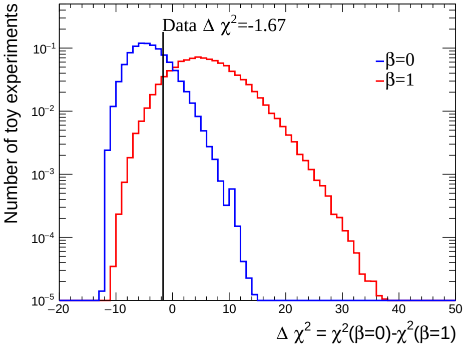


- We see a preference for normal ordering with a Bayes factor of 7.9
- We see a preference for the upper octant with a Bayes factor of 3.4
- Bayes factor between 3.16 and 10 corresponds to 'substantial' on the Jeffreys scale, but no strong statistical conclusions

$\bar{\nu}_e$ appearance

- Two hypotheses:
  - Standard 3-flavour $\bar{\nu}_e$ appearance ($\beta = 1$)
  - No $\bar{\nu}_e$ appearance ($\beta = 0$)
- Rate + shape analysis:

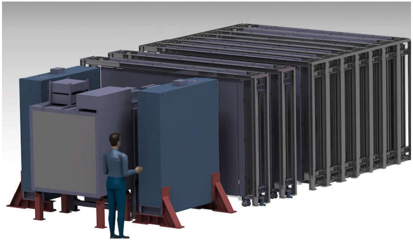
β	Hypothesis	p-value
$\beta = 0$	No appearance	$p = 0.233$
$\beta = 1$	Appearance	$p = 0.0867$



- No strong statistical conclusion yet

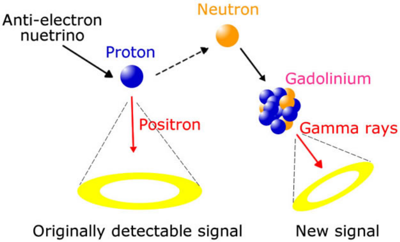
Recent developments

- WAGASCI and BabyMIND near detectors recently installed
- WAGASCI:
  - Measures neutrino interaction cross-sections on hydrocarbon and water
  - On-axis modules taking data since 2016, with off-axis modules installed this year
- BabyMIND:
  - Magnetised spectrometry and charge ID for WAGASCI, with plastic scintillators made at INR, Russia
  - Constructed at CERN and installed in ND280 complex this year



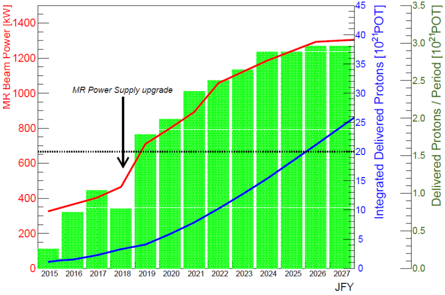
SK Gadolinium upgrade

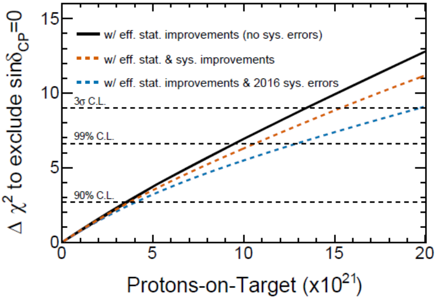
- Super-Kamiokande tank is open for maintenance and repairs
- This will be followed by Gadolinium doping
- Gadolinium has a high neutron capture cross-section and produces a delayed 8 MeV photon cascade allowing $\bar{\nu}$ tagging
  - Initial phase 0.02% *Gd* for 50% neutron capture rate
  - Later phase 0.2% *Gd* for 90% neutron capture rate
- Greater CP-Violation sensitivity due to charge discrimination



T2K run extension

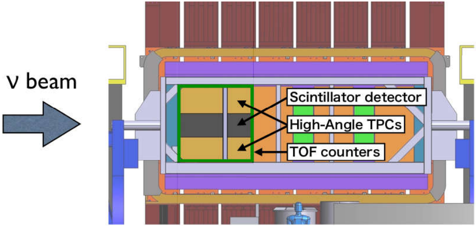
- T2K's primary goal is now observation of CP-violation in the neutrino sector
- Propose to collect $2 \times 10^{22}|$ POT by $\sim$ 2026 (arXiv:1609.04111)
- Provides up to 3σ CP-violation sensitivity





ND280 upgrade

- As part of the run extension aim to reduce systematics to $\sim 4\%$
  - Full polar angle acceptance
  - Fiducial mass of a few tonnes
  - High efficiency for short tracks
  - Good timing to determine track direction
- Submitted proposal to CERN SPSC (http://cds.cern.ch/record/2299599)
- TDR by end of year
- Aim to install 2021



Conclusion

- Significant increase to data set with addition of Run 9a-9c, with 2.61×10^{21} total POT
- Ongoing analysis including Run 9d will see this increase to 3.16×10^{21} total POT
- CP-conservation excluded at 2σ
- Preference for normal mass ordering with a Bayes factor of 7.9
- Various upgrades allow for the possibility of observing evidence for CP-violation with current generation experiments

Backup

Systematic errors

	1-Ring μ		**1-Ring e**			
Error source	ν	$\bar{\nu}$	ν	$\bar{\nu}$	ν 1 d.e.	$\nu/\bar{\nu}$
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK Final State and Secondary Interactions	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
Binding energy	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93