Updated Results from the T2K Experiment with 3.13×10^{21} Protons on Target

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For the T2K Collaboration

January 10, 2019

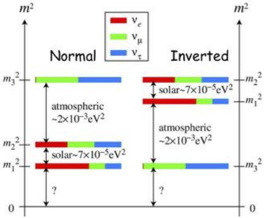
Outline

- Neutrino Oscillations
- The Tokai to Kamioka Long Baseline Neutrino Oscillation Experiment (T2K)
- T2K Analysis Method and Systematic Errors
- T2K Latest Results
- Future Long-Baseline Neutrino Oscillation Physics Prospects

Neutrinos and Neutrino Oscillation

Neutrinos and Neutrino Oscillation

- There are (at least) three types of neutrinos ("neutrino flavors"): ν_e, ν_μ, ν_τ (+ 3 anti-neutrinos: $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$)
- Neutrinos are very light ($<4 \times 10^{-6} m_e$) and very weakly interacting
- When neutrinos propagate, they can change flavor (or oscillate): i.e. $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_\tau$
  - This is because neutrinos propagate in a mass eigenstate, which is a mixture of lepton flavor eigenstates
  - However, they are produced and interact in the flavor eigenstate
- So, you can think of neutrinos in two ways: either as associated with a charged lepton (ν_e, ν_μ, and ν_τ), or with a specific mass (ν_1, ν_2, and ν_3)
  - Mass states ν_1, ν_2, and ν_3 are made up of some combination of ν_e, ν_μ, and ν_τ



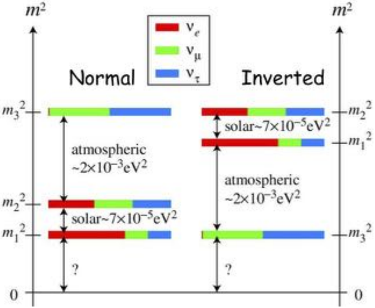
- The neutrino oscillation probability depends on the neutrino's energy, distance it has traveled, mass splittings, and oscillation parameters given by the PMNS mixing matrix

Current Understanding of the Neutrino Oscillation Parameters

Neutrino oscillation can be described by the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) mixing matrix:

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +C_{23} & +S_{23} \\ 0 & -S_{23} & +C_{23} \end{pmatrix} \begin{pmatrix} +C_{13} & 0 & +S_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta_{CP}} & 0 & +C_{13} \end{pmatrix} \begin{pmatrix} +C_{12} & +S_{12} & 0 \\ -S_{12} & +C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$(C_{ij} = \cos\theta_{ij},\ S_{ij} = \sin\theta_{ij})$



- MH completely unknown

Precisely measure all parameters to fully understand neutrino oscillation

- $\theta_{12} = 33.6^\circ \pm 0.8^\circ$ – solar ν's
- $\theta_{23} = 45.6^\circ \pm 2.3^\circ$
  – is θ_{23} maximal?
- $\theta_{13} = 8.3^\circ \pm 0.2^\circ$ – recent reactor $\bar{\nu}_e$ disappearance measurements

δ_{CP} unknown $\rightarrow$ possibility of CP violation in the lepton sector

$\rightarrow$ May be able to help explain the dominance of matter over anti-matter in the Universe

Oscillation Probabilities

- Long-baseline $\nu_\mu \rightarrow \nu_e$ appearance probability depends most strongly on $\sin^2 2\theta_{13}$ and δ_{CP}
  - (But also depends on θ_{23} and other parameters)

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) && \rightarrow \text{Leading, matter effect} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} && \rightarrow \text{CP conserving} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} && \rightarrow \text{CP violating} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21} && \rightarrow \text{Solar} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E} \cos\Phi_{32} \sin\Phi_{31} && \rightarrow \text{Matter effect}
\end{aligned}
$$

$(C_{ij} = \cos\theta_{ij},\ S_{ij} = \sin\theta_{ij},\ \Phi_{ij} = \Delta m_{ij}^2 L/4E)$

- Long-baseline $\nu_\mu \rightarrow \nu_\mu$ disappearance probability depends most strongly on $\sin^2 2\theta_{23}$ and Δm_{32}^2
  - (But degeneracy is broken by $\sin^2 2\theta_{13}$)

$$
P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - (\underbrace{\cos^4\theta_{13} \sin^2 2\theta_{23}}_{\text{Leading Term}} + \underbrace{\sin^2 2\theta_{13} \sin^2\theta_{23}}_{\text{Next-to-Leading}}) \sin^2 \frac{\Delta m_{31}^2 L}{4E}
$$

The Tokai to Kamioka Long-Baseline Neutrino Oscillation Experiment

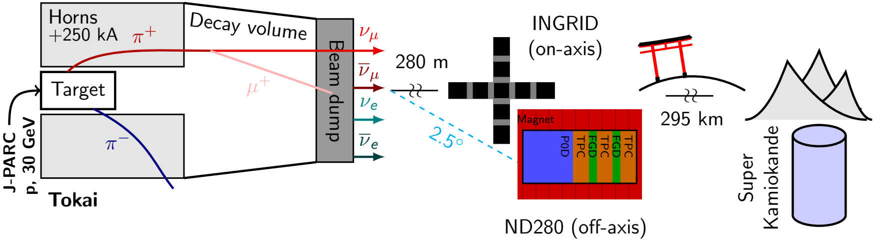
The T2K Experiment

- Primarily ν_μ or $\bar{\nu}_\mu$, 2.5° off axis neutrino beam produced at J-PARC
- ND280 Near Detector – 280 m from ν source
  - Constrains systematic errors
  - Measures ν cross sections and beam backgrounds
- Neutrino interactions detected at the Super-Kamiokande (SK) far detector – 295 km from ν source
  - Cherenkov detector filled with 50kT of ultra-pure water
  - Good performance of ν_e/ν_μ particle ID for sub-GeV energy ν's
  - ν_e appearance and ν_μ disappearance ν oscillation information

The T2K Collaboration

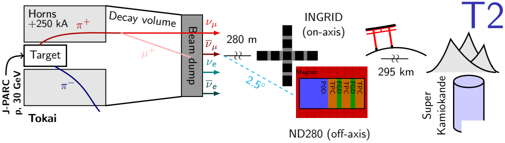
The T2K collaboration has ∼500 members
from 66 institutes in 12 countries

T2K + How to Make a Neutrino Beam



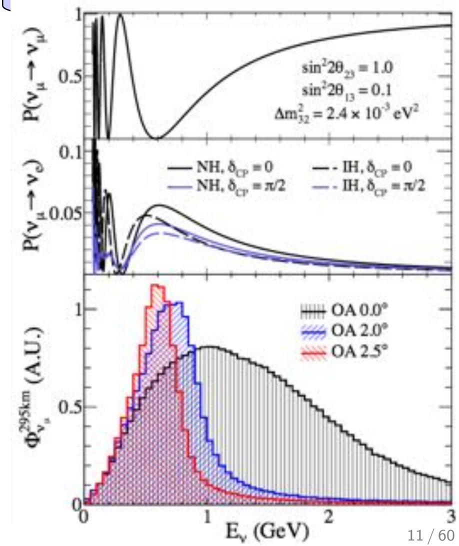
- Slam high-intensity 30GeV proton beam into 90-cm carbon target
- Focus outgoing hadrons (pions, kaons, etc.) in 3 electro-magnetic focusing horns
  - Switch between ν- or $\bar{\nu}$-mode by changing the horn polarity
- Pions decay to muons and ν_μ's in 100-m-long decay volume
- Stop interacting particles in beam dump; neutrinos continue on to near and far detectors
  - Monitor >5GeV muon beam by Muon Monitor in beam dump
- Number of neutrinos is proportional to number of protons

