Neutrino flux

δ_{cp}

θ_{13}

θ_{23}

Δm^2_{32}

Neutrino interaction model

Latest results from T2K

Son Cao, IPNS, KEK

On behalf of T2K Collaboration

The T2K collaboration

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
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KEK
Kobe U.
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Miyagi U. Edu.
Okayama U.
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U. Silesia, Katowice
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Stony Brook U.
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U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Vietnam
IFIRSE
IOP, VAST

Main subject: Neutrino oscillations

Neutrino oscillations, now well-established phenomenon:

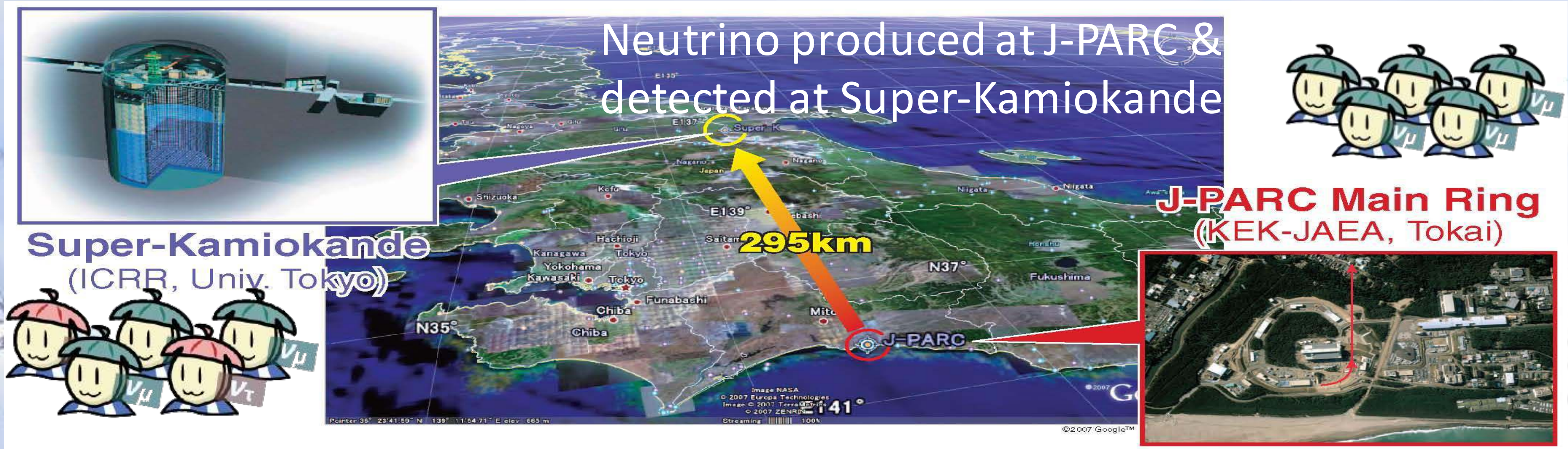
- ✧ Indicate massive neutrinos
- ✧ Mix flavor and mass eigenstates
- ✧ Beyond the Standard Model (the only lab-based evidence)

After 90 yrs., neutrinos still keep surprising us!

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospherics / Accelerators | Reactors/ Accelerators | Solar/ Reactors

The T2K experiment



- ✧ Discovered appearance of $\nu_\mu \to \nu_e$ (2013) Phys. Rev. Lett. 112, 061802 (2014)
- ✧ Leading effort of CP violation search Phys.Rev. D96, 9, 092006 (2017)
- ✧ Vibrant programs of non-standard physics & neutrino interactions

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

T2K sensitive parameters (with Δm^2_{31})

Neutrino Oscillations at T2K

Disappearance channel

Extract $\Delta m^2_{32}, \theta_{23}$

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23}\right)\cdot\sin^2\frac{\Delta m^2_{31}\cdot L}{4E}$$

Leading-term — Next-to-leading

Appearance channel

Extract θ_{13}, δ_{CP}

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ & + 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\ & - 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\ & + 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21} \end{aligned}$$

Leading term — θ_{13}

CPC

CPV

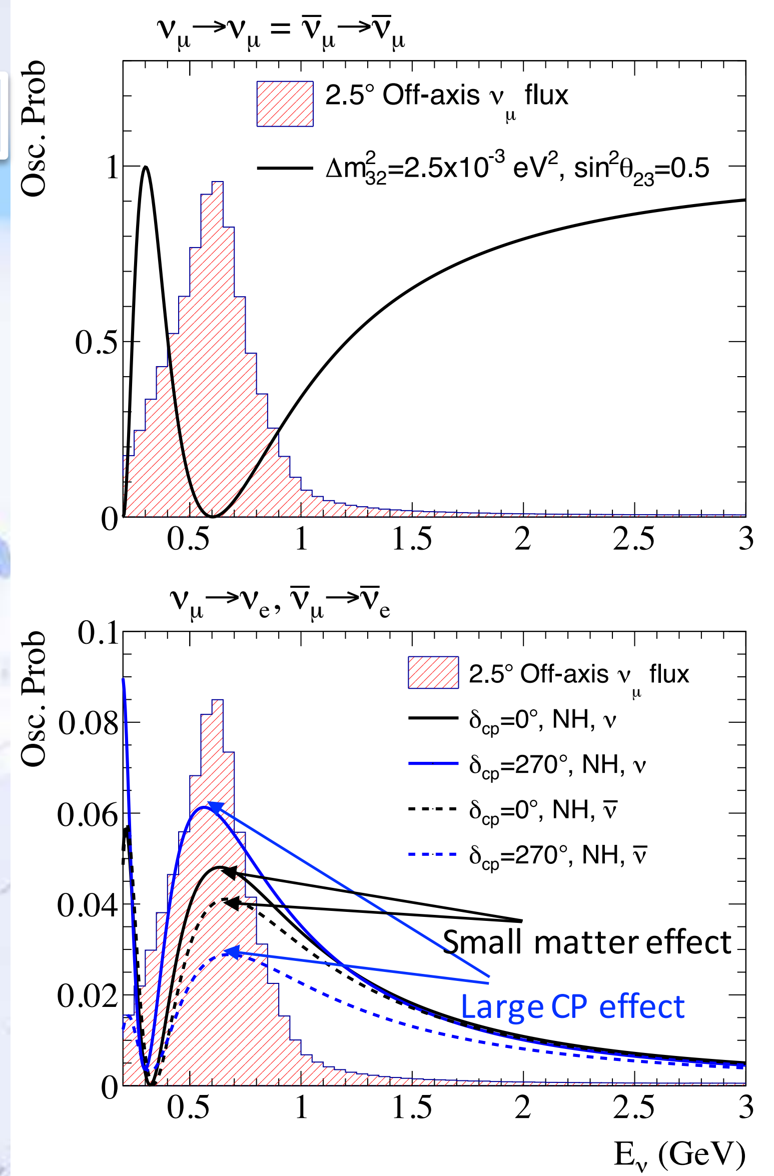
Solar

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

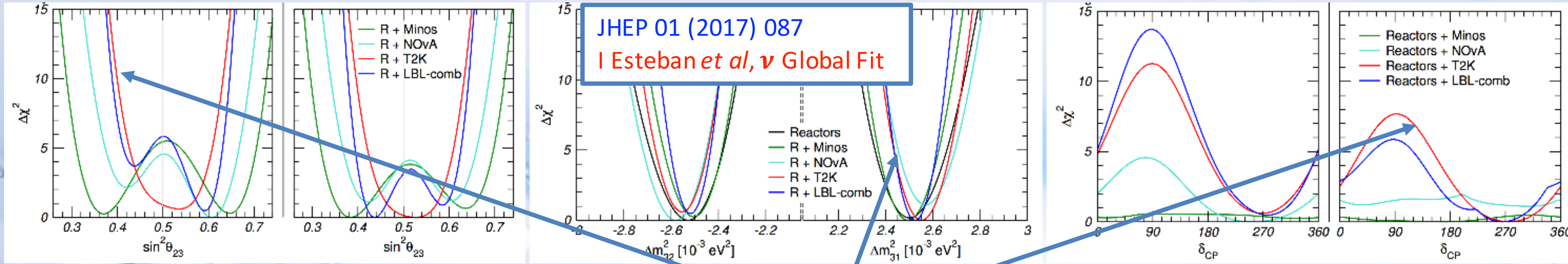
$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E_\nu}$

replace δ by $-\delta$ for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$

CP violating term introduced by interference among three-flavor mixing



Neutrino Oscillations at T2K (cont'd)



