



The T2K Experiment: Current Status and Results

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Outline

- T2K Overview
- Experiment details
- Oscillation analysis & results
- The future of T2K

T2K Overview

What is T2K?

The T2K (Tokai to Kamioka) experiment is an accelerator-based, multi-detector long baseline ν oscillation experiment, which utilises an intense ν_{μ} / $\bar{\nu}_{\mu}$ beam sharply peaked at 0.6 GeV at an off-axis angle of 2.5°



The T2K Collaboration



~500 members, 68 institutions, 12 countries





T2K at NuFACT2019

Come and see our other talks:

- Details of the T2K oscillation analyses
 - Christophe Bronner
 - 11:30 12:00, Thurs. 29th Aug.
 - Working group 1 (oscillations)
- ND280 upgrade
 - John Nugent
 - 16:00 16:22, Thurs. 29th Aug.
 - Working group 1+2 (detector technology)
- Wagasci/BabyMind
 - Kenji Yasutome
 - 16:22 16:44, Thurs. 29th Aug.
 - Working group 1+2 (detector technology)

What Physics can T2K do?

- Constrain PMNS oscillation parameters and the mass splittings by:
 - Searching for v_{μ}/\bar{v}_{μ} disappearance Sensitive to $\sin^2\theta_{23}$ and $|\Delta m_{32}^2|$
 - Searching for v_e/\bar{v}_e appearance Sensitive to $\sin^2 2\theta_{13}$ and δ_{CP}
- Constrain the mass ordering
- Measure cross-sections at the near detectors
- Exotics e.g. sterile ν search, Lorentz violation

- 5 new T2K papers published since last summer:
 - CP violation search with $2.2 \times 10^{21} POT$ (PRL) arXiv:1807.07891
 - New electron-multiplier-tube-based beam monitor for muon monitoring (PTEP) - arXiv:1805.07712
 - Characterisation of nuclear effects in muon-neutrino scattering on hydrocarbon (PRD) arXiv:1802.05078
 - Search for light sterile neutrinos at Super-K (PRD) - arXiv:1902.06529
 - Search for neutral-current induced single photon production at ND280 (J. Phys. G) - arXiv:1902.03848

T2K Details

Beam and Detector Overview



Beam Production



- 30 GeV p beam hits graphite target, decays predominantly into π^{\pm} , K^{\pm}
- π^{\pm} , K^{\pm} decay into μ^{\pm} and $\nu/\bar{\nu}$
- 3 magnetic horns focus π^{\pm} , K^{\pm} to select the beam mode:
 - Forward horn current (FHC) to select a u_{μ} beam
 - Reverse horn current (RHC) to select a $ar{v}_\mu$ beam
- Undecayed π^{\pm} , K^{\pm} stopped by the beam dump
- μ^{\pm} measured by the muon monitor to characterise the beam
- Hadron production models constrained by the NA61/SHINE experiment – reduces flux uncertainties

Near Detectors



Multiple near detectors:

- INGRID (on-axis)
- ND280 (2.5° off-axis)
- WAGASCI/BabyMIND (2.5° off-axis)



Flux at ND280



High purity, stable $\nu/\bar{\nu}$ beam operation at ~480 kW



Near Detectors - INGRID



- Measures beam direction, profile and intensity
- 16 scintillator modules sandwiched with iron plates
- Proton module at the centre to constrain CCQE interaction model



Near Detectors – ND280



- Suite of detectors in a 0.2 T magnetic field:
 - 2 fine-grained detectors (1 scintillator, 1 scintillator + water) provide interaction mass and vertex reconstruction
 - 3 time projection chambers measure particle momentum and charge
 - π^0 detector
 - Electromagnetic calorimeter measures energies of photons escaping the inner detector and can distinguish tracks from showers.
- Constrains unoscillated off-axis flux and the $\boldsymbol{\nu}$ interaction model



Far Detector – Super-Kamiokande (Super-K)



