Recent Results from the T2K Experiment

Megan Friend (KEK)

新学術領域研究「ニュートリノフロンティア」研究会

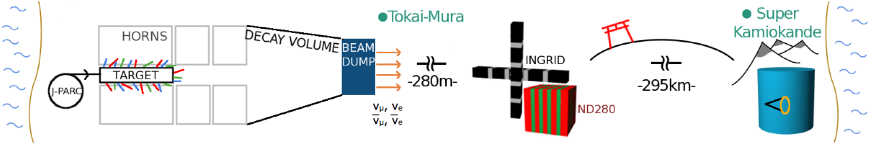
December 21, 2014

Outline

1. The T2K Long Baseline Neutrino Experiment
   - Data-Taking Status
2. Latest T2K Results
   - T2K Run 1-4 Joint Appearance + Disappearance Analysis
   - Other Measurements
3. T2K Expected Sensitivity
   - T2K Sensitivity to δ_{CP}

The T2K Collaboration

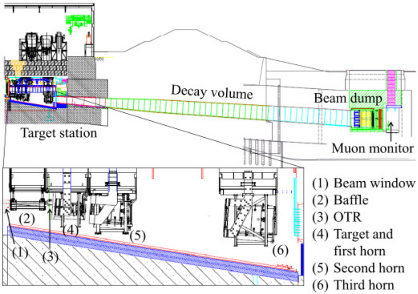
∼500 members from 59 institutes in 11 countries



The T2K Experiment (Tokai to Kamioka Long Baseline Neutrino Experiment)

- Primarily ν_μ, 2.5° off axis neutrino beam produced at J-PARC
- ND280 Near Detector at J-PARC – 280 m from ν source
- Neutrino interactions detected at the Super-Kamiokande (SK) far detector – 295 km from ν source
  - $\nu_\mu \to \nu_e$ appearance and $\nu_\mu \to \nu_\mu$ disappearance ν oscillations information from SK
    - (most ν_μ's oscillate to undetected ν_τ's)

Producing the T2K Neutrino Beam

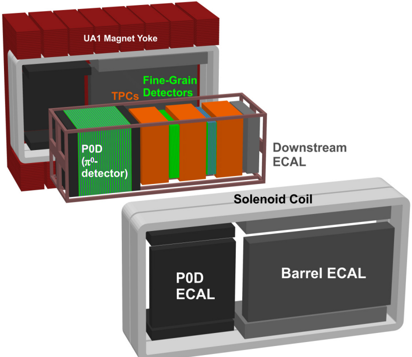


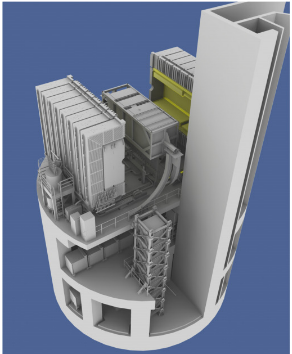
- 30 GeV protons from the J-PARC Main Ring hit a long carbon target and produce (mostly) π's and (some) K's
- π's and K's are focused in electromagnetic horns
- $(+)$ horn polarity focuses π^+'s, which mostly decay into μ^+ and ν_μ in ~100-m-long decay volume
- $(-)$ horn polarity focuses π^-'s, which mostly decay into μ^- and $\bar{\nu}_\mu$
- The decay μ's are monitored using a muon monitor and stop in shielding, while the ν's continue on to ND280 and SK

$\rightarrow$ Understanding hadron interactions in the target is very important for understanding the ν flux (NA61 experiment)

The T2K Experiment – ND280

- The near detector complex is used to measure the ν flux ON (INGRID) and OFF (ND280) axis near the ν source
- INGRID monitors ν beam position and angle
- Very important for constraining uncertainties on the flux and other systematic errors on the oscillation measurement
- Also used to make precision cross section measurements, sterile neutrino searches, other exotic physics searches

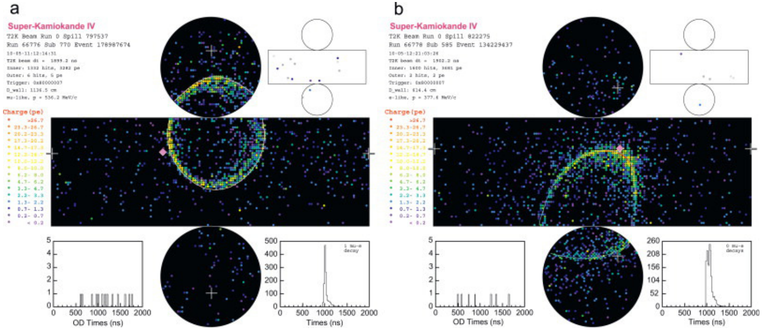




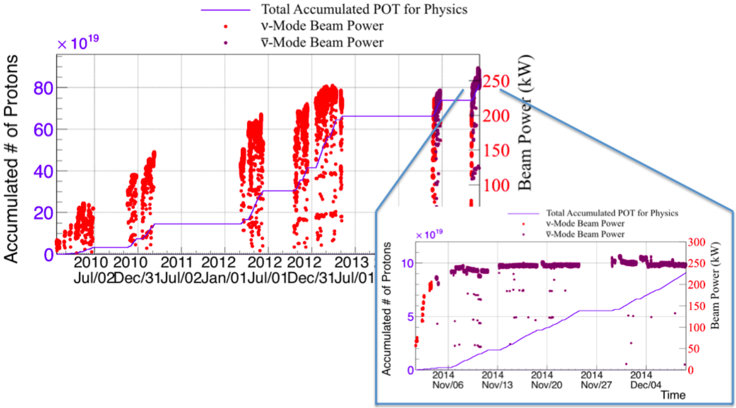
The T2K Experiment – SK Far Detector

- Huge water Cherenkov detector holding 50 ktons of ultra-pure water
- Muons (produced by ν_μ) travel basically undisturbed and produce sharp Cherenkov rings
- Electrons (produced by ν_e) re-scatter and produce fuzzy ones
  $\rightarrow$ Excellent ν_e/ν_μ particle ID for sub-GeV energy ν's