T2K is leading the effors to measure θ_{23}, Δm^2_{32} and δ_{CP}

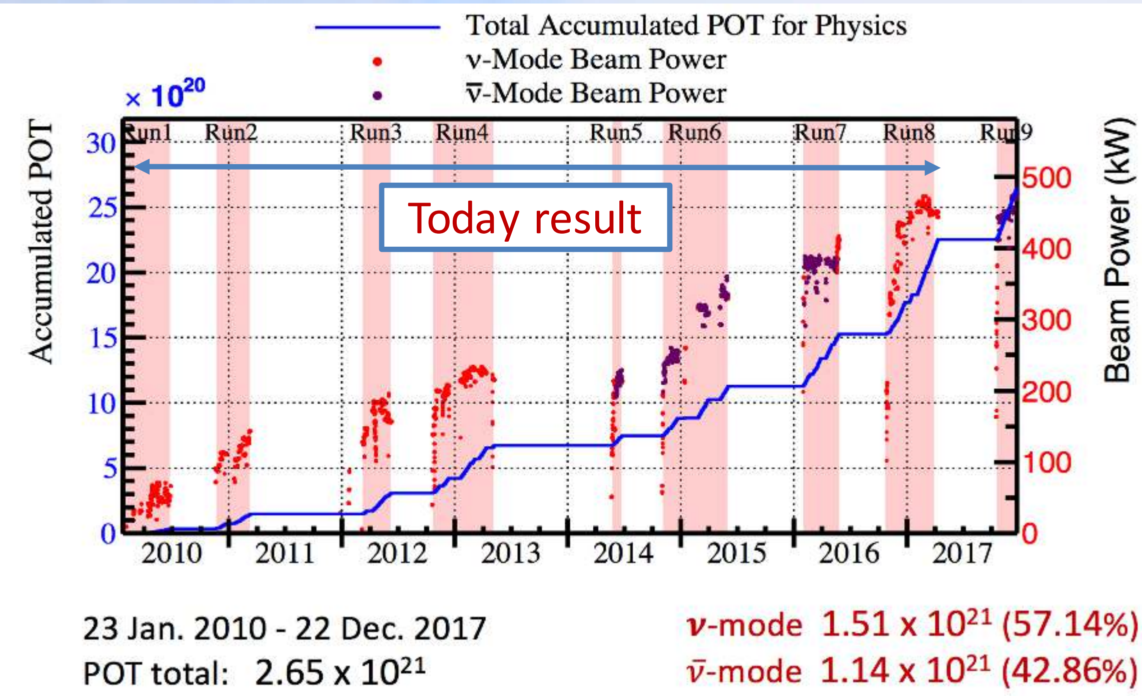
Key ingredients for T2K

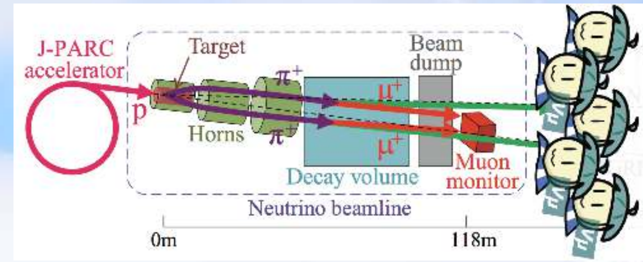
- Most intense and well-monitored neutrino beam, J-PARC
- Large WC detector & good flavor identification, Super-Kamiokande
- Support programs (hadron production, neutrino interaction models)

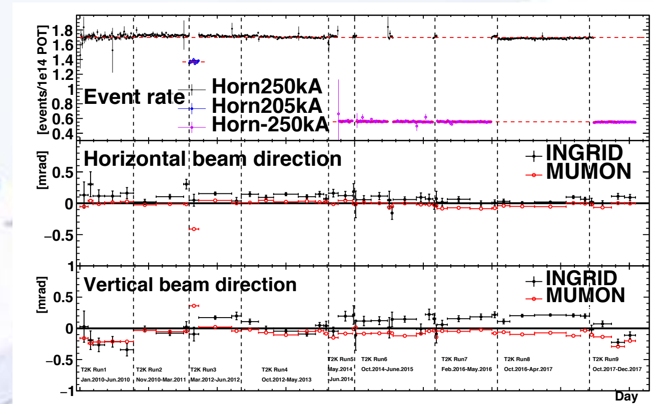
T2K data taking and latest results

T2K neutrino beam

High intensity, almost pure muon (anti) neutrino beam from J-PARC







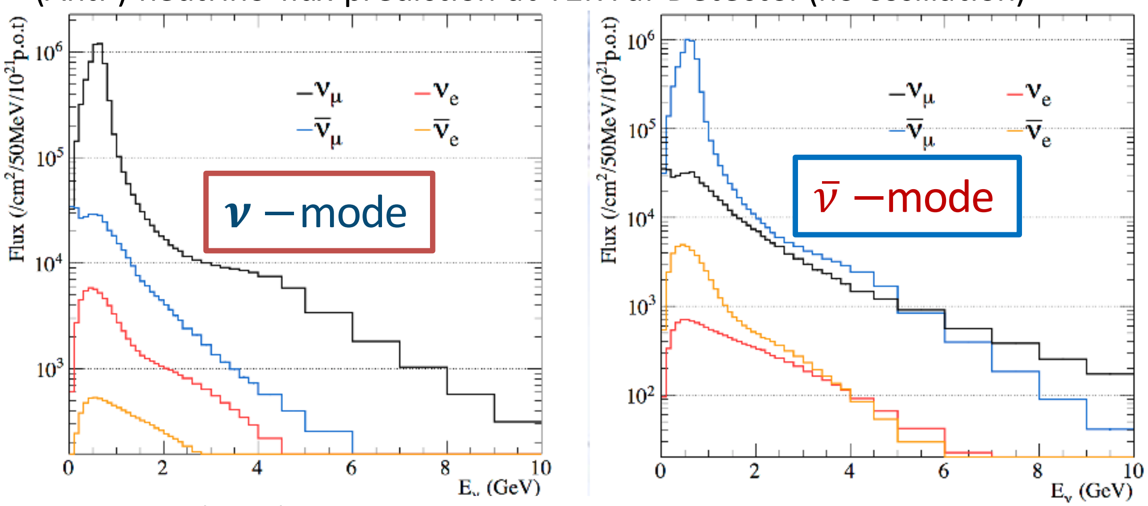
- ✧ Beam power steadily increased to 475 kW, high-quality data delivered
- ✧ 2.65×10^{21} Protons-on-target (POT) delivered. Data sample for results presented today:
  - ✧ Neutrino-mode: 1.47×10^{21} POT
  - ✧ Antineutrino-mode: 0.76×10^{21} POT

Next results will be released by this summer

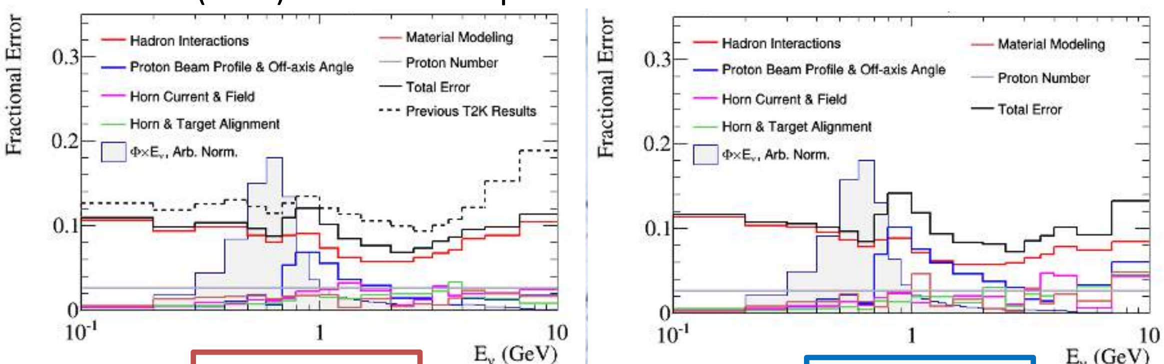
T2K neutrino beam (cont'd)

High intensity, almost pure muon (anti) neutrino beam from J-PARC

(Anti-) neutrino flux prediction at T2K Far Detector (no oscillation)



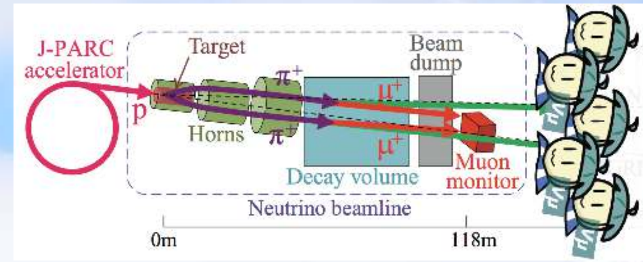
Errors of (anti-) neutrino flux prediction at T2K Far Detector