- 50 kt ultrapure water Cherenkov detector
- 11,000 PMTs in the inner detector for 40% photocoverage
- ~1 km rock overburden for background reduction
- v_{μ} & v_{e} interact with water to produce μ^{-} & e^{-}
- μ^- & e^- produce Cherenkov light, which is detected by the PMTs
- Measures the oscillated v spectra



Super-K PID



Analysis Procedure

Analysis Strategy



Flux Model and Constraints

Flux prediction:

- 1. FLUKA simulation Simulate p + C interactions in the target
- JNUBEAM Tracks particles exiting the target and their decays into v
- 3. Hadron Production tuning Tune π production multiplicity and interaction rates _____ND280: Neutrino Mode, v_{μ}

Hadron interactions are the dominant uncertainty

Hadron yields and multiplicity constrained using the NA61/SHINE experiment:

- Measurements using a 31 GeV/c p beam at CERN
- Covers nearly all of the T2K phase space
- Data from a thin (2 cm) thin target and a T2K replica target

Gives a significant flux uncertainty reduction



Flux Model and Constraints

More info:

- NA61/SHINE facility at the CERN SPS: beams and detector system (JINST) arXiv:1401.4699
- Measurements of π[±], K[±], K⁰_S, Λ and proton production in proton-carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS (Eur. Phys. J. C) arXiv:1510.02703 ND280: Neutrino Mode, v_u
- Measurements of π[±] differential yields from the surface of the T2K replica target for incoming 31 GeV/c protons with the NA61/SHINE spectrometer at the CERN SPS (Eur. Phys. J. C) arXiv:1603.06774



Cross Section Model

- The dominant interaction is CCQE
- Model interactions using the NEUT generator tuned to data from MiniBooNE, MINERvA and bubble chambers etc.
- Constrain cross-sections using the near detector & propagate to the far detector fit

See talk by Christophe Bronner for details (11:30, Thurs.)



ND280 Fit

- Fit to data binned in μ momentum and angle, with both C and O targets
- Post-fit is in much better agreement with the data
- Constrains event rates and greatly reduces systematic parameter errors



PRELIMINARY

2019-08-26

NUFACT2019 – T2K Status & Results – Francis Bench

PRELIMINARY

ND280 Fit

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Effect of ND280 Fit on Super-K Predictions



Total event rate errors

Super-K Selection	Pre-fit Error (%)	Post-fit Error (%)	
$ u_{\mu}$ CCQE-like	14.7	5.1	
v_e CCQE-like	16.9	8.8	
v_e CC1 π -like	21.8	18.4	
$\bar{\nu}_{\mu}$ CCQE-like	12.5	4.5	
$\bar{\nu}_e$ CCQE-like	14.4	7.1	





Data & Results

Accumulated Beam Exposure

- POT = Protons On Target, directly correlates with the number of v produced
- Since NuFACT2018, analyses with 46% increased RHC exposure have been completed



Super-K Data

 v_{μ} CCQE-like

1.5

T2K Run1-9 Preliminary

NC

2.5

2

v Reconstructed Energy (GeV)

 v_{e}/\overline{v}_{e} intrinsic

intrinsic

v. intrinsic

Number of Events

24

22 -

20 E

18

16

14 12 10

8

0.5



Prediction = Coloured hists. Generated with:

Number of Events

30

25

20

15

10

5

0.5

- Normal Ordering ٠
- $\delta_{CP} = -1.601$ •
- $\sin^2 \theta_{13} = 0.0212$
- $\sin^2 \theta_{23} = 0.528$
- $\sin^2 \theta_{12} = 0.304$
- $\left|\Delta m_{32}^2\right| = 2.509 \times 10^{-3} eV^2/c^4$ •
- $\Delta m_{21}^2 = 7.53 \times 10^{-5} eV^2/c^4$