Muon Neutrino Detected | Electron Neutrino Detected



The T2K Experiment Status – Integrated Protons on Target (to Mid-December)



- Began taking first $\bar{\nu}$-mode data in June 2014!
- Integrated for Physics so far: $\sim 8.3 \times 10^{20}$ POT
- Integrated $\bar{\nu}$-Mode for Physics so far: $\sim 1.4 \times 10^{20}$ POT
  $\rightarrow$ ∼11% of T2K approved full statistics (7.8×10^{21} POT)

Current Understanding of the Neutrino Oscillation Parameters

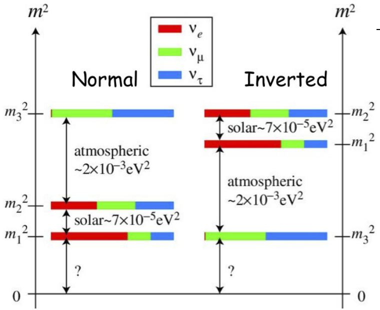
Neutrino oscillation parameters are described by the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) mixing matrix:

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

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

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

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



- MH completely unknown
- $\theta_{12} = 33.6^\circ \pm 1.0^\circ$
- $\theta_{23} = 45^\circ \pm 6^\circ$ (90% C.L.)
  – is θ_{23} maximal?
- $\theta_{13} = 9.1^\circ \pm 0.6^\circ$ – from recent reactor $\bar{\nu}_e$ disappearance measurements
- Can be probed with long-baseline neutrino oscillation experiments

Oscillation Probabilities

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

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) \quad \to \text{Leading, matter effect}$$

$$+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} \quad \to \text{CP conserving}$$

$$- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} \quad \to \text{CP violating}$$

$$+ 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21} \quad \to \text{Solar}$$

$$- 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E} \cos\Phi_{32} \sin\Phi_{31} \quad \to \text{Matter effect}$$

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

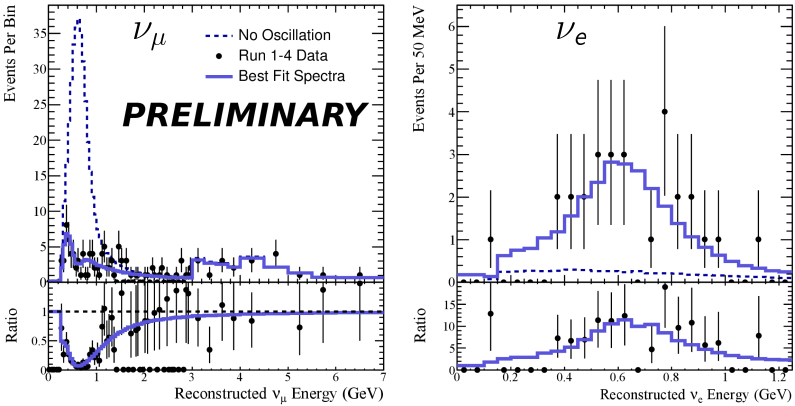
- Long-baseline $\nu_\mu \to \nu_\mu$ disappearance probability depends most strongly on $\sin^2 2\theta_{23}$ and Δm_{32}^2
  - (But degeneracy is broken by $\sin^2 2\theta_{13}$)

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

Leading Term — Next-to-Leading

T2K Run 1-4 $\nu_\mu \to \nu_e$ Appearance and $\nu_\mu \to \nu_\mu$ Disappearance Spectra in SK

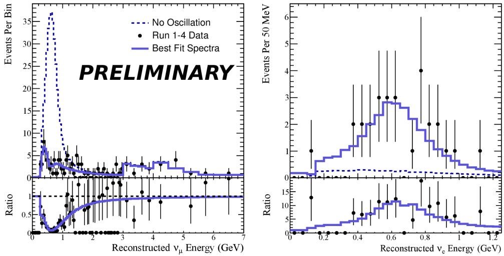
- Observed a clear ν_μ disappearance spectrum
- Observed 28 ν_e candidate events (with expected 4.6 ± 0.5 background events) $\to$ 7.3σ appearance observation
- Can fit ν_e and ν_μ simultaneously to obtain most robust results



T2K Joint Appearance + Disappearance Analysis Method

Unlike previous T2K analysis methods:

- Use both $\nu_\mu \to \nu_e$ appearance and $\nu_\mu \to \nu_\mu$ disappearance information simultaneously
  - Fit the reconstructed energy spectra of the ν_e appearance and ν_μ disappearance data simultaneously
    - Could also do a joint fit of the outgoing lepton momentum and angle
  - Uncertainties on $\sin^2 2\theta_{13}$, δ_{CP}, $\sin^2\theta_{23}$, and Δm^2_{32} are all considered (all 4 parameters are fit simultaneously)

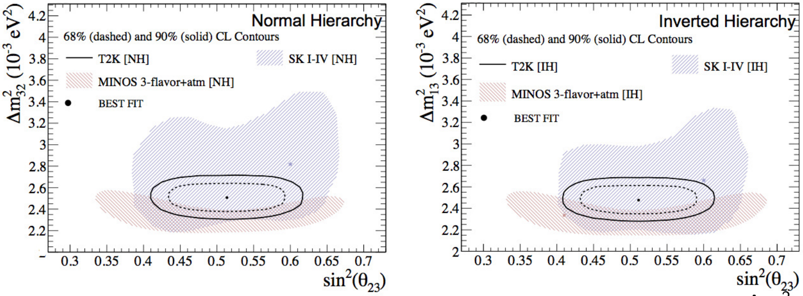


Systematic Errors for T2K Joint Fit

	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$
# of Detected Events at SK	28	120
Predicted # of Detected Events	21.06	124.98
Error Source**		
Flux + ND Constrained XSec (w/out ND280)	26.0%	21.7%
Flux + ND Constrained XSec (w/ ND280)	3.2%	2.7%
ND Non-Constrained XSec	4.7%	5.0%
SK + FSI + PN	3.7%	5.0%
Total error (w/out ND280)	26.8%	23.5%
Total error (w/ ND280)	6.8%	7.7%