ν −mode

$\bar{\nu}$ −mode

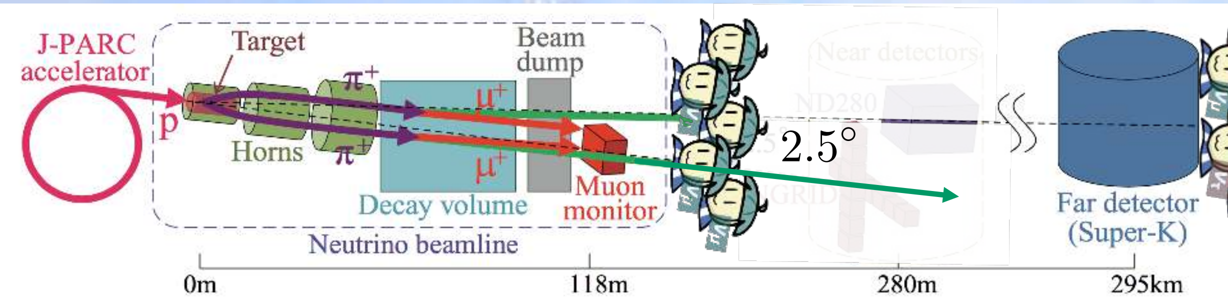
(Beam modes changed by switching horn polarity)

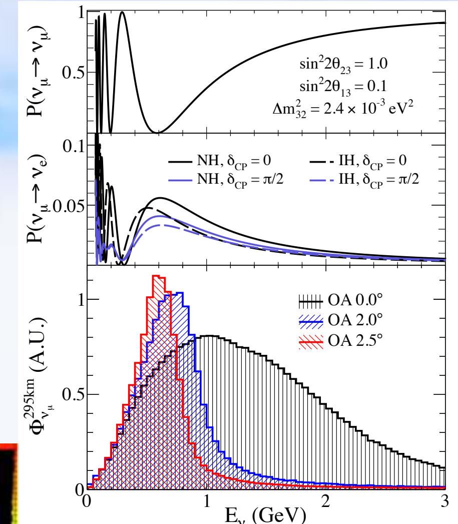


- ✧ Hadron production at target needed to infer ν flux
- ✧ Constrained by external data from NA61/SHINE
  - ○ Flux uncertainty ~ 10% (absolute error)
  - ○ ~2-4% effect to analysis w/ Near Detector constraint

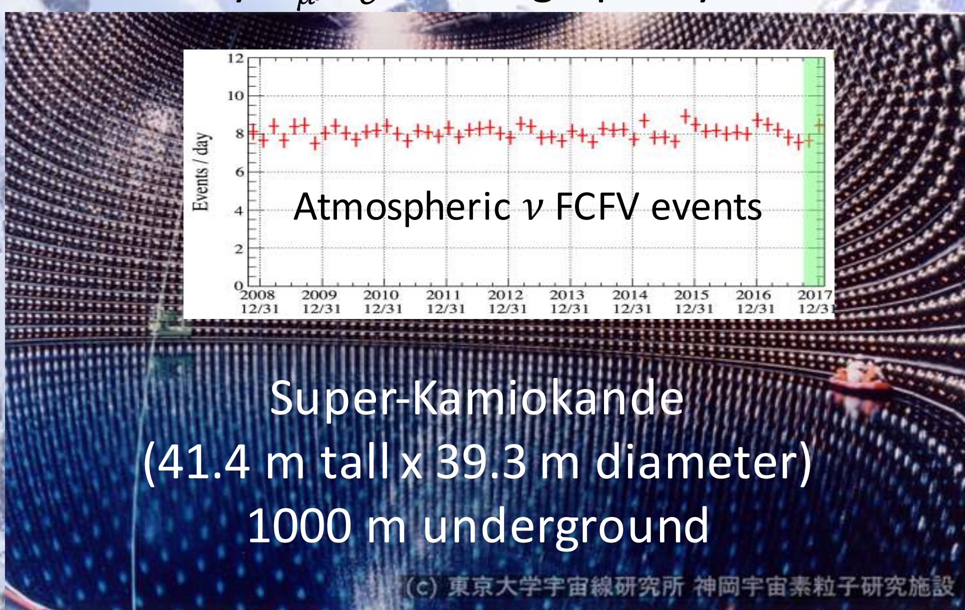
T2K far detector

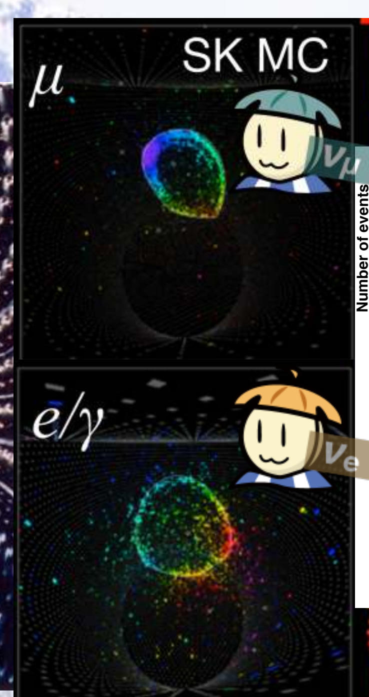
- ✧ Super-K is 2.5^0 off the beam's axis to achieve narrow band beam peaked at oscillation maximum (0.6 GeV)

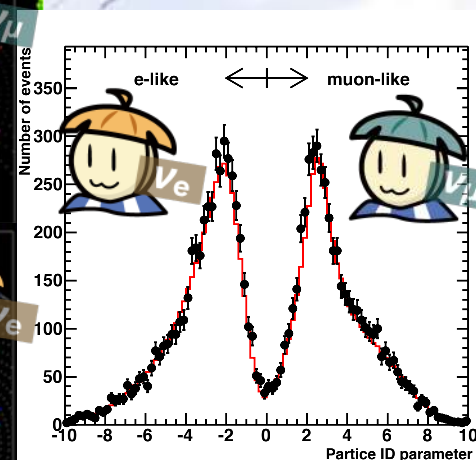




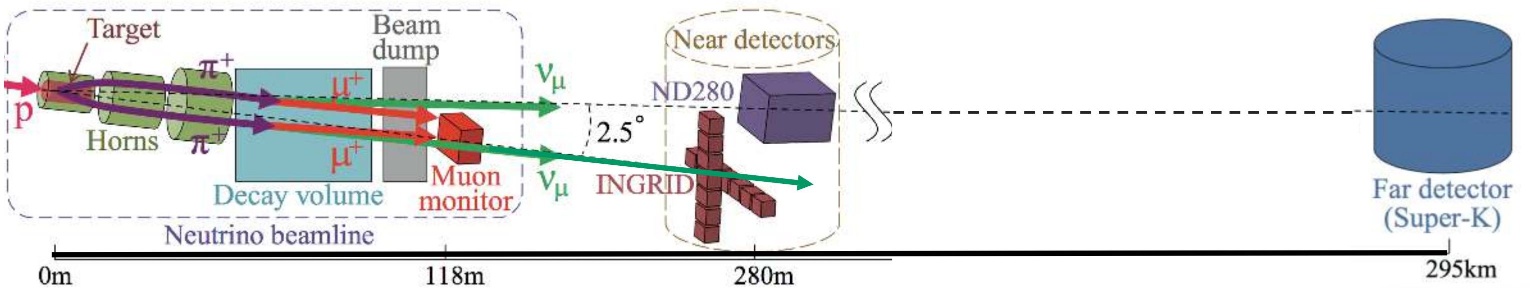
- ✧ Muon and electron are well-separated
  → identify ν_μ/ν_e with high purity