1.2

Number of Events

0.04

0.02

T2K Run1-9 Preliminary

 \bar{v}_{μ} CCQE-like

1.5

ŃC

2.5

2

v Reconstructed Energy (GeV)

 $v_{\rm e}/\overline{v}_{\rm e}$ intrinsic

v., intrinsic

v. intrinsic

Super-K Data

Super-K		Observed			
Selection	$\delta_{CP} = -\pi/2$	$\delta_{CP}=0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi/2$	Observed
v_{μ} CCQE-like	272.4	272.0	272.4	272.8	243
v_e CCQE-like	74.4	62.2	50.6	62.7	75
v_e CC1 π -like	7.0	6.1	4.9	5.8	15
$\bar{\nu}_{\mu}$ CCQE-like	139.5	139.2	139.5	139.9	140
\bar{v}_e CCQE-like	17.1	19.6	21.7	19.3	15

$2D \ \delta_{CP} \ vs. \ sin^2 \ \theta_{13}$





- Reactor constraint on $\sin^2 2\theta_{13}$ gives a much improved constraint on δ_{CP}
- T2K-only data is compatible with the reactor $\sin^2 2\theta_{13}$ data
- T2K data still gives a stronger constraint than predicted (upwards fluctuation in v_e CC1 π -like sample but only RHC beam running since last summer)

1D δ_{CP}

- δ_{CP} best-fit values (radians)
 - For NO: -1.885
 - For IO: -1.382
- 2σ ranges
 - For NO: [-2.966, -0.628]
 - For IO: [-1.799, -0.979]
- CP conservation $(\sin \delta_{CP} = 0)$ is excluded at 2σ for both mass orderings!
- More data and/or a reduction of systematic errors is needed to exclude CP conservation at 3σ



$2D \Delta m^2 vs. sin^2 \theta_{23}$



- $\sin^2 \theta_{23}$ best-fit values Δm^2 best-fit values $(10^{-3} eV^2/c^4)$
 - For NO: 0.532
 - For IO: 0.532
 - 1σ ranges
 - For NO: [0.495, 0.562]
 - For IO: [0.497, 0.561]

- For NO: 2.452
- For IO: 2.432
- 1σ ranges
 - For NO: [2.382, 2.523]
 - For IO: [2.361, 2.501]

- Data and sensitivity are compatible
- Best-fit lies in the upper-octant, but is also compatible with maximal mixing

Mass Ordering



Substantial preference for NO, with a Bayes factor of 8.0 (from Bayesian MCMC analysis, equal prior probability for NO and IO)

\bar{v}_e Appearance

• Modify the oscillation probability:

•
$$P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}) \rightarrow \beta \times P_{PMNS}(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e})$$

- Test two independent null hypotheses:
 - PMNS $\bar{\nu}_e$ appearance ($\beta = 1$)
 - No $\bar{\nu}_e$ appearance ($\beta = 0$)
- Using both rate and shape information:
 - Disfavour no \bar{v}_e appearance at 2.4σ
 - Compatible with PMNS $\bar{\nu}_e$ appearance (1.0 σ)
- No significant evidence of $\bar{\nu}_e$ appearance yet



Bi-event Plot



- Ellipses show number of v_e/\bar{v}_e mode CCQE-like events as a function of δ_{CP}
- Different ellipses for different MO and $\sin^2 \theta_{23}$ values
- Shows T2K's preference for maximal CP violation, normal mass ordering and the upperoctant in a single plot!