  $\rightarrow$ Increase beam power to increase neutrino flux

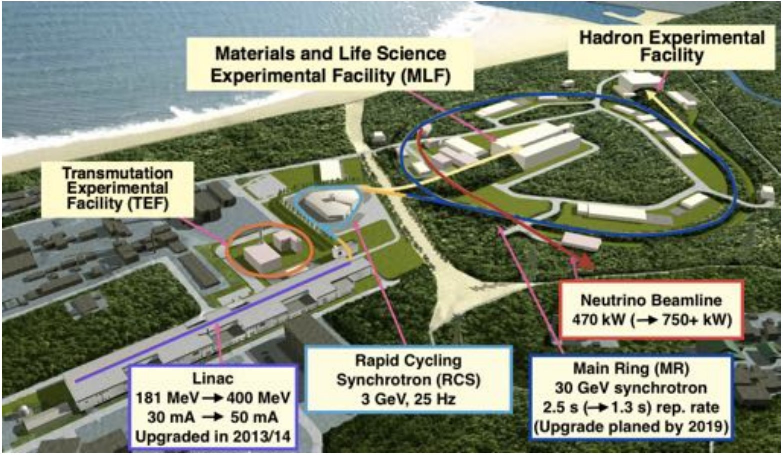


T2K Off-Axis Beam

- T2K was the first-ever neutrino experiment to use an “off-axis” beam :
  - The T2K far detector is not sitting at the center of the neutrino beam – instead it is 2.5° off-axis
- The “off-axis” beam concept gives a smaller range of neutrino energies
  - Can choose the peak energy to be at the oscillation maximum
- Precise control of the beam parameters is very important

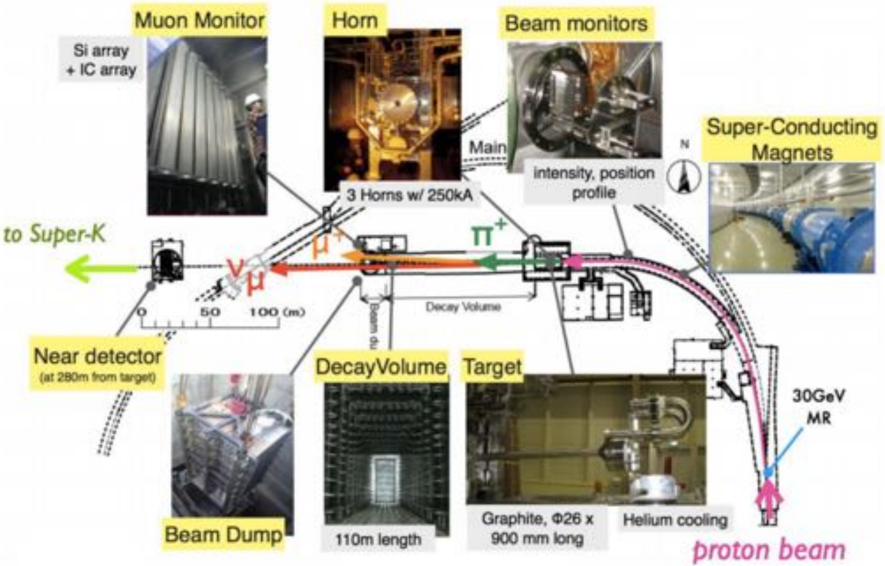


J-PARC Accelerator

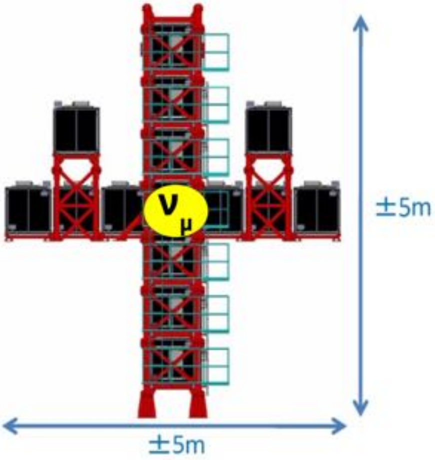


- J-PARC = Japan Proton Accelerator Research Complex
- Accelerates proton beam to 30 GeV by:
  - 400 MeV Linac (linear accelerator) → 3 GeV RCS (Rapid Cycling Synchrotron) → 30 GeV MR (Main Ring)
- MR design beam power: 750 kW (currently ∼485 kW)

J-PARC Neutrino Beamline



INGRID On-Axis Near Detector

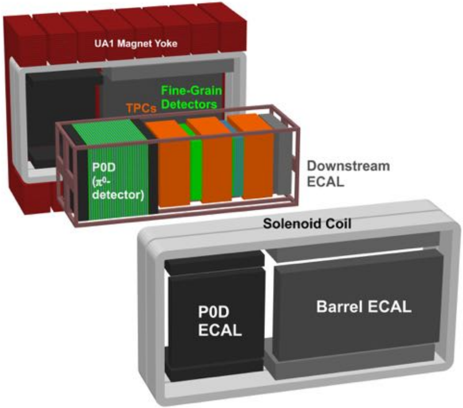


- 14 identical modules arranged in a cross
- Each module consists of sandwiched iron plates and tracking scintillator planes
- Used to measure the neutrino beam stability and direction
- Also used to measure cross sections/neutrino interactions

ND280 Off-Axis Near Detector

Consists of many parts:

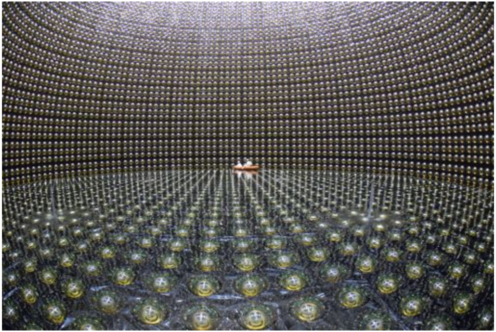
- In a magnet, so can sign-select charged particles
- P0D (π^0 Detector) – Measures pions (π^0's), water target
- TPCs (Time Projection Chambers) – Track particles, particle identification
- FGDs (Fine-Grain Detectors) – Act as detector target, include interaction vertex information
- ECALs (Electromagnetic Calorimeters) – Detect and identify particles exiting the detector, such as γ's, π^0's



$\rightarrow$ ND280 upgrades underway

ND280 is used to constrain the neutrino flux and measure neutrino cross sections

The Super Kamiokande Far Detector

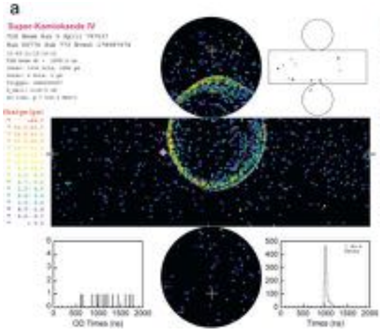


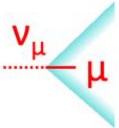
- Super Kamiokande is a huge water Cherenkov detector – cylindrical tank holding 50 ktons of ultra-pure water
    - Walls lined with photo-sensors (PMTs) to detect Cherenkov light
    - $\sim$11,000 20" PMTs in inner detector (40% photo coverage)
- Deep underground (2700mwe) – very low background event rate
- Neutrinos passing through SK may interact with the water stored inside the tank and produce muons or electrons, which then produce Cherenkov light while passing through the water