**Errors are given on the predicted number of far detector events

T2K Run 1-4 $\nu_\mu \rightarrow \nu_\mu$ Disappearance



$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\frac{\Delta m^2_{31}L}{4E}$$

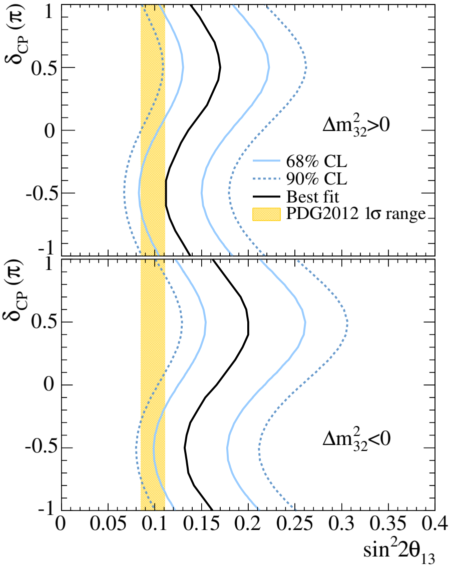
Leading Term — Next-to-Leading

- Joint fit best fit point:
  $\sin^2\theta_{23} = 0.528^{+0.051}_{-0.059}$ $\Delta m^2_{32} = (2.50 \pm 0.10) \times 10^{-3}$ eV^2
- World's best constraint on $\sin^2\theta_{23}$
- Best fit point is at maximal disappearance

Includes a constraint on $\sin^2 2\theta_{13}$ based on reactor measurements:
$\sin^2 2\theta_{13} = 0.095 \pm 0.01$

*from Phys. Rev. Lett. 112, 181801 (2014)

T2K Run 1-4 $\nu_\mu \rightarrow \nu_e$ Appearance

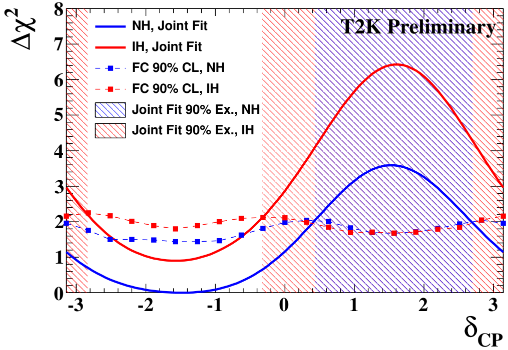


- Blue lines show T2K-alone C.L. regions
  - NOTE: δ_{CP} values are fixed when generating these plots, they are not 2D contours
- Yellow band shows $\sin^2 2\theta_{13}$ as measured by reactor ($\bar{\nu}_e$ disappearance) experiments
  - Daya Bay, RENO, Double Chooz
- Combination of the T2K result with the reactor experiment result can give a constraint on δ_{CP}
  - Since T2K has some sensitivity to δ_{CP}
  - And reactor experiments have measured $\sin^2 2\theta_{13}$ very precisely, but have no sensitivity to δ_{CP}

*from Phys. Rev. Lett. 112, 061802 (2014)

T2K Run 1-4 $\nu_\mu \to \nu_e$ Appearance – Frequentist Analysis

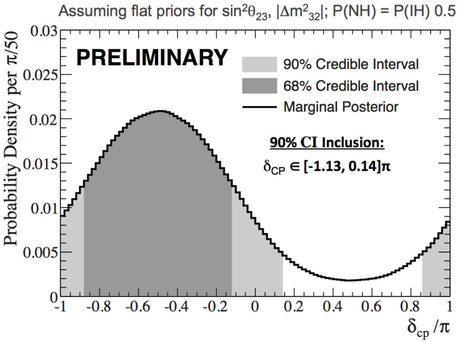
T2K (Joint Fit) + Reactor ($\sin^2 2\theta_{13} = 0.095 \pm 0.01$) combined:



	90% C.L. Ex. Region
NH	$0.14\pi \sim 0.86\pi$
IH	$-0.10\pi \sim 1.11\pi$

T2K Run 1-4 $\nu_\mu \rightarrow \nu_e$ Appearance – Bayesian Analysis

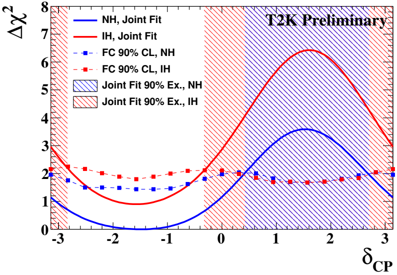
T2K (Joint Fit) + Reactor ($\sin^2 2\theta_{13} = 0.095 \pm 0.01$) combined:



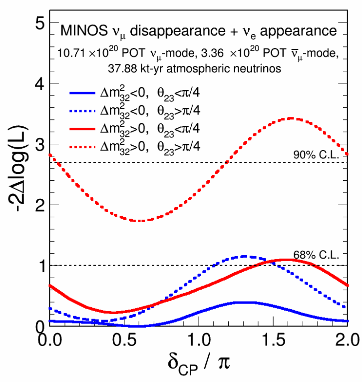
	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18%	8%	26%
$\sin^2\theta_{23} > 0.5$	50%	24%	74%
Sum	68%	32%	100%

T2K Run 1-4 vs. MINOS δ_{CP} Measurement Results

T2K joint fit



MINOS (beam+atmospheric data)*

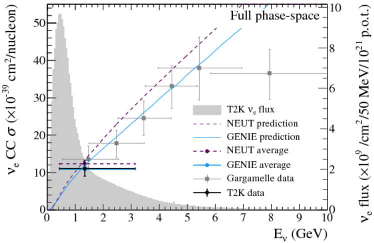


- Note the reversed *x*-axes – results not in agreement!
- Note the different *y*-axis scales