Strategy for oscillation analyses

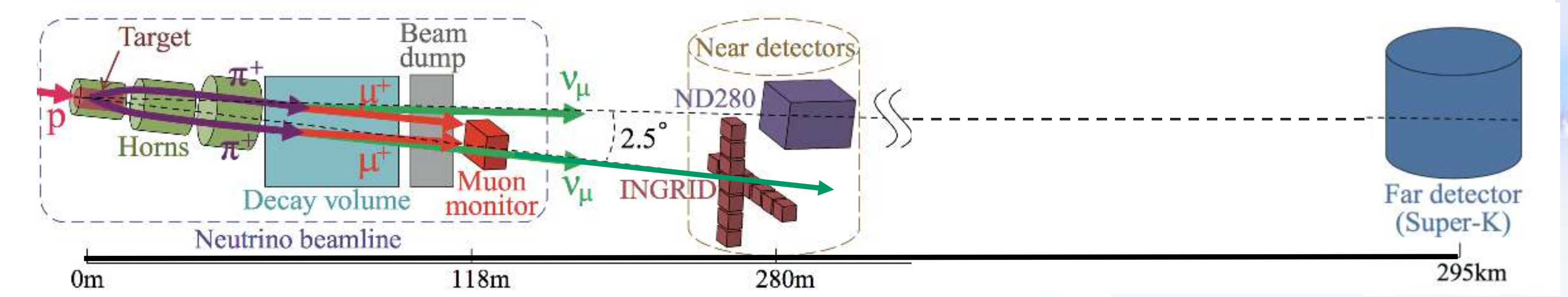


Hadron prod. data (NA61/SHINE)

Beam monitors

Constrain flux

Strategy for oscillation analyses



Hadron prod. data (NA61/SHINE)

Beam monitors

Constrain flux

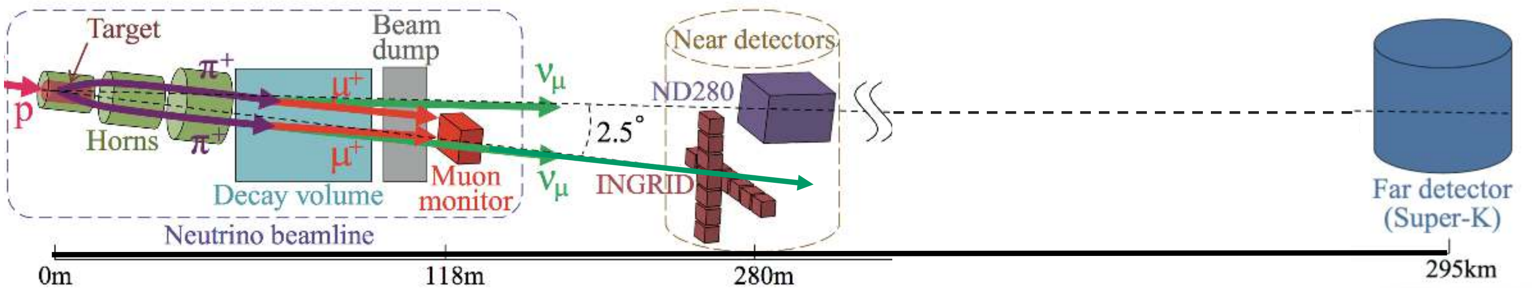
ND280 data

Neutrino interaction model

External cross-section data

Constrain flux & interaction model simultaneously (due to convolution of these factors on data)

Strategy for oscillation analyses



Super-K data

Hadron prod. data (NA61/SHINE)

Beam monitors

Constrain flux

ND280 data

Neutrino interaction model

External cross-section data

SK detector model

Oscillation fit & extract parameters

Constrain flux & interaction model simultaneously (due to convolution of these factors on data)

Data are used as much as possible to reduce model dependence

Insensitive osc. parameters

T2K Improvements in 2017 analysis

- Super-K event selection & new data sample
  - Use reconstruction algorithm (fiTQun complete charge & time information) → enables to extend detector fiducial volume, leads to 20% effective statistic increase in selecting e-like events
  - Add charged-current 1π e-like sample → increases 10% for neutrino-mode e-like sample

- Usage of ND280 data to constrain flux & neutrino interaction model
  - Incorporate FGD2 (water target) data to include interactions on water (In previous analysis, only FGD1 (carbon target) data samples were used)

- Interaction models in neutrino event generator (NEUT)
  - Improve pion production model by tuning to external data from Bubble Chambers, MiniBooNE and MINERvA
  - Include a model for multi-nucleon (2p-2h) scattering (~10-20% relative to charged current quasi-elastic, main signal at T2K) Phys. Rev. C83 (2011) 045501
  - Improve charged-current quasi-elastic model by including effect of long-range correlations in nucleus

Systematic errors

Error source	% errors on predicted event at SK					
	1 ring μ-like		1 ring e-like			
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π (NEW)	$\nu/\bar{\nu}$ [4]
SK detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI+SI+PN	2.20	1.98	3.01	2.31	11.43	1.57
ND280-constrained flux & cross section	3.22	2.72	3.22	2.88	4.05	2.50
$\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)}, \frac{\sigma(\bar{\nu}_e)}{\sigma(\bar{\nu}_\mu)}$ [1]	0.00	0.0	2.63	1.46	2.62	3.03
NC 1γ [2]	0.00	0.0	1.08	2.59	0.33	1.49
NC other [3]	0.25	0.25	0.14	0.33	0.98	0.18
Total error	**4.40**	**3.76**	**6.10**	**6.51**	**20.94**	**4.77**

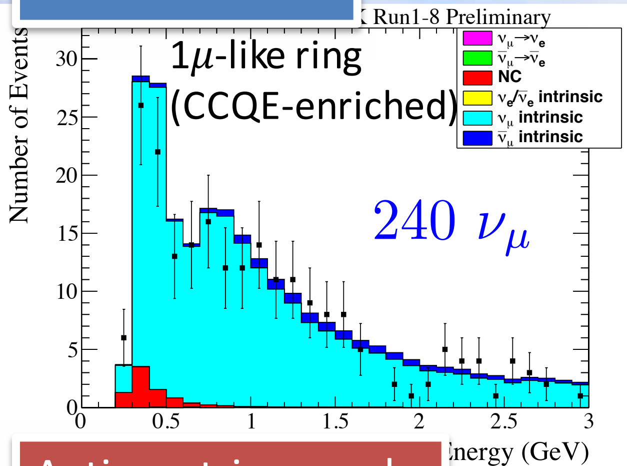
[1] Theoretically motivated error based on Phys.Rev. D86 (2012) 053003

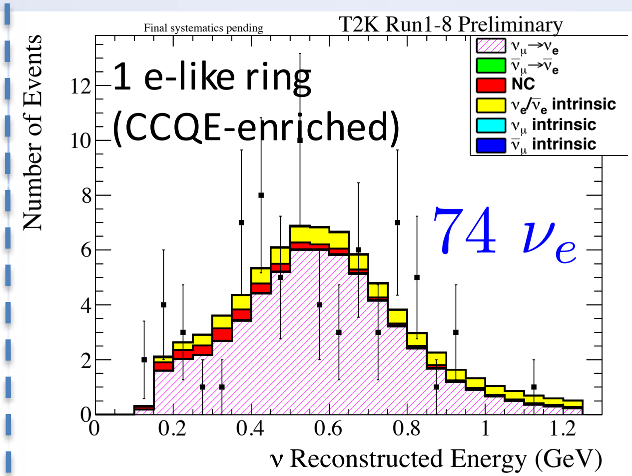
[2],[3] Not constrained by ND280, theoretical model & external data

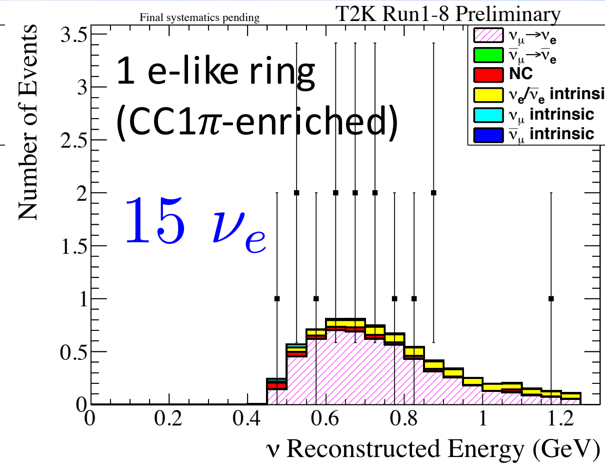
[4] These errors are relevant for extracting δ_{CP} phase