Super Kamiokande Neutrino Detection

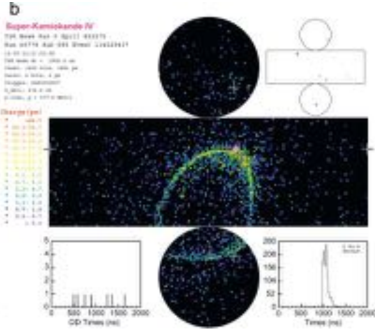
- Use Cherenkov light to reconstruct the particle energy, direction, etc
- Can distinguish between muons (produced by ν_μ) and electrons (produced by ν_e) at T2K beam energies for CC interactions :

Muon Neutrino Detected



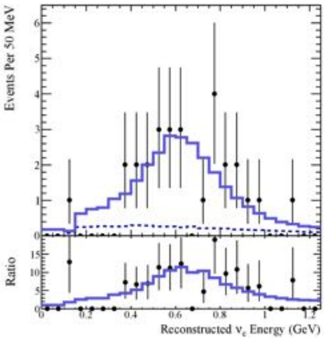


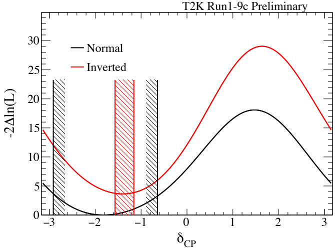
Electron Neutrino Detected



Some Important T2K Results

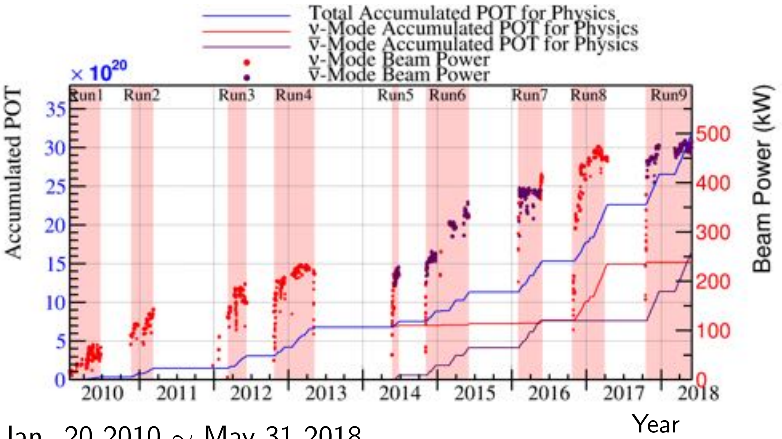
- 2011 : first ever indication of ν_e appearance from a ν_μ beam (2.5σ)
- 2013 : made world's first observation of ν_e appearance from a ν_μ beam (7.3σ)
- 2014 : similar dataset used to show very first 90% CL *hint* of $\delta_{CP} \neq 0$
- 2014 : started taking first $\bar{\nu}$-mode data
  - Aim to observe $\bar{\nu}_e$ appearance, measure δ_{CP} by T2K w/out external constraint on $\sin^2\theta_{13}$
- 2015∼2016 : continue to improve statistical significance of ν and $\bar{\nu}$ results
- 2017 : increased SK fiducial volume, added new SK ν_eCC1π sample, etc...
  - Stronger hint of CP violation in neutrinos (CP conserving values of δ_{CP} are outside of 2σ CL)





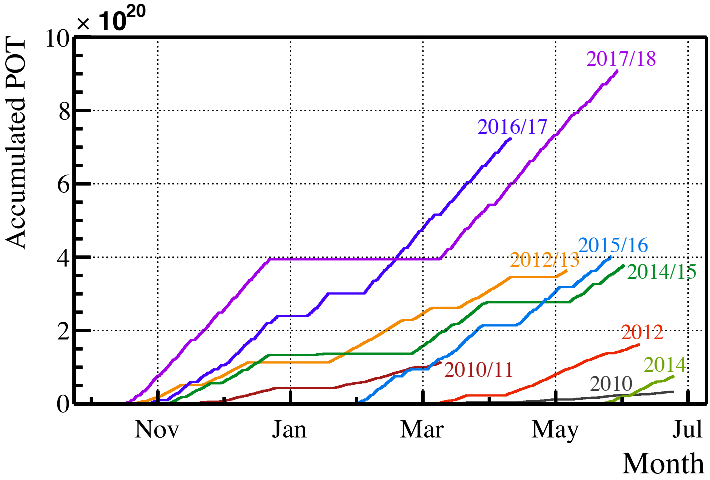
T2K Latest Dataset

T2K Data-Taking Status



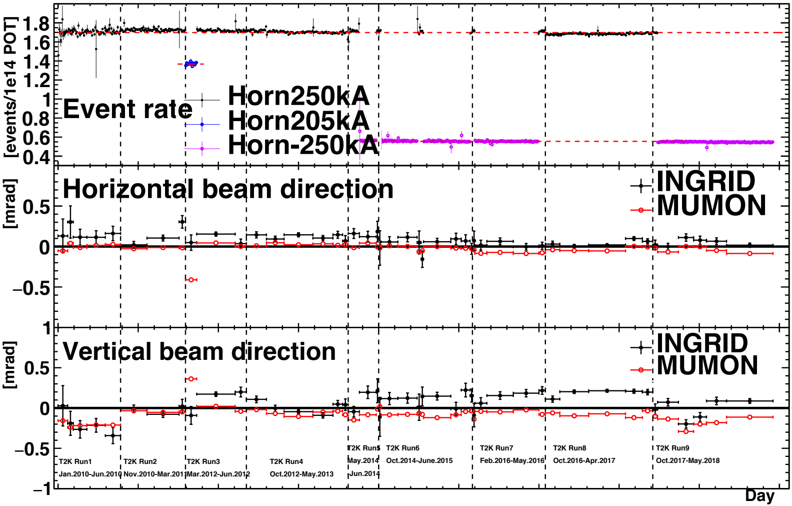
- Jan. 20 2010 $\sim$ May 31 2018
- 3.16×10^{21} Protons On Target (POT) accumulated so far
  - 1.51×10^{21} POT ν-Mode + 1.65×10^{21} POT $\bar{\nu}$-Mode
- Latest oscillation results based on :
  - $3.13 \times 10^{21} = \sim 1.49 \times 10^{21}\ \nu + \sim 1.63 \times 10^{21}\ \bar{\nu}$ POT
  - 40% of the total approved T2K statistics (7.8×10^{21} POT)

T2K Yearly POT



- Last year (2017∼2018) was our best year for datataking so far!
- (Thanks to J-PARC center members !)