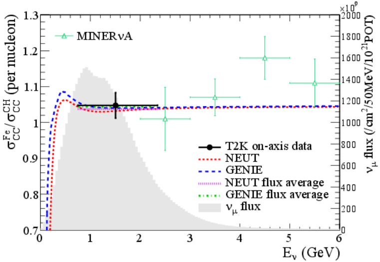
*Phys. Rev. Lett. 112, 191801 (2014)

Selection of Other New Results From T2K

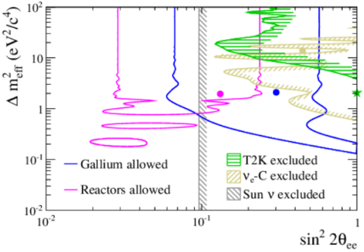
Phys. Rev. Lett. 113, 241803 (2014)



Phys. Rev. D 90 052010 (2014)



arXiv:1410.8811 [hep-ex]



- ν_e CC xsec measurement by off-axis ND280
- ν_μ inclusive CC xsec on Fe and CH measurement by on-axis near detector
- Search for short baseline ν_e disappearance (sterile search) by off-axis ND280

The T2K Experiment – Physics Goals

The physics goals of the first phase of T2K are (from LOI):

1. "... a factor of 20 more sensitive search for $\nu_\mu \to \nu_e$ appearance: $\sin^2 2\theta_{\mu e} \simeq 0.5 \sin^2 2\theta_{13} > 0.003$ ..."
2. "... an order of magnitude better precision in the $\nu_\mu \to \nu_\tau$ oscillation measurement:
   $\delta(\Delta m^2_{23}) = 10^{-4}$ eV^2 and $\delta(\sin^2 2\theta_{23}) = 0.01$ ..."
3. "... a confirmation of the $\nu_\mu \to \nu_\tau$ oscillation or discovery of sterile neutrinos by detecting the neutral current events ..."

- Requested: 750 kW $\times$ 5×10^7 s (115 days $\times$ 5 years) at 30 GeV $=$ 7.80×10^{21} POT

The T2K Experiment – Physics Goals

The physics goals of the first phase of T2K are (from LOI):

1. "… a factor of 20 more sensitive search for $\nu_\mu \to \nu_e$ appearance: $\sin^2 2\theta_{\mu e} \simeq 0.5 \sin^2 2\theta_{13} > 0.003$ …"
2. "… an order of magnitude better precision in the $\nu_\mu \to \nu_\tau$ oscillation measurement:
$\delta(\Delta m^2_{23}) = 10^{-4}$ eV^2 and $\delta(\sin^2 2\theta_{23}) = 0.01$ …"
3. "… a confirmation of the $\nu_\mu \to \nu_\tau$ oscillation or discovery of sterile neutrinos by detecting the neutral current events …"

- Requested: 750 kW $\times$ 5×10^7 s (115 days $\times$ 5 years) at 30 GeV = 7.80×10^{21} POT

$\to$ Can now update the T2K experimental goals following the 7.3σ observation of ν_e appearance by T2K and the precise measurement of $\sin^2 2\theta_{13}$ by reactor experiments:

- Precisely measure θ_{23} and Δm^2_{32}
- Obtain hints about δ_{CP}, θ_{23} Octant, Mass Hierarchy

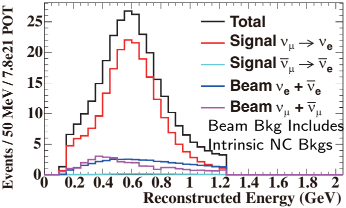
Considerations for T2K Sensitivity Studies

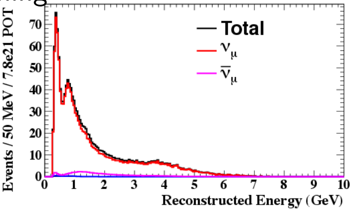
- $\nu_\mu \rightarrow \nu_e$ appearance and $\nu_\mu \rightarrow \nu_\mu$ disappearance combined fit (like joint fit)
- Uncertainties on $\sin^2 2\theta_{13}$, δ_{CP}, $\sin^2 \theta_{23}$, and Δm^2_{32}
- With $\bar{\nu}$-mode running information
- Realistic systematic errors (2012 errors generally used here)
- Contributions from outside experiments
  - $\sin^2 2\theta_{13}$ can be constrained by future projected error of reactor experiments
    - Constrained as $\delta(\sin^2 2\theta_{13}) = 0.005$
  - Combination with NOνA, SK atmospheric data, or other experiments may enhance sensitivity
- Results recently posted on arXiv:1409.7469 [hep-ex]

Far Detector Reconstructed Energy Spectra at Full Statistics (7.8×10^{21} POT)

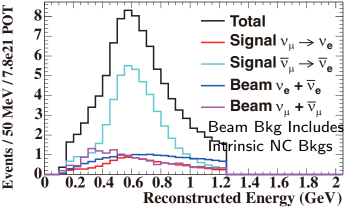
ν_e Appearance | ν_μ Disappearance

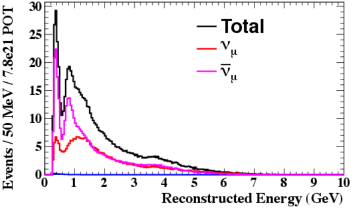
ν-Running





$\bar{\nu}$-Running





NOTE: must always choose set of "true" oscillation parameters:
$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$, NH

Reduction of Systematic Errors

ν_e App. Sys. Err.*	2012	2014
BANFF (Flux & Cross Section)	5.0%	2.9%
ND Un-Constrained Cross Section	7.5%	4.9%
SK Detector and FSI	3.9%	3.6%
Total	9.7%	6.7%

Disappearance systematic errors*:

$$13.3\% \text{ (2013)} \rightarrow 7.6\% \text{ (2014)}$$

→ Excellent systematic error reduction in the last two years!