Far detector data samples with fit

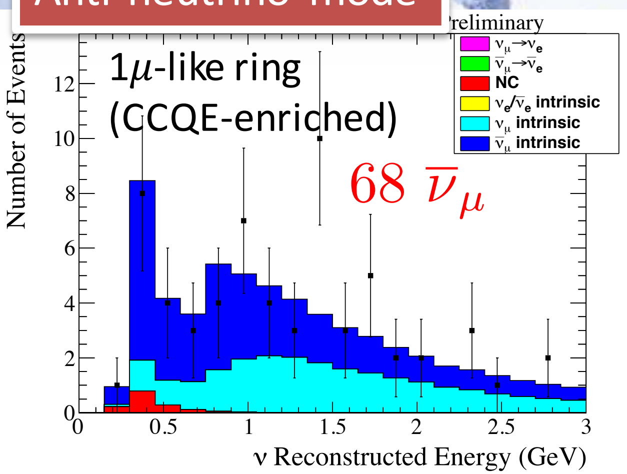
Neutrino mode

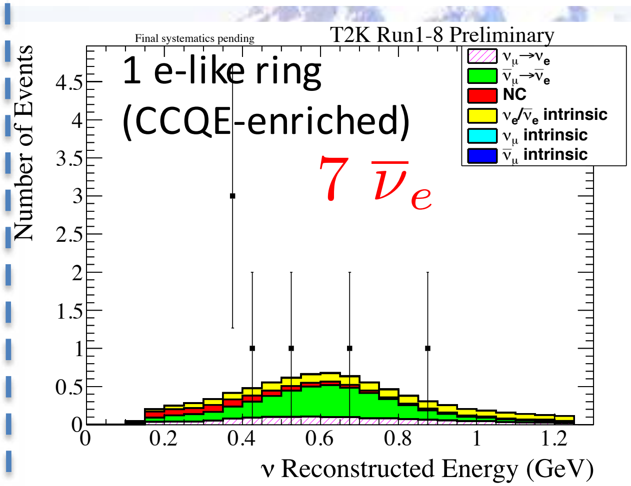






Anti-neutrino mode





No CC1π in anti-neutrino mode due to π^- absorption

Disappearance channel

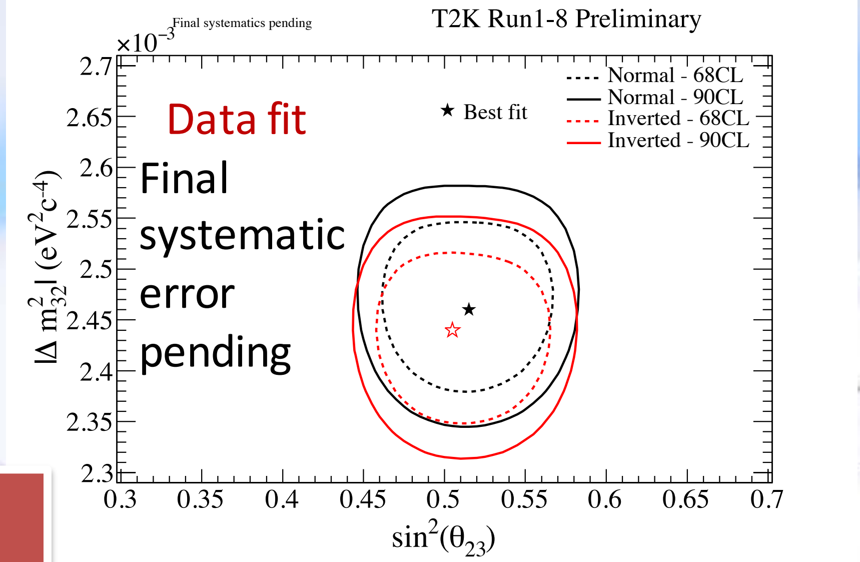
Appearance channel

Δm^2_{32}, θ_{23} measurements

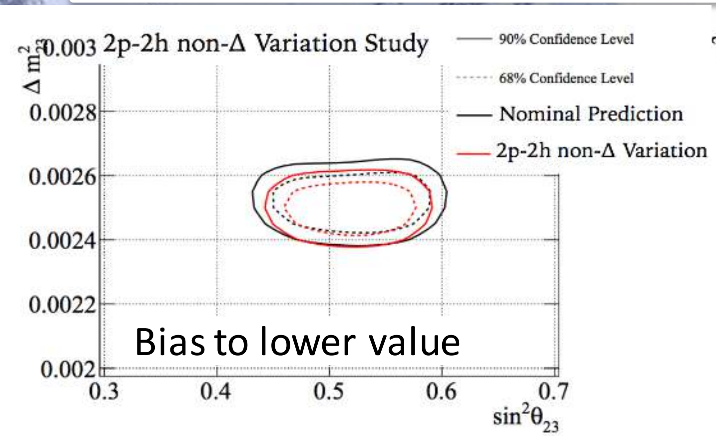
✧ Data are fitted separately for normal and inverted hierarchy

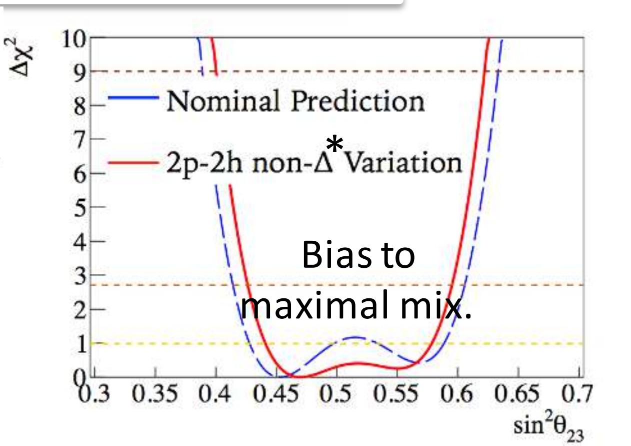
(Bayesian posterior probabilities)

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.193	0.674	0.868
IH ($\Delta m^2_{32} < 0$)	0.026	0.106	0.132
Sum	0.219	0.781	



✧ Pending final systematic error, results will be updated in future





(Study of ND data-driven variation shows effect on Δm^2_{32}, θ_{23} parameters)

[*] 2p-2h non-*Δ* is a pure nucleon-nucleon correlation process

Mixing angle θ_{13} & δ_{CP}

- T2K $\sin^2\theta_{13}$ measurement is consistent with PDG 2016 average

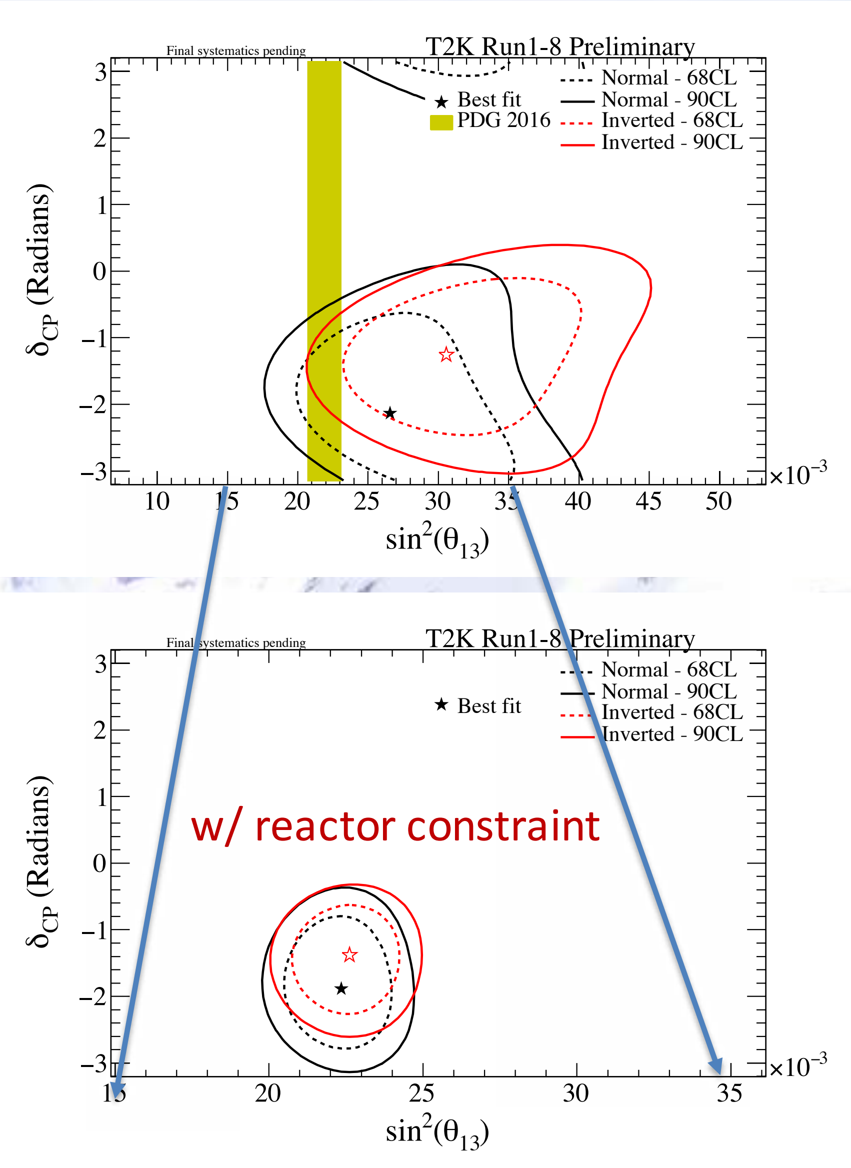
T2K value:

$$\sin^2\theta_{13} = 0.0277^{+0.0054}_{-0.0047}\ \text{(NH)}$$

PDG 2016:

$$\sin^2\theta_{13} = 0.0210 \pm 0.0011$$

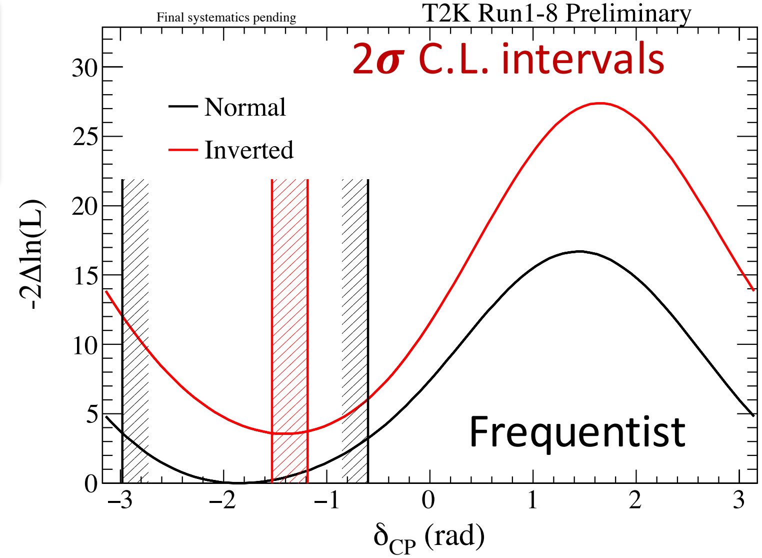
- Including the reactor constraint on θ_{13} improves constraint on δ_{CP}

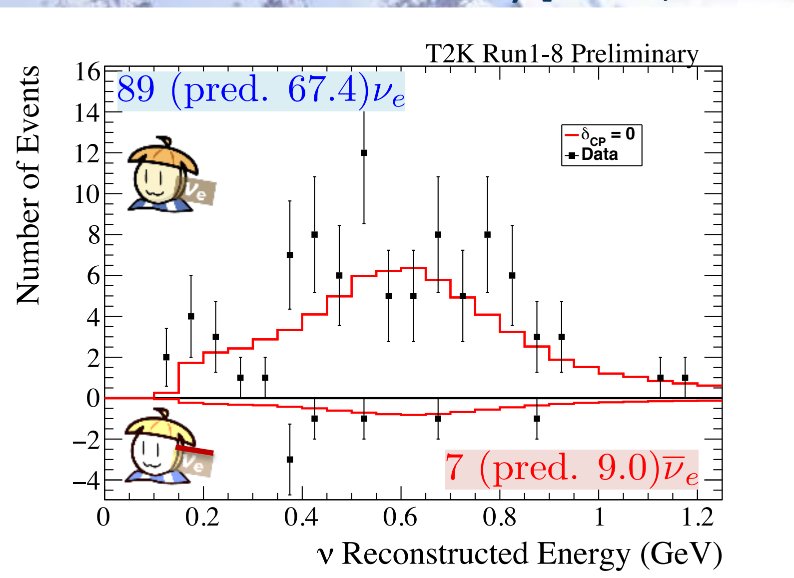


δ_{CP} measurement

CP conserving values (0, π) fall outside of the 2σ C.L. confidence/credible interval

- 1σ C.L. confidence interval
  - Normal Hierarchy [-2.49, -1.23] rad.
- 2 σ C.L. confidence interval
  - Normal hierarchy [-2.91, -0.60] rad.
  - Inverted hierarchy [-1.54, -1.19] rad.

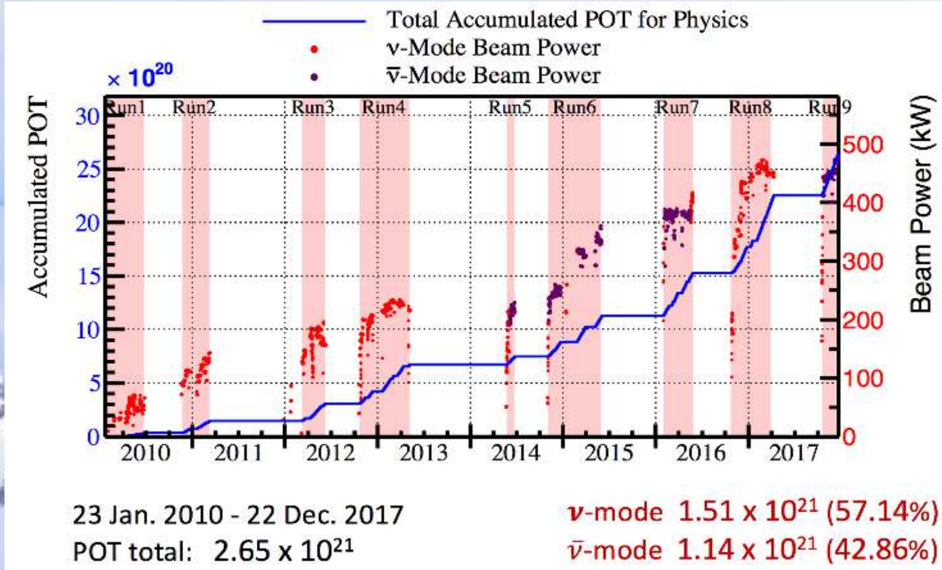


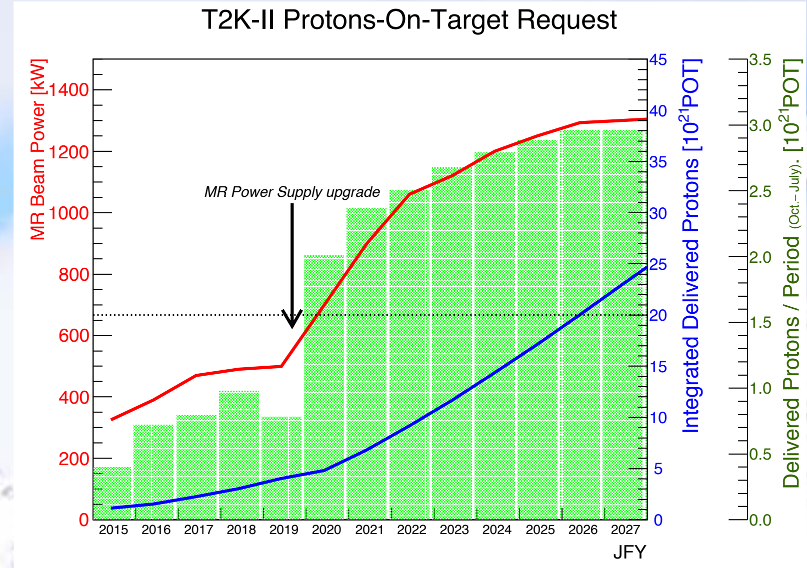


Sample	Prediction at true δ_{CP}			Data
	$-\pi/2$	0	$+\pi/2$	
ν_e QE	73.5	61.5	49.9	74
ν_e 1π	6.9	6.0	4.9	15
$\bar{\nu}_e$ QE	7.9	9.0	10.0	7
ν_μ QE	267.8	267.4	267.7	240
$\bar{\nu}_\mu$ QE	63.1	62.9	63.1	68