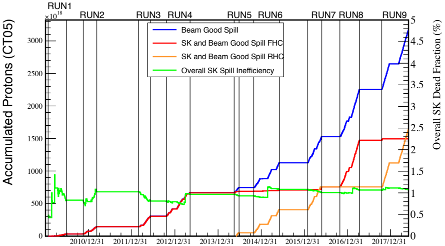
Neutrino Beam Stability

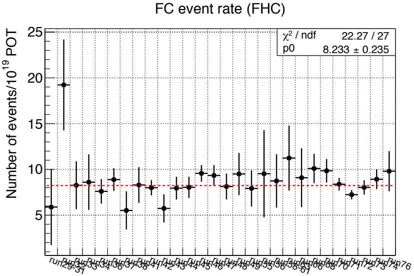


- INGRID + Muon Monitor stability – neutrino beam event rate and off-axis angle are stable with time

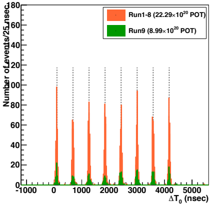
FHC = ν-mode
RHC = $\bar{\nu}$-mode

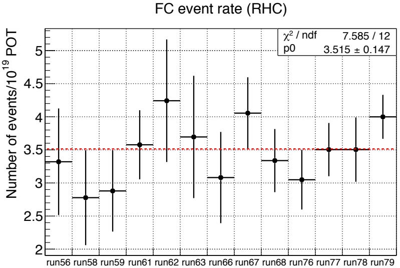
Super-Kamiokande Stability





- SK running with very high efficiency (~1% inefficiency)
- Stable event rate in both modes
- Event timing as expected





Major Updates Since Last T2K Result

- Increased $\bar{\nu}$-mode dataset $1.12 \times 10^{21} \rightarrow 1.63 \times 10^{21}$ POT
    - $\sim$45% increase
- Updated the reactor constraint to match PDG2018 values :
    - Old : PDG2016 value – $\sin^2 \theta_{13} = 0.0219 \pm 0.0012$ ($\sin^2 2\theta_{13} = 0.086$)
    - New : PDG2018 value – $\sin^2 \theta_{13} = 0.0212 \pm 0.0008$ ($\sin^2 2\theta_{13} = 0.083$)

Oscillation Analysis and Systematic Errors

Neutrino Oscillation Analysis Method

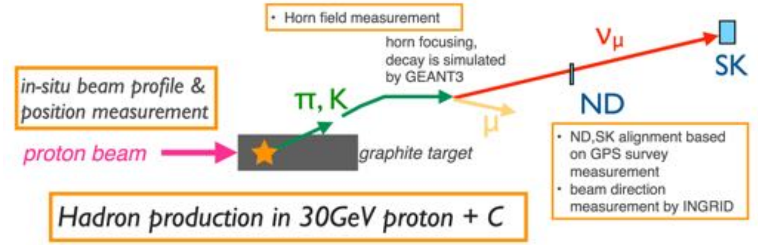
Number of neutrino events observed :

$N^{far} = \sum_i^{E_\nu\, bins} \sum_j^{flavors} P_{\nu_j \to \nu_k} \Phi_j^{far} \sigma_k^{far} \epsilon^{far} M_{det}^{far}$

$N^{near} = \sum_i^{E_\nu\, bins} \sum_j^{flavors} \Phi_j^{near} \sigma_k^{near} \epsilon^{near} M_{det}^{near}$

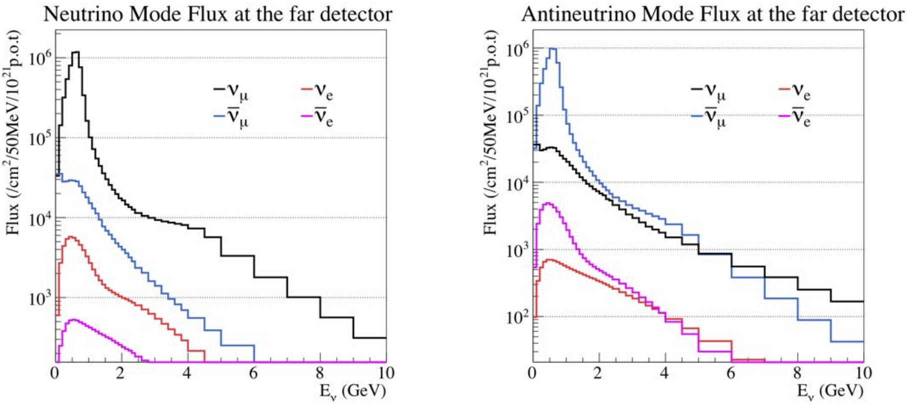
- Compare observed rates at far detector (after neutrino oscillation) to predictions under oscillation hypothesis
- Constrain by observed rates at near detector (before neutrino oscillation)
- Depends on :
  - Oscillation probabilities
  - Neutrino flux
  - Neutrino interaction cross sections
  - Detection efficiency
  - Detector resolution

T2K Flux Prediction



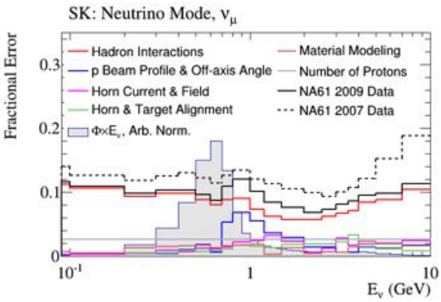
- The ν flux is predicted by simulations which take into account :
  - Hadron interactions inside + outside the production target
    - Simulated by Fluka+GEANT3 and tuned to external measurements by NA61/SHINE experiment at CERN, etc
  - Proton beam current, position, angle, profile
    - Measured by proton beam monitoring
  - Neutrino beam off-axis angle
    - Measured by proton beam monitoring, confirmed by INGRID on-axis near detector
  - Horn current, field, horn and target alignment, etc...

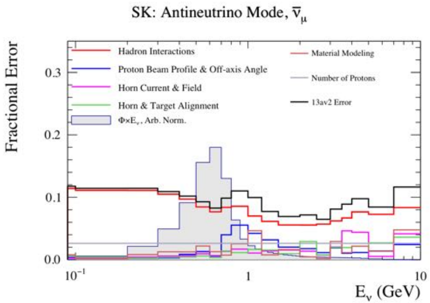
T2K Flux



- Predicted fluxes at Super Kamiokande
- $<$1% intrinsic beam ν_e's at peak energy
- Wrong-sign component (ν's in $\bar{\nu}$ mode) is larger in $\bar{\nu}$-mode

T2K Flux Errors



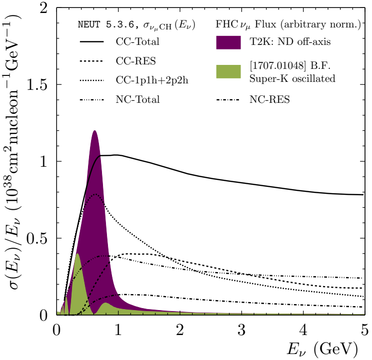


- Largest uncertainties on the neutrino flux come from hadron interactions, then the proton beam profile + ν beam off-axis angle
- Note, flux errors mostly cancel when we do our near/far fit
  - However, reducing flux errors can help reduce errors on cross section measurements

- Analysis improvements to include NA61/shine replica target data will be ready very soon
  - Will significantly reduce hadron interaction errors

Neutrino Cross Sections

- Main interaction at T2K neutrino energies is Charged Current Quasi-Elastic (CCQE)
    - $\nu_\mu + n \to \mu^- + p$
    - Can reconstruct ν energy using mass, energy, momentum, scattering angle of outgoing charged lepton: $E_\nu^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$
- Charged Current single pion (CC1π) sample also contributes
    - $\nu_\mu + n/p \to \mu^- + \pi^+ + n/p$