The Future of T2K

T2K-II Proposal & Beam Upgrade

- Current exposure: 3.16×10^{21} POT
- T2K target: 7.8×10^{21} POT
- Approved extension (T2K-II): 20×10^{21} POT
- Allows 3σ sensitivity to exclude $sin(\delta_{CP}) = 0$
- See arXiv:1908.05141 for details
- Beam upgrade expected complete by 2022
- Current operation stable at 450 500 kW
- Upgrade to 750 *kW* − 1.3 MW
 - Mostly from the increase rep rate from 2.48 s to 1.16 s <
 - Also more protons in each pulse
- Increase magnetic horn power from 250 to 350 kA
 - $\sim 10\%$ more flux at Super-K
 - $\sim 5 10\%$ reduction in wrong-sign background



ND280 Upgrade

- Upgrade ND280 during the beam upgrade
- T2K-II goal: reduce detector systematics to ~4%
- Replace much of the π^0 detector with a scintillator detector & 2 high-angle TPC and 6 TOF counters
 - Gives 4π acceptance (same as Super-K)
 - Increases target mass from 2.2 ton to 4.2 ton
- Approved as a project of the CERN Neutrino Platform (NP07)
- See arXiv:1901.03750, CERN-SPSC-2018-001 & SPSC-P-357



See talk by John Nugent for details (16:00, Thurs.)

WAGASCI/Baby MIND

• WAGASCI

- = WAter Grid And SCIntillator
- Measure the ν differential cross-section on carbon and water
- Aims to reduce T2K systematic uncertainties
- Located both at on-axis and off-axis locations
- 1st physics run recently completed
- BabyMIND
 - = Magnetised Iron Neutrino Detector
 - Spectrometer & charge ID for WAGASCI
 - Currently being upgraded

See talk by Kenji Yasutome for details (16:22, Thurs.)



Super-K Gadolinium Upgrade

- Repairs to the tank completed
- ^{157}Gd will be added to water
 - ¹⁵⁷*Gd* has a very large *n* capture cross-section:
 - 0.01% concentration 2019/2020 detectabl – gives 50% n capture rate
 - 0.1% concentration later
 gives 90% n capture rate
 - Enhanced low-energy $\bar{\nu}_e$ detection using delayed coincidence of 8 *MeV* γ
 - Improved v_e/\bar{v}_e separation
 - Possible supernova relic ν detection



Summary

- 46% increase in RHC exposure compared to summer 2018
- 2σ exclusion of CP conservation using data collected up to summer 2018
- $\sin^2 \theta_{23}$ consistent with maximal mixing, best fit lies in the upper octant
- Substantial preference for normal mass ordering
- Preparations for T2K-II:
 - Beam upgrade
 - ND280 upgrade
 - Super-k Gd
- Next run of T2K data to be collected Oct. 2019 Feb. 2020
- T2K-II has potential for 3σ exclusion of CP conservation



Near Detectors – ND280 Tracking and PID





- Fine-grained detectors (FGDs):
 - Main interaction mass
 - FGD1 Polystyrene (C) scintillator
 - FGD2 6 layers of water sandwiched with scintillator. Measures the ν cross-section on water
- Time projection chambers (TPCs):
 - Gas mixture (mostly Ar) drift volume
 - Measure particle momentum and charge using the 0.2 T magnetic field
- Electromagnetic calorimeters (ECals):
 - Plastic scintillator and lead layers
 - Detect and measure the energies of particles escaping the inner detector.
- π^0 detector:
 - Layers of scintillator, brass and water
- PID uses the amount of ionisation, the momentum and the energy from the ECal. Very good μ/e separation

ND280 Selections

FHC selections:



- To constrain Super-K flux and interaction parameters, data are fit at ND280
- FHC selections:
 - ν_μ CC 0π
 - ν_{μ} CC $1\pi^+$
 - ν_{μ} CC Other
- RHC selections:
 - $\bar{\nu}_{\mu}$ CC 1-track (right sign)
 - $\bar{\nu}_{\mu}$ CC N-track (right sign)
 - v_{μ} CC 1-track ("wrong" sign)
 - v_{μ} CC N-track ("wrong" sign)

RHC selections:



• Selections use both FGDs:

CH and CH + H_2O

Systematic Error Sources at Super-K

	1-Ring μ		$1-\mathbf{Ring} \ e$			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
SK FSI+SI+PN	2.21	1.98	3.00	2.31	11.43	1.57
Flux + Xsec constrained	3.27	2.94	3.24	3.10	4.09	2.67
E _b	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(u_e)/\sigma(ar u_e)$	0.00	0.00	2.63	1.46	2.61	3.03
$ m NC1\gamma$	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Osc	0.03	0.03	2.69	2.49	2.63	0.77
All Systematics	5.12	4.45	8.81	7.13	18.38	5.96
All with osc	5.12	4.45	9.19	7.57	18.51	6.03

Super-K Data and v_e CC1 π -like p-value

Super-K		Observed			
Selection	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi/2$	
v_{μ} CCQE-like	272.4	272.0	272.4	272.8	243
v_e CCQE-like	74.4	62.2	50.6	62.7	75
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Upwards fluctuation in the v_e CC1 π -like sample. The p-value for observing this fluctuation in any of the 5 samples is 5 – 13% depending on the true values of the oscillation parameters and the method used

Oscillation Analysis

- Results presented here: Oscillation **Prior Probability Distribution Parameter** • Constrain δ_{CP} Gaus. 0.0830 ± 0.0031 • Compatibility of $\sin^2 \theta_{13}$ with Driven by v_e/\bar{v}_e $\sin^2 2\theta_{13}$ (2018 PDG from reactor reactor experiments appearance experiments) • Precision measurements of $\sin^2 \theta_{23}$ Gaus. 0.846 ± 0.021 $\sin^2 2\theta_{12}$ and $|\Delta m_{32}^2|(NO) / |\Delta m_{13}^2|(IO)|$ (2018 PDG) Driven by v_{μ}/\bar{v}_{μ} Gaus. • $\bar{\nu}_e$ appearance disappearance $(7.53 \pm 0.18) \times 10^{-5} eV^2/c^4$ Δm^2_{21} Mass ordering preference (2018 PDG) • Simultaneous fit to all 5 Super-K event $\sin^2 \theta_{23}$ samples $|\Delta m_{32}^2|(NO)|/$ Uniform $|\Delta m_{13}^2|(IO)$ Constrained by the ND fit and priors δ_{CP}
- Marginalise out nuisance parameters
- Produce confidence regions on oscillation parameters of interest

Oscillation Analysis

- 3 different T2K fitter groups perform complementary analyses:
 - Frequentist log-likelihood ratio fit
 - $E_{\nu}^{\text{rec.}}$, θ_e for *e*-like event samples
 - $E_{\nu}^{\text{rec.}}$ for μ -like event samples
 - Propagate separate ND280 fit to Super-K
 - Frequentist log-likelihood ratio fit
 - p_e , θ_e for *e*-like event samples
 - $E_{\nu}^{\text{rec.}}$ for μ -like event samples
 - Propagate separate ND280 fit to Super-K
 - Bayesian Markov Chain MC (MCMC)
 - $E_{\nu}^{\text{rec.}}$, θ_e for *e*-like event samples
 - $E_{\nu}^{\text{rec.}}$ for μ -like event samples
 - Simultaneous MCMC fit to ND280 & Super-K
- Excellent agreement in the results from all 3 groups

Mainly showing these results today

 δ_{CP} Prior



Conclusions unchanged: still exclude $sin(\delta_{CP}) = 0$ at the 2σ CL

Extremity of the T2K Data

- T2K data falls within the 2σ range of pseudo-experiments
- Stronger than expected constraint is compatible with being a statistical fluctuation



Interpretation of Bayes Factor

Bayes factor is a ratio of marginal likelihoods for two models, X and Y, given the data, D:

$$B = \frac{L(D \mid X)}{L(D \mid Y)}$$

B	log ₁₀ <i>B</i>	Strength of evidence for model X
< 1	< 0	Data prefers model Y
1 - 3.16	0 - 0.5	Poor preference for model X
3.16 - 10	0.5 - 1	Substantial preference for model X
10 - 100	1 – 2	Strong preference for model X
> 100	> 2	Decisive preference for model X