Future prospects

T2K future prospects



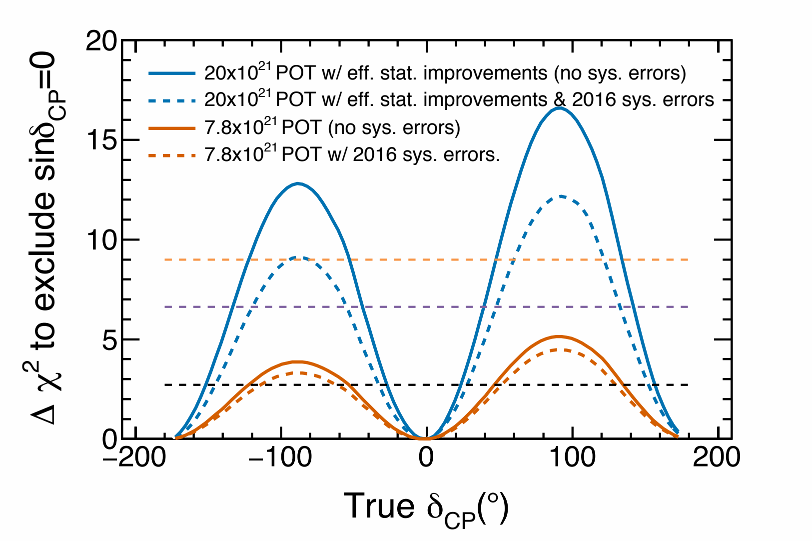


- ✧ Stay tuned for summer result w/ doubled data in anti-neutrino mode
- ✧ Approved T2K statistics, 7.8 x10^{21} POT, can be accumulated by 2021
- ✧ J-PARC beam aims for upgrade & operation at > 1MW from 2021
- ✧ Hyper-K and DUNE are expected to start around 2026

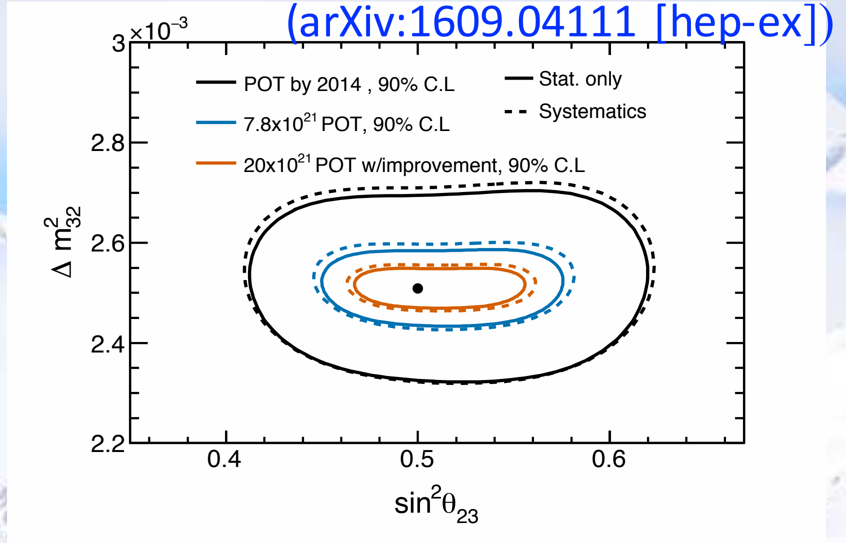
→ T2K-II, if extend T2K operation until 2026, will collect 20x10^{21} POT.

Such amount of data along with neutrino beamline upgrade & analysis improvements makes T2K(-II) physics potentials even more interesting!

T2K future prospects (cont'd)

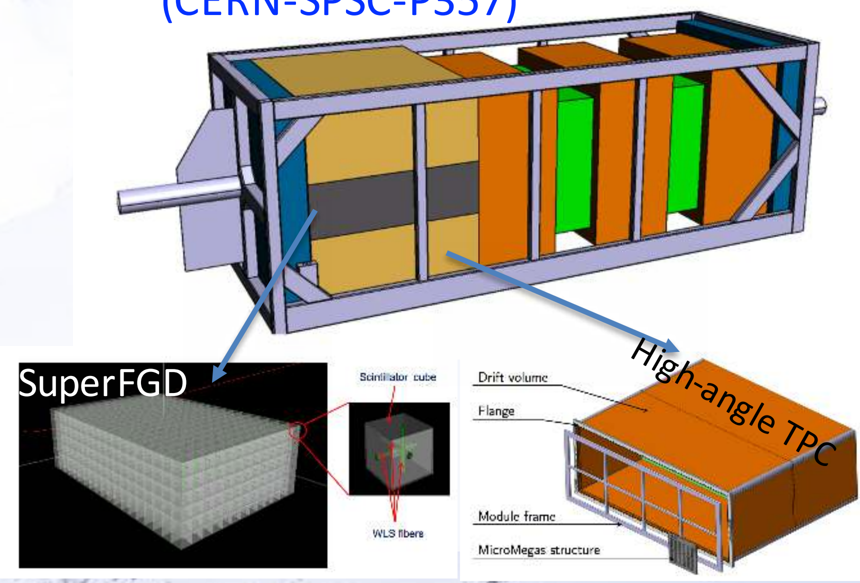


(arXiv:1609.04111 [hep-ex])



- ✧ 3σ or higher significance sensitivity to CP violation if δ_{CP} close to - $\pi/2$
  - ✧ Systematic error has large impact
  - → **Motivate for ND280 upgrade**
- ✧ 1% precision of Δm^2_{32}, 0.5° - 1.7° precision of θ_{23} (depend on the truth)

(CERN-SPSC-P357)



Exciting programs!
Welcome new collaborators.

Summary

- Stable operation at 470-475 kW beam power allows T2K to double neutrino data in one year (also expectedly double anti-neutrino data by this summer)

- Updates in T2K oscillation analyses:
  - New reconstruction and event selections: statistically effective improvement by 30%
  - Improving neutrino interaction model

- CP conserving values $(0, \pi)$ fall outside of the $2\boldsymbol{\sigma}$ C.L. confidence/credible interval

- T2K-II, an extended program to collect $20\text{x}10^{21}$ POT, has been proposed in order to achieve $3\boldsymbol{\sigma}$ C.L. to exclude CP conserving values for favorable true value of δ_{CP}

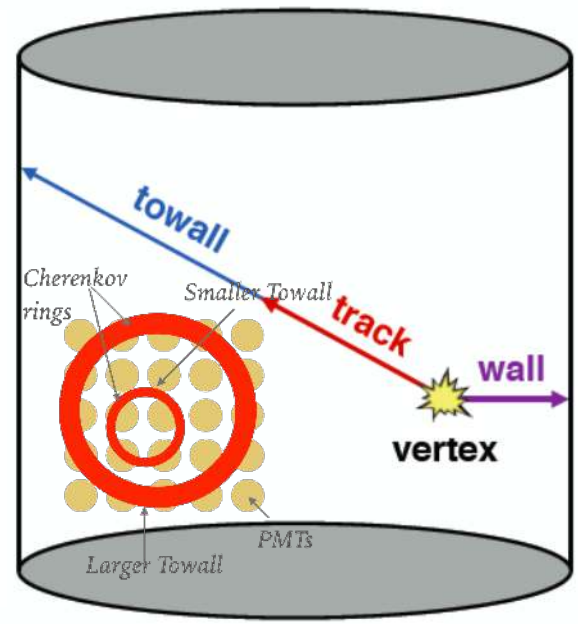
*A few anime drawings taken http://higgstan.com

Backup

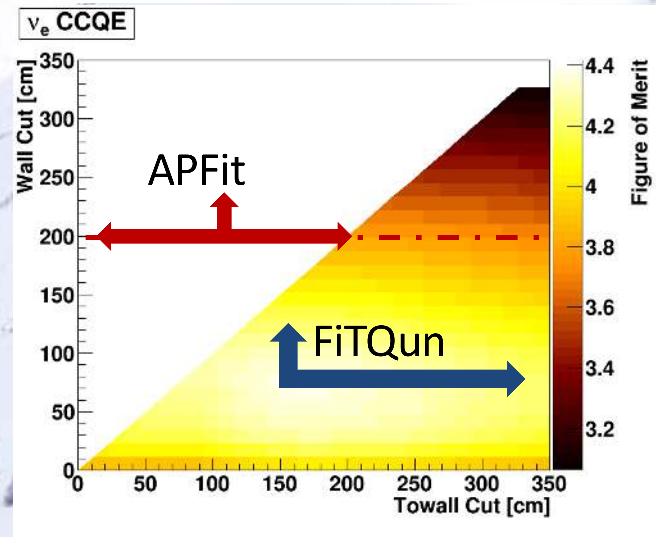
Expansion of Super-K fiducial volume

fiTQun, a maximum-likelihood approach for event reconstruction at SK, offers significant improvement in performance and allows us to re-optimize the fiducial cut

- **APFit - based fiducial volume:** requires to have reconstructed vertex > 2 m from the detector wall
- **fiTQun - based fiducial volume**: 2-dimensional cut on
  - **"wall":** minimum distance from vertex to the wall
  - **"towall":** distance along the particle track to the wall