Reaching $\sim$5% error for both ν_e and ν_μ seems to be achievable

Projected systematic errors (conservative)*:

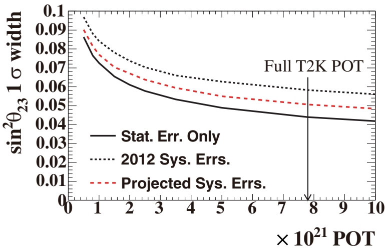
$$7\%\ \nu,\ 14\%\ \bar{\nu}$$

*Systematic error on the number of events detected at SK assuming $\sin^2 2\theta_{13} = 0.1$

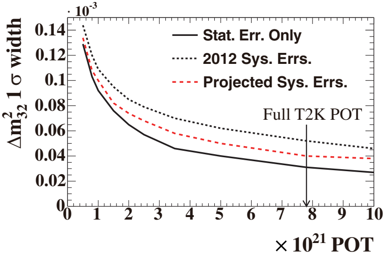
T2K $\sin^2\theta_{23}$ and Δm^2_{32} Precision vs. POT

Solid Lines: no sys. err.
Black Dashed: with 2012 sys. err. ($\sim$10% ν_e, $\sim$13% ν_μ)
Red Dashed: with conservative projected sys. err. ($\sim$7% ν, $\sim$14% $\bar{\nu}$)

$\sin^2\theta_{23}$



Δm^2_{32}



$\rightarrow$ Statistical limits at full POT:

$$\delta(\sin^2\theta_{23}) \simeq 0.045\ (2.6^\circ),\ \delta(\Delta m^2_{32}) \simeq 4\times 10^{-5}\ \text{eV}^2$$
$$(\text{Current PDG limits: } \delta(\sin^2\theta_{23}) \simeq \pm 6^\circ,\ \delta(\Delta m^2_{32}) \simeq \pm 1\times 10^{-4})$$

Similar sensitivities seen for 50% POT ν + 50% POT $\bar{\nu}$

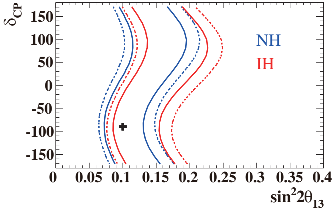
Assuming: 100% POT ν-mode, θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$
$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0^\circ$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4\times 10^{-3}$ eV^2, NH

Impact of ν- vs. $\bar{\nu}$-Mode Running

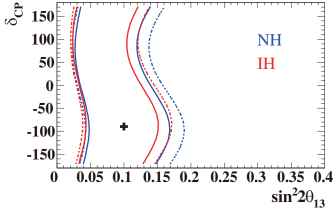
90% C.L. Solid: no sys. err., Dashed: with 2012 sys. err.

True MH is NH; contours drawn for two MH assumptions

3.9×10^{21} POT ν



3.9×10^{21} POT $\bar{\nu}$



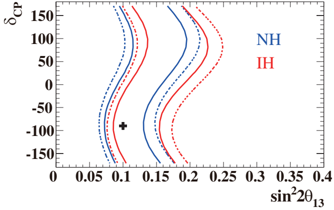
$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = -90^\circ$, $\sin^2 \theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$, NH

Impact of ν- vs. $\bar{\nu}$-Mode Running

90% C.L. Solid: no sys. err., Dashed: with 2012 sys. err.

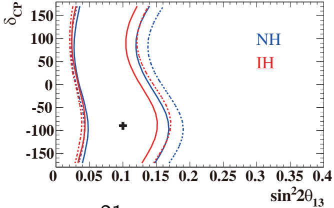
True MH is NH; contours drawn for two MH assumptions

3.9×10^{21} POT ν



$+$

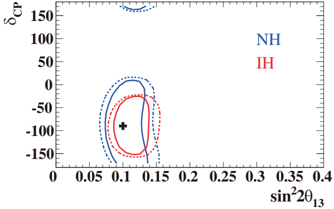
3.9×10^{21} POT $\bar{\nu}$



Difference in sensitivity to δ_{CP} for ν- vs. $\bar{\nu}$-mode beam means that δ_{CP} can be constrained with combined ν+$\bar{\nu}$ data

$\rightarrow$

3.9×10^{21} POT both $\nu + \bar{\nu}$



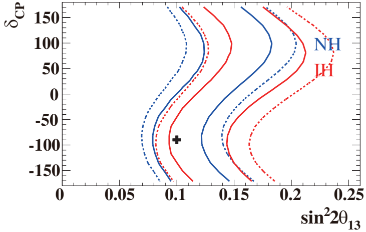
$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = -90^\circ$, $\sin^2\theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\mathrm{eV}^2$, NH

Appearance 90% C.L. Sensitivity at 7.8×10^{21} POT, True $\delta_{CP} = -90^\circ$

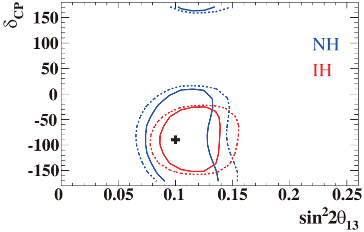
Solid: no sys. err., Dashed: with 2012 sys. err.

True MH is NH; contours drawn for two MH assumptions

100% POT ν



50% POT ν + 50% POT $\bar{\nu}$



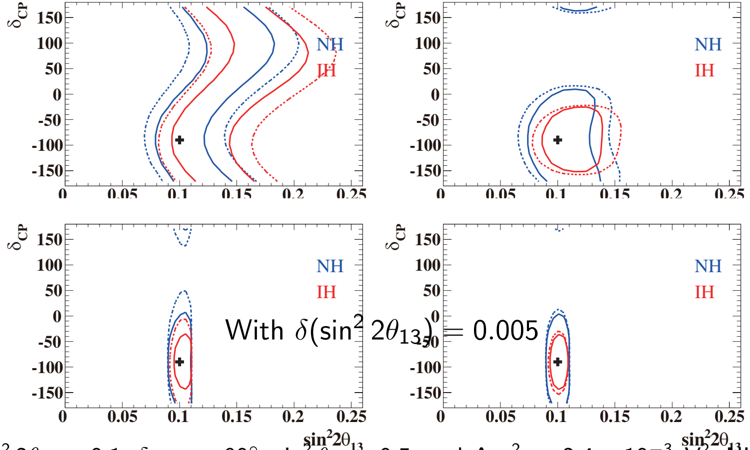
$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = -90^\circ$, $\sin^2 \theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3} \text{eV}^2$, NH

Appearance 90% C.L. Sensitivity at 7.8×10^{21} POT, True $\delta_{CP} = -90^\circ$

Solid: no sys. err., Dashed: with 2012 sys. err.