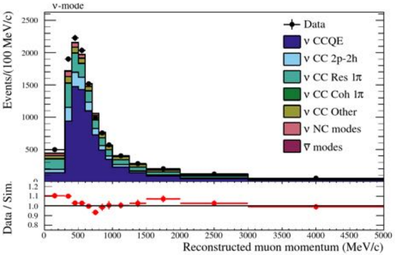


- Charged Current multinucleon (scattering on correlated pair of nucleons) can mimic CCQE – uncertainty on model for this scattering process
- Neutral Current (NC) and Deep Inelastic Scattering (DIS) interactions can be additional backgrounds

$\to$ Observe interactions + constrain cross sections by Near Detector

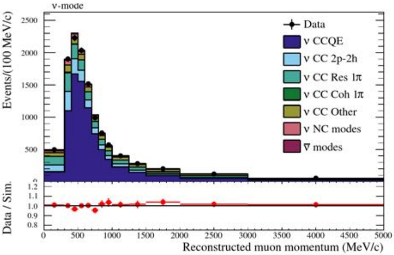
Near Detector Fit

Pre-Fit



PRELIMINARY

Post-Fit



PRELIMINARY

- Data fit to simulation for CC0π samples shown above
- Currently using a subset of T2K full dataset to constrain flux and cross section errors
  - Now working to update to use full Near Detector dataset
- Errors on SK event rates reduced by Near Detector fit :
  - ν-mode 1-ring CCQE μ-like 14.6% $\rightarrow$ 5.1%
  - ν-mode 1-ring CCQE e-like 16.9% $\rightarrow$ 8.8%
  - $\bar{\nu}$-mode 1-ring CCQE μ-like 12.5% $\rightarrow$ 4.5%
  - $\bar{\nu}$-mode 1-ring CCQE e-like 14.4% $\rightarrow$ 7.1%

FHC $=\nu$-mode
RHC $=\bar{\nu}$-mode
1 d.e. $=$ CC1π sample

T2K Systematics

% Errors on Predicted Event Rates

	1-Ring μ		**1-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
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	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

- SK detector errors – dominate for new-ish CC1π sample

FHC = ν-mode
RHC = $\bar{\nu}$-mode
1 d.e. = CC1π sample

T2K Systematics

% Errors on Predicted Event Rates

	1-Ring μ		**1-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
$\rightarrow$ 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
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
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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

- SK Final State Interaction + Secondary Interaction + Photo-Nuclear effect errors – pion-nucleon interaction modeling

FHC = ν-mode
RHC = $\bar{\nu}$-mode
1 d.e. = CC1π sample

T2K Systematics

% Errors on Predicted Event Rates

	1-Ring μ		1-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
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	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

- Flux and cross section errors constrained by ND280

FHC = ν-mode
RHC = $\bar{\nu}$-mode
1 d.e. = CC1π sample

T2K Systematics

% Errors on Predicted Event Rates

	1-Ring μ		**1-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
$\rightarrow$ E_b	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	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

- Nuclear binding energy error – uncertainties related to scattering on nucleons bound in nucleus

FHC = ν-mode
RHC = $\bar{\nu}$-mode
1 d.e. = CC1π sample

T2K Systematics

% Errors on Predicted Event Rates

	1-Ring μ		1-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
$\rightarrow$ $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	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

- Uncertainties on $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ arise since ν_e, $\bar{\nu}_e$ cross sections are not precisely measured at ND280

FHC = ν-mode
RHC = $\bar{\nu}$-mode
1 d.e. = CC1π sample

T2K Systematics

% Errors on Predicted Event Rates

	1-Ring μ		**1-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
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$\rightarrow$ NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
$\rightarrow$ 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

- Uncertainties on neutral current modes not constrained by ND280

FHC = ν-mode
RHC = $\bar{\nu}$-mode
1 d.e. = CC1π sample

T2K Systematics

% Errors on Predicted Event Rates

	1-Ring μ		**1-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
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NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
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$\rightarrow$ 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

- Error due to uncertainties on the oscillation parameter values (solar + θ_{13})

FHC = ν-mode
RHC = $\bar{\nu}$-mode
1 d.e. = CC1π sample

T2K Systematics

% Errors on Predicted Event Rates

	1-Ring μ		1-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
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$\rightarrow$ All Systematics	5.12	4.45	8.81	7.13	18.38	5.96
$\rightarrow$ All with osc	5.12	4.45	9.19	7.57	18.51	6.03

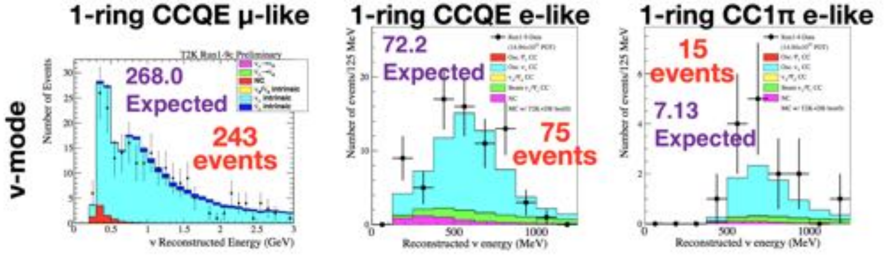
- Total systematic errors – $\sim$4$\sim$9% for 4 dominant samples

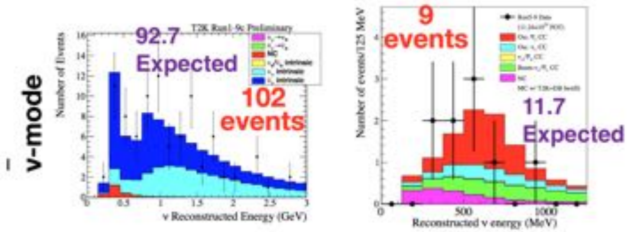
T2K Latest Results

Previous T2K Dataset (∼Dec 2017)

Reconstructed energy distributions at Super-K

$\sim 1.49 \times 10^{21}\ \nu + \sim 1.12 \times 10^{21}\ \bar{\nu}$ POT



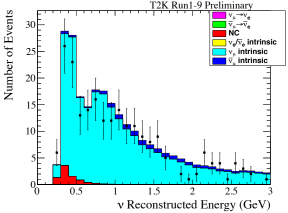
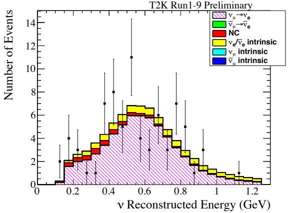
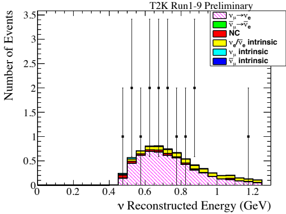
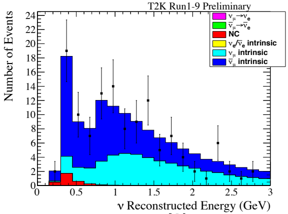
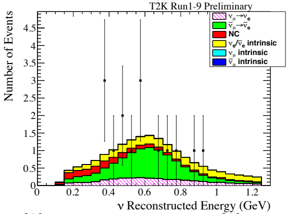


MC assumption

- **δ=−1.601**
- **Normal hierarchy**
- **$\sin^2\theta_{23}$=0.528**
- **$\sin^2\theta_{13}$=0.0219**

Latest T2K Dataset ($\sim$May 2018)

$\sim 1.49 \times 10^{21}\ \nu$ + $\sim 1.63 \times 10^{21}\ \bar{\nu}$ POT

	1-ring CCQE-μ-like	1-ring CCQE-e-like	1-ring CC1π-e-like
ν-mode			
$\bar{\nu}$-mode			