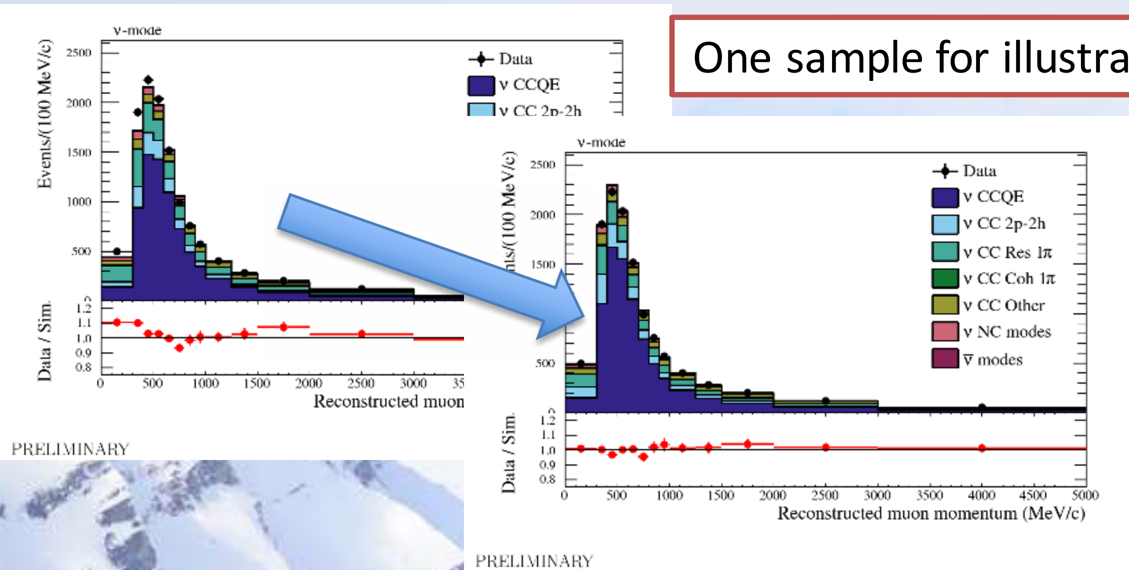


Samples	New selection		Previous selection	
	Signal (MC)	Purity	Signal (MC)	Purity
ν_e QE	69.5	81.2%	56.5	81.4%
ν_e 1π	6.9	78.8%	5.6	72.0%
$\bar{\nu}_e$ QE	7.6	62.0%	6.1	63.7%
ν_μ QE	261.6	79.7%	268.7	68.1%
$\bar{\nu}_\mu$ QE	62.0	79.7%	65.4	70.5%

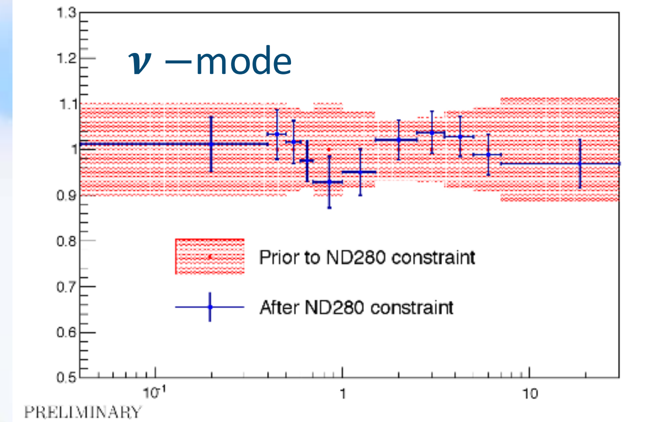


Near Detector Data Fit

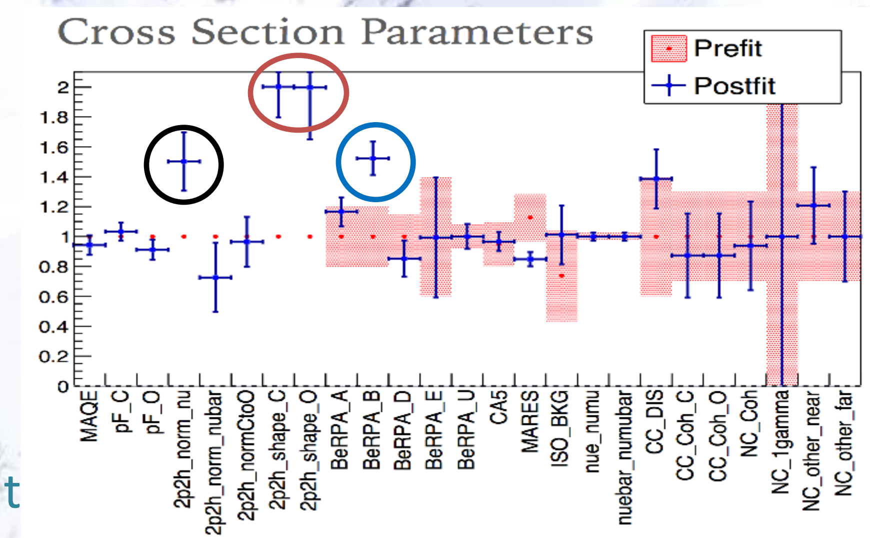
One sample for illustration



Flux parameters @SK

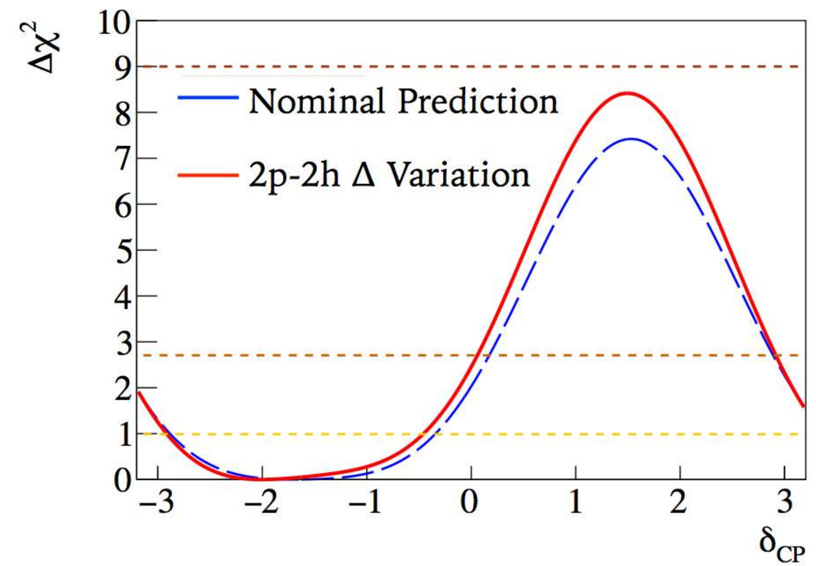


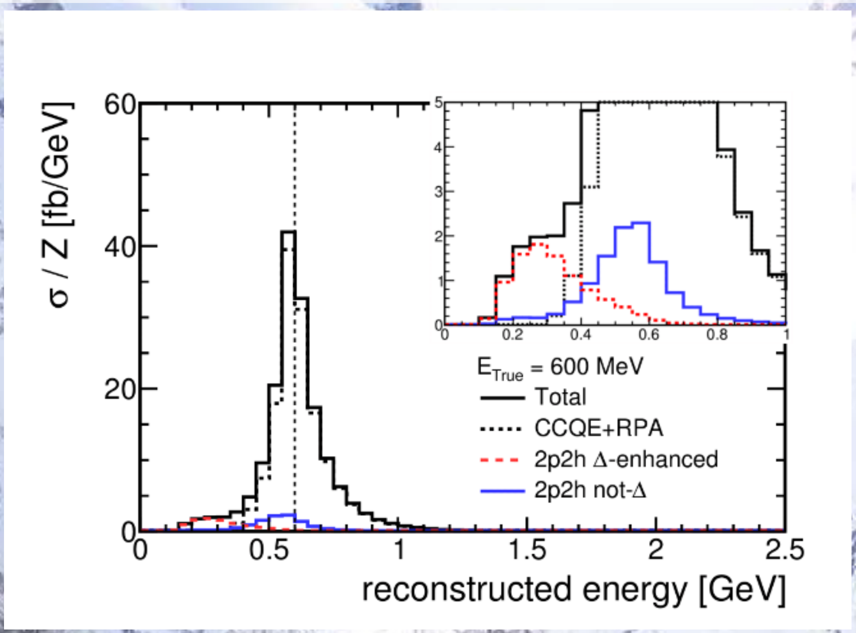
- 2p-2h for neutrinos is enhanced by 50%
- 2p-2h shape is shifted, tend to increase Δ–enhanced component to maximum
- Fitted value of RPA parameter for low Q^2 ($<1GeV^2$) is increase, i.e CCQE enhancement