True MH is NH; contours drawn for two MH assumptions

100% POT ν | 50% POT ν + 50% POT $\bar{\nu}$



With $\delta(\sin^2 2\theta_{13}) = 0.005$

$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = -90^\circ$, $\sin^2\theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\mathrm{eV}^2$, NH

Appearance 90% C.L. Sensitivity at 7.8×10^{21} POT, True $\delta_{CP} = -90^\circ$

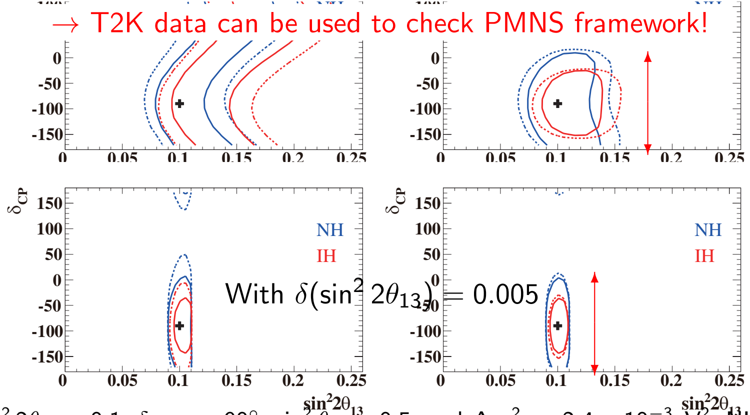
Solid: no sys. err., Dashed: with 2012 sys. err.

True MH is NH; contours drawn for two MH assumptions

100% POT ν 50% POT ν + 50% POT $\bar{\nu}$

T2K $\nu + \bar{\nu}$ data can constrain δ_{CP} as well as T2K + reactor data

$\rightarrow$ T2K data can be used to check PMNS framework!



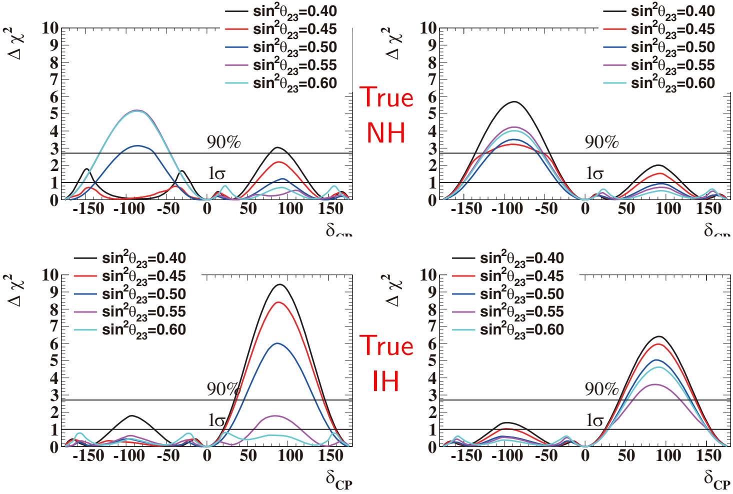
With $\delta(\sin^2 2\theta_{13}) = 0.005$

$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = -90^\circ$, $\sin^2 \theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\mathrm{eV}^2$, NH

T2K Sensitivity for Resolving $\sin\delta_{CP} \neq 0$

7.8×10^{21} POT; Without systematic error

100% POT ν 50% POT ν + 50% POT $\bar{\nu}$



Assuming true: $\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

Conclusion

T2K recent results and current status:

- World-leading long-baseline neutrino oscillation results
  - 7.3σ ν_e appearance observation
  - World's best precision on ν_μ disappearance parameters
  - First hints of possible non-zero δ_{CP}
  - Many other measurements made using the 280m Near Detector
- Analysis of first $\bar{\nu}$-mode data is ongoing
  - See talk on Tuesday by T. Hiraki

T2K expected sensitivity at 7.8×10^{21} POT:

- At the full statistics, T2K may have sensitivity to constrain δ_{CP} and determine the θ_{23} octant

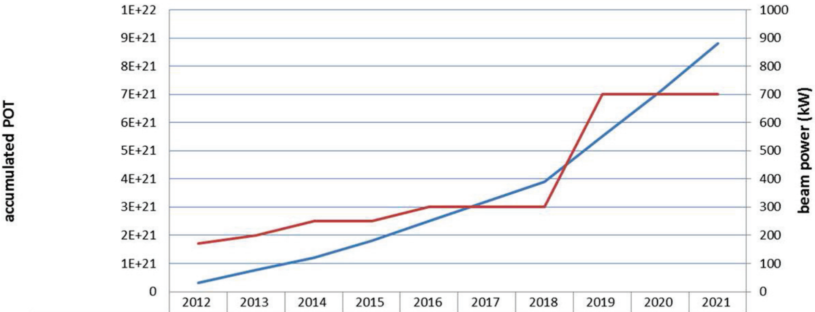
T2K future running:

- T2K plans to continue to take high-quality data (including more $\bar{\nu}$-mode data), continue to reduce systematic errors

Backup Slides

T2K POT Accumulation Scenario

Possible scenario based on the J-PARC accelerator upgrade plan



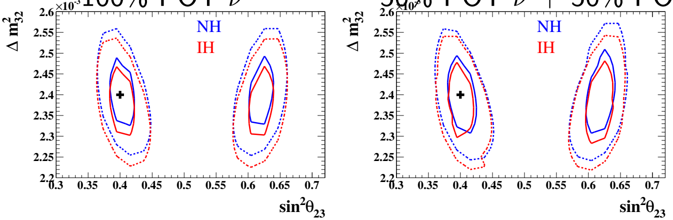
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
accumulated POT	3.1E+20	7.8E+20	1.2E+21	1.8E+21	2.50E+21	3.20E+21	3.90E+21	5.50E+21	7.10E+21	8.80E+21
beam power	170	200	250	250	300	300	300	700	700	700

Disappearance 90% C.L. Sensitivity at 7.8×10^{21} POT, True $\sin^2\theta_{23} = 0.4$

Solid: no sys. err., Dashed: with 2012 sys. err.