MC assumption :

$\delta_{CP} = -\pi/2$

Normal Hierarchy

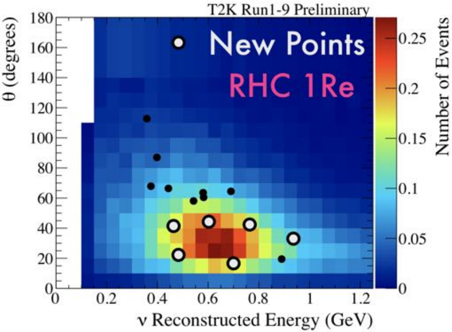
$\sin^2\theta_{23} = 0.528$

$\sin^2\theta_{13} = 0.0212$

	μ-like exp.	μ-like meas.	e-like exp.	e-like meas.
$\bar{\nu}$ Previous	92.7	102	11.7	9
$\bar{\nu}$ Updated	139.5	140	17.1	15
ν Updated	272.4	243	74.4(7.0cc1π)	75(15cc1π)

New T2K $\bar{\nu}_e$ Appearance Data

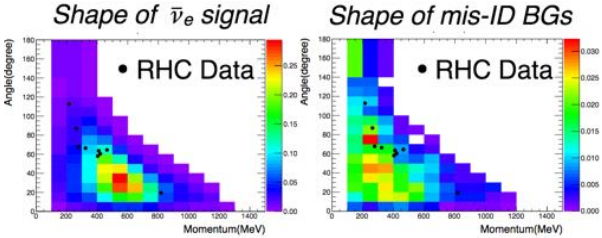
Full Dataset (~May 2018) :



← Lepton angle vs reconstructed energy for $\bar{\nu}$-mode 1-ring CCQE-e-like events

- Distribution of new points looks more like $\bar{\nu}_e$-signal
  → Better constraint on possible $\bar{\nu}_e$ appearance
- Note : main backgrounds are $\nu_\mu \to \nu_e$ and beam intrinsic $\bar{\nu}_e + \nu_e$

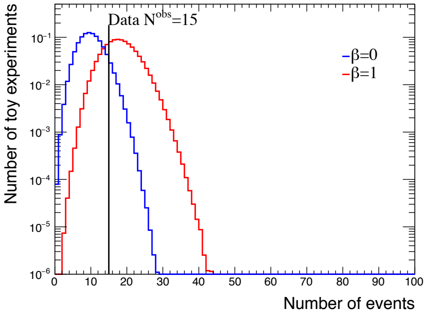
Previous Dataset (~Dec 2017) :



New T2K $\bar{\nu}_e$ Appearance Result

- Search for $\bar{\nu}_e$ appearance
- Compare consistency with PMNS $\bar{\nu}_e$ appearance (β=1) and no $\bar{\nu}_e$ appearance (β=0) : $P(\bar{\nu}_\mu \to \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \to \bar{\nu}_e)$

Rate-only analysis



Blue: expected # of $\bar{\nu}_e$ events w/ NO $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation (β=0, 9.4 evts)

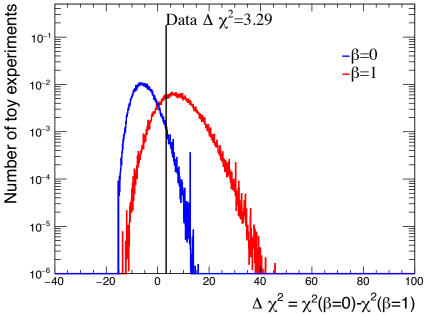
Red: expected # of $\bar{\nu}_e$ events w/ $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation (β=1, 17.2 evts)

- For rate-only analysis, data agrees with both hypotheses
- Result statistically not conclusive yet – need more data

New T2K $\bar{\nu}_e$ Appearance Result

- Search for $\bar{\nu}_e$ appearance
- Compare consistency with PMNS $\bar{\nu}_e$ appearance (β=1) and no $\bar{\nu}_e$ appearance (β=0) : $P(\bar{\nu}_\mu \to \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \to \bar{\nu}_e)$

Rate+shape analysis



Blue: expected # of $\bar{\nu}_e$ events w/ NO $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation (β=0, 9.4 evts)

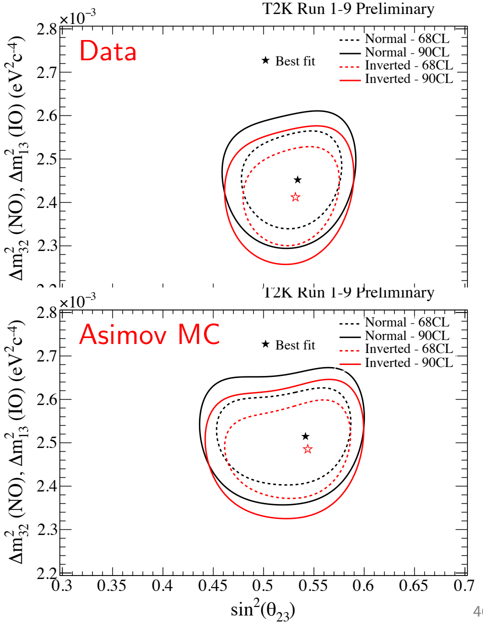
Red: expected # of $\bar{\nu}_e$ events w/ $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation (β=1, 17.2 evts)

- For rate+shape, the $\beta = 0$ hypothesis is excluded by 2σ
- Result statistically not conclusive yet – need more data

Analysis	P-value for $\beta = 0$ (σ excl.)	P-value for $\beta = 1$ (σ excl.)
Rate only	0.0686 (1.82σ)	0.246 (1.16σ)
Rate+shape	0.0244 (2.25σ)	0.261 (1.12σ)

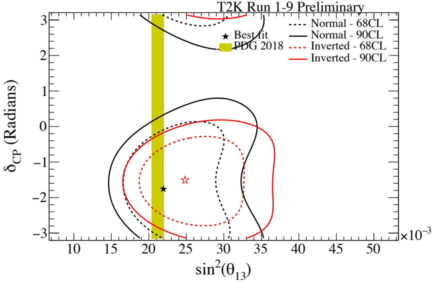
T2K ν_μ Results (~May 2018)

- CL contours for $\nu_\mu \to \nu_\mu$ disappearance parameters, including reactor constraint on $\sin^2\theta_{13}$
- Best fit points :
  $\sin^2\theta_{23} = 0.532$
  $\Delta m^2_{32} = 2.452 \times 10^{-3}$ eV^2
- T2K data compatible with maximal mixing ($\sin^2\theta_{23} = 0.52$)
- Stronger $\sin^2\theta_{23}$ constraint in data than expected from sensitivity studies



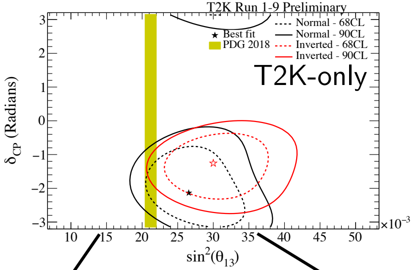
Latest T2K CP Violation Search Result

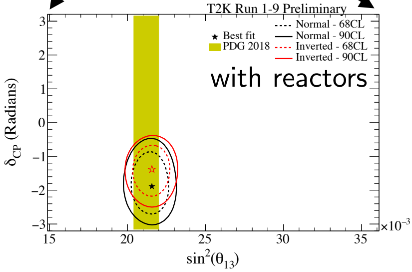
T2K-only sensitivity :



- Preference for values of $\delta_{CP} \sim -\pi/2$
- Sensitivity improved due to lower value of $\sin^2\theta_{13} = 0.0212$
- Note : data-fit result gives a stronger constraint than the sensitivity

Data Fit :

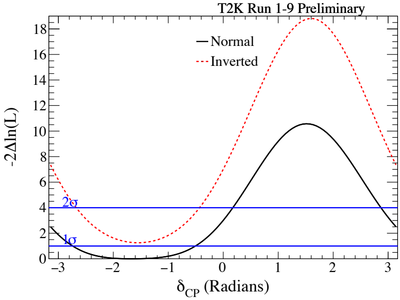




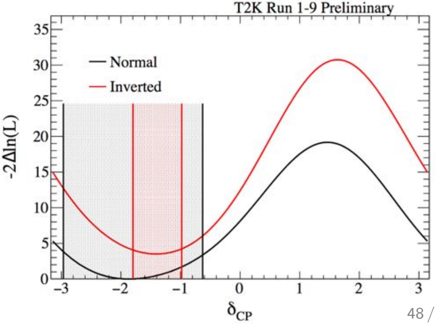
T2K Search for δ_{CP}

- T2K fit with reactor constraint on $\sin^2\theta_{13}$:
  - Best fit point : $\delta_{CP} = -1.885$ radians in Normal Hierarchy
  - δ_{CP} 2σ CL confidence interval :
    - Normal mass hierarchy : [-2.966, -0.628] radians
    - Inverted mass hierarchy : [-1.799, -0.979] radians
  - CP conserving values $(0, \pi)$ fall outside of the 2σ CL intervals !
    - Still fall within the 3σ CL intervals
    - Suggestive result, but need more data

Sensitivity

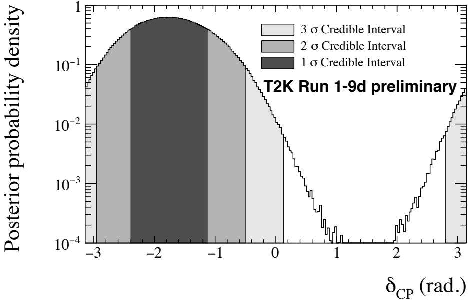


Data (2σ CL)

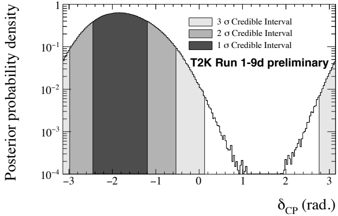


T2K Search for δ_{CP} – Bayesian Analysis

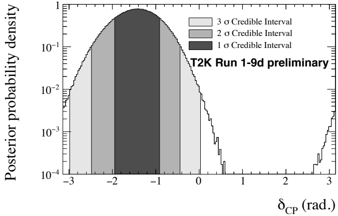
Both Hierarchies



Normal Hierarchy



Inverted Hierarchy



- T2K excludes CP conservation at 2σ, but not 3σ
- Most probable value, marginalized over hierarchy, is $\delta_{CP} = -1.74$

Other T2K Measurements

- T2K also has a rich program of non-oscillation physics
  - Many many world-leading cross section measurements
  - Exotic physics searches (sterile neutrinos, heavy neutrinos, etc..)

Some recent xsec results :

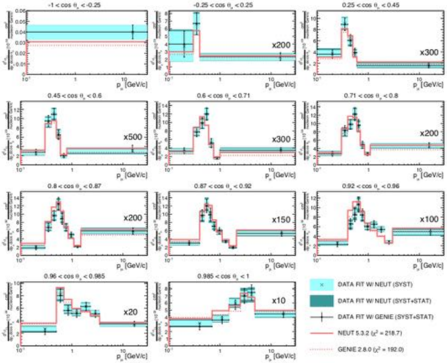
- CC-inclusive on CH, Fe, H_2O
- CC0π on CH, H_2O, ...
- CC1π on CH, H_2O
- NC$1\pi^0$

Some ongoing xsec analyses :

- CC inclusive $\bar{\nu}_\mu$, on Ar
- CC0π ν+$\bar{\nu}$, C+O, C+Pb, ...
- CC1π ν_μ on H_2O and C
- NC$1\pi^0$, CC$1\pi^0$ on H_2O, CH
- NC1γ
- + many others !

Example new result :

ν_μ CC inclusive on CH

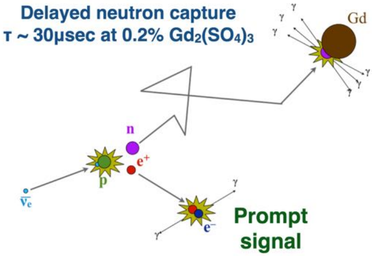


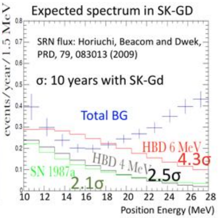
(PRD 98, 012004 (2018))

Future Long-Baseline Neutrino Oscillation Physics Prospects

Super Kamiokande : SK-Gd Upgrade

- Super Kamiokande now undergoing SK-Gd upgrade !
- Gd loading to capture thermal neutrons $\rightarrow$ delayed gamma signal
- Can be used to tag $\bar{\nu}_e$
- SK-Gd physics targets :
  - Supernova relic neutrino (3σ discovery after 10 years)
  - Improve pointing accuracy for galactic supernovae
  - Nearby supernova Si-burning precursor detection
  - Reduction of solar ν BG
  - Reactor neutrinos
  - Reduce proton decay background
  - $\nu/\bar{\nu}$ discrimination
- No negative impact on water quality, high-energy background, etc.
- May help T2K $\nu/\bar{\nu}$ discrimination

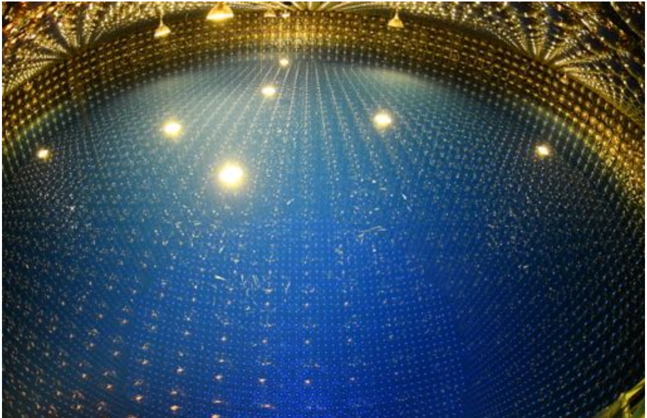




Super-K Refurbishment for SK-Gd

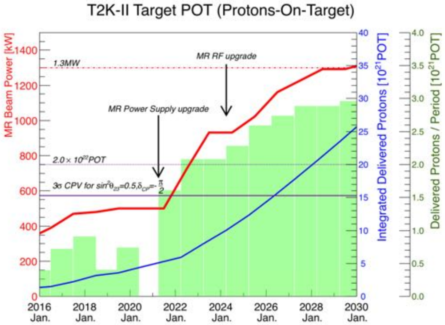
- Super-K tank was opened summer 2018 (first time since 2006)
- Refurbishment work ongoing in preparation for Gd loading :
  - Cleaning + water sealing reinforcement
  - Improvement of tank piping
  - Replacement of defective PMTs
- Currently re-filling water + finishing work at top of tank + taking data with $\sim$90% filled tank
- Gd loading schedule will be decided w/ input from T2K/J-PARC
  - Tentatively plan to add 0.01% Gd in late 2019/early 2020
  - Will then load with 0.1% Gd later

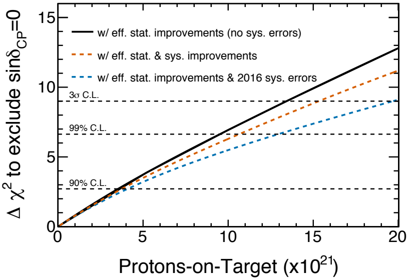
Super-K Tank Open Work

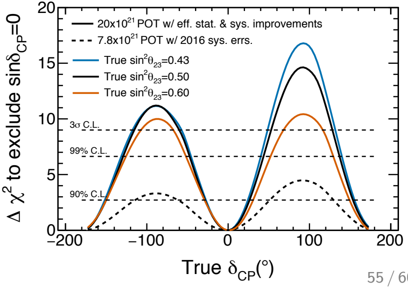


T2K Future Prospects

- Proposal for extension of T2K :
  - May have 3σ sensitivity to $\delta_{CP} \neq 0$ by around 2026
  - 20×10^{21} POT by 2027∼2028
  - Target beam power : 1.3 MW
  - Increase effective statistics
    - More new SK event samples
    - 320kA horn current
  - Reduce sys. error $\sim 9\% \rightarrow \sim 4\%$
- KEK/J-PARC Stage-1 status







J-PARC Beam Power Upgrades

Beam Power	485kW (achieved)	750kW (proposed) [original]	1MW (demonstrated)	1.3MW (proposed)
# of protons/ pulse	2.4×10^{14}	2.0×10^{14} [3.3×10^{14}]	2.6×10^{14}	+25% +18% 3.2×10^{14}
Operation cycle	2.48 s	1.3 s [2.1 s]	1shot	1.16 s

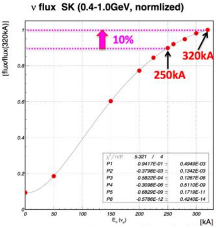
- Currently : 485 kW with 2.48 s repetition rate
  - 500+ kW achieved during beam tests
- Plan to upgrade MR power supplies in 2020/2021 to reach 1.3 s repetition rate
  - RF improvements can allow for further decrease to 1.16 s
- Plan to improve beam stability, reduce MR beam losses to increase number of protons per pulse

- Upgrades to J-PARC neutrino beamline needed to accept high power beam

J-PARC Neutrino Beamline Upgrades

- Upgrades to the neutrino beamline necessary to accommodate the high power proton beam
  - + Others to improve T2K datataking
- Primary beamline upgrades :
  - Upgrade to semi-remote handling at most downstream part of beamline
  - Upgrades to beam profile monitoring
  - Upgrades to monitor readout electronics and beam interlock system
  - etc..
- Secondary beamline upgrades :
  - Increase horn current
  - Upgrades to target and horn cooling
  - Upgrades to radioactive water disposal scheme
  - etc..
- Beamline upgrade TDR under review now
- Necessary upgrades to be completed by 2021

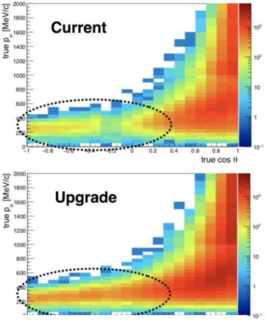
2018 Primary Beamline Work

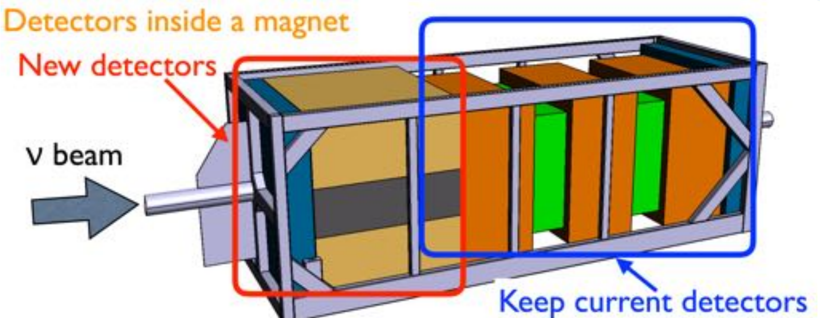


Flux Improvement @320kA

ND280 Upgrades

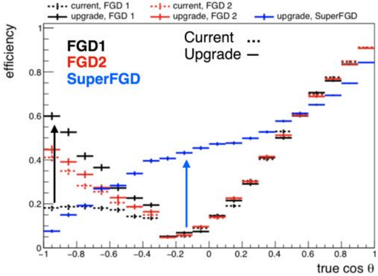
- Reduce ND systematics to <4%
  - Improve acceptance for high-angle and backwards tracks
- Replace P0D with : superFGD + 2 High-Angle TPCs + TOF
- CERN joined upgrade team in 2018
- Upgrade TDR under review now
- Plan to install in late 2021

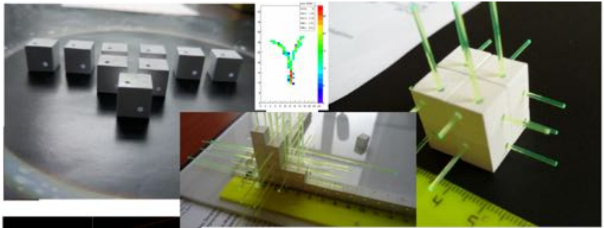




SuperFGD R&D for ND280 Upgrade

- Many R&D items ongoing for ND280 upgrade
- SuperFGD is a major new component
  - 2,000,000 1x1x1cm^3 scintillator cubes
  - 3D readout by wavelength shifting fibers
- Muon tracking efficiency significantly improved for high-angle tracks

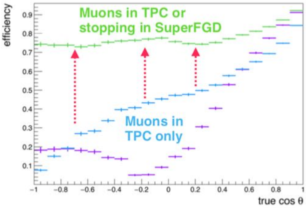




1x1x1 cm^3 plastic scintillator cubes with 3 fibers readout along x, y, z
Detailed (3 2-D projections) and highly segmented view of the interaction
Successful tests of prototypes
Good tracking, PID, timing

+ Stopping muons in superFGD

↓↓↓



Conclusion

- Latest T2K result is very exciting !
- Rate + shape analysis gives 2σ hint of $\bar{\nu}_e$ appearance from a $\bar{\nu}_\mu$ beam
  - Need more $\bar{\nu}$-mode data for T2K measurement of $\bar{\nu}_e$ appearance
- CP conserving values of δ_{CP} $(0, \pi)$ fall outside of the 2σ CL intervals !
  - However, constraint is tighter than sensitivity – need more ν-mode data to make a reliable/precise measurement
- May reach 99% CL for CP violation in the very near future !
  - Need more data !
- T2K extended running proposed to improve sensitivity
- Various upgrades underway for increased beam power + improved systematics

Backup Slides

T2K ν_μ Results (~Dec 2017)

- T2K data compatible with maximal mixing ($\sin^2\theta_{23} = 0.52$)
- Contours slightly narrower than expected for maximal mixing