True MH is NH; contours drawn for two MH assumptions

100% POT ν 50% POT ν + 50% POT $\bar{\nu}$



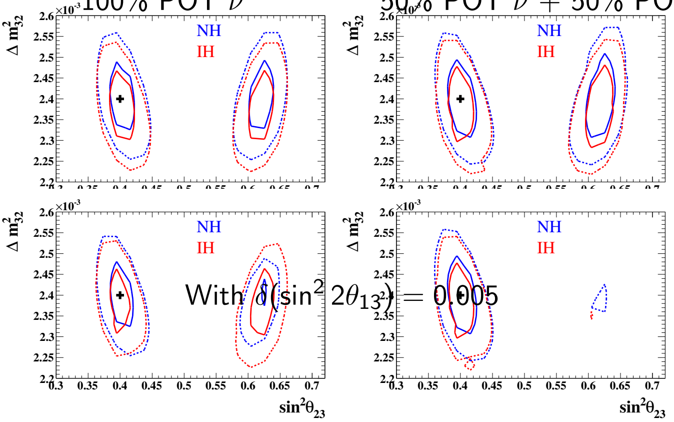
$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0^\circ$, $\sin^2\theta_{23} = 0.4$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$, NH

Disappearance 90% C.L. Sensitivity at 7.8×10^{21} POT, True $\sin^2\theta_{23} = 0.4$

Solid: no sys. err., Dashed: with 2012 sys. err.

True MH is NH; contours drawn for two MH assumptions

100% POT ν 50% POT ν + 50% POT $\bar{\nu}$



With $\delta(\sin^2 2\theta_{13}) = 0.005$

$\sin^2\theta_{23}$ octant nearly determined!

$\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0^\circ$, $\sin^2\theta_{23} = 0.4$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\text{eV}^2$, NH

Combination of T2K + NOνA

The NOνA experiment:

- NuMI Off-Axis ν_e Appearance experiment – Detects ν's produced at Fermilab in northern Minnesota
- Has started commissioning with a partial detector
- Expected POT is 3.6×10^{21} POT in 6 years
  - 3 years ν-mode, 3 years $\bar{\nu}$-mode running planned
- Baseline length: 810 km (295 km for T2K) – NOνA is more sensitive to matter effects than T2K
- Detector mass: 15 kT (22.5 kT for T2K)

Combined T2K + NOνA Results:

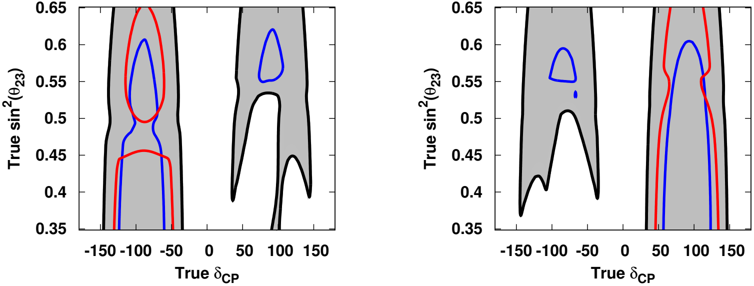
- Gives enhanced sensitivity for both δ_{CP} and the MH

T2K + NOνA Sensitivity to $\sin\delta_{CP} \neq 0$

Red: T2K Alone, Blue: NOνA Alone, Black: T2K + NOνA

Region where CP violation can be discovered at the > 90% C.L.

True Normal MH　　　　True Inverted MH



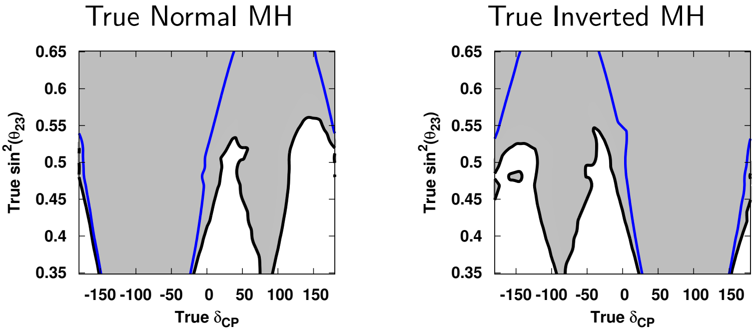
→ 90% C.L. sensitivity to CP violation enhanced with combination of T2K + NOνA data

Assuming: Simple normalization systematic errors
Both T2K and NOνA run with 50% POT ν + 50% POT $\bar{\nu}$
$\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2
θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

T2K + NOνA Sensitivity to MH

Red: T2K Alone, Blue: NOνA Alone, Black: T2K + NOνA

Region where MH can be discovered at the $>$ 90% C.L.



$\rightarrow$ 90% C.L. sensitivity to MH enhanced with combination of T2K + NOνA data (T2K has no sensitivity to measure the MH alone)

Assuming: Simple normalization systematic errors

Both T2K and NOνA run with 50% POT ν + 50% POT $\bar{\nu}$

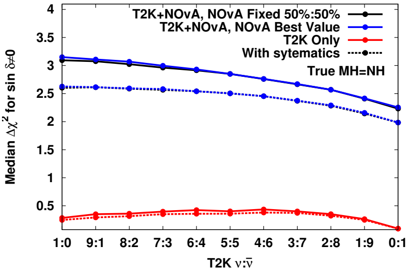
$\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

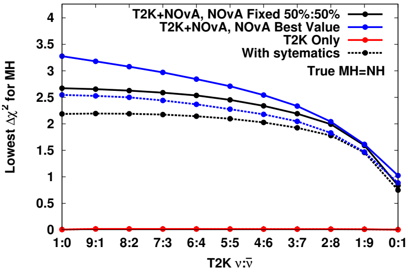
T2K and NOνA ν and $\bar{\nu}$ Running Ratios

Red: T2K Alone, Blue: T2K + NOνA, NOνA Best Running Ratio, Black: T2K + NOνA, NOνA 50%+50%

$\sin(\delta_{CP}) \neq 0$ Sensitivity



MH Sensitivity

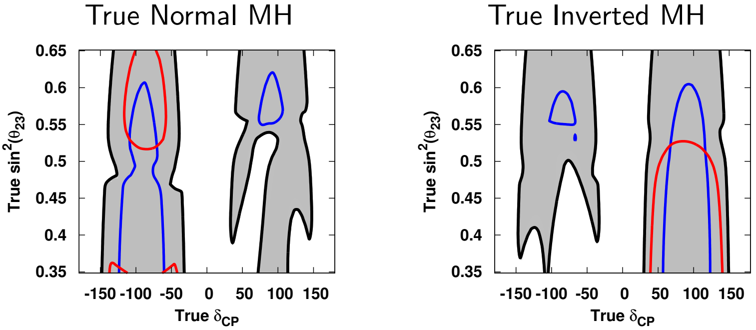


$\rightarrow$ Results fairly independent of T2K and NOνA running ratios when experiments are combined

Assuming: Simple normalization systematic errors
$\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2, NH
θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

T2K + NOνA Sensitivity to $\sin\delta_{CP} \neq 0$

Red: T2K Alone, Blue: NOνA Alone, Black: T2K + NOνA



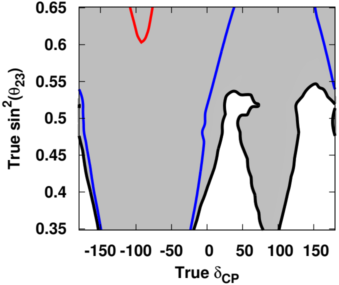
$\rightarrow$ 90% C.L. sensitivity to CP violation enhanced with combination of T2K + NOνA data

Assuming: Simple normalization systematic errors
NOνA run with 50% POT ν + 50% POT $\bar{\nu}$ T2K run with 100% POT ν
$\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2
θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

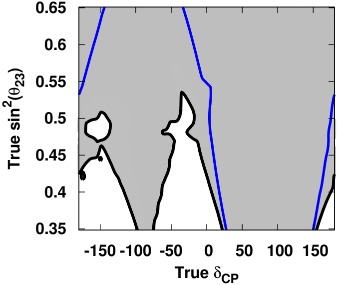
T2K + NOνA Sensitivity to MH

Red: T2K Alone, Blue: NOνA Alone, Black: T2K + NOνA

True Normal MH



True Inverted MH



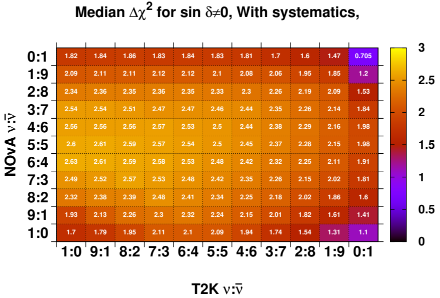
T2K has almost no sensitivity to measure the MH alone
$\rightarrow$ 90% C.L. sensitivity to MH enhanced with combination of T2K + NOνA data

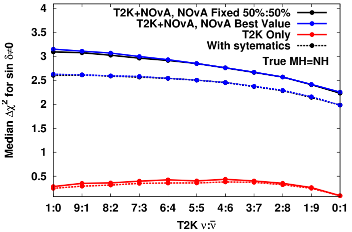
Assuming: Simple normalization systematic errors
NOνA run with 50% POT ν + 50% POT $\bar{\nu}$ / T2K run with 100% POT ν
$\sin^2 2\theta_{13} = 0.1$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2
θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

T2K + NOνA Sensitivity to $\sin\delta_{CP} \neq 0$

Red: T2K Alone, Blue: T2K + NOνA, NOνA Best Running Ratio, Black: T2K + NOνA, NOνA 50%+50%

$\rightarrow$ $\Delta\chi^2$ value for which 50% of true δ_{CP} values can be distinguished from $\delta_{CP} = 0, \pi$





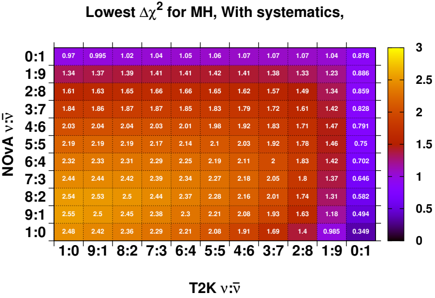
$\rightarrow$ Results fairly independent of T2K and NOνA running ratios

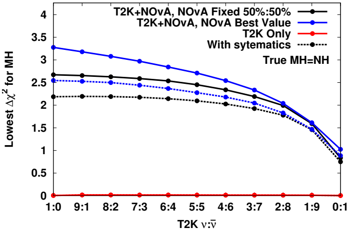
Assuming: Simple normalization systematic errors
$\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2, NH
θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$

T2K + NOνA Sensitivity to MH

Red: T2K Alone, Blue: T2K + NOνA, NOνA Best Running Ratio, Black: T2K + NOνA, NOνA 50%+50%

$\rightarrow$ $\Delta\chi^2$ value at which the MH can be distinguished for 100% of true δ_{CP} values





$\rightarrow$ Results independent of T2K running ratio if NOνA runs 50% ν, 50% $\bar{\nu}$

Assuming: Simple normalization systematic errors
$\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4\times10^{-3}$ eV^2, NH
θ_{13} constrained by $\delta(\sin^2 2\theta_{13}) = 0.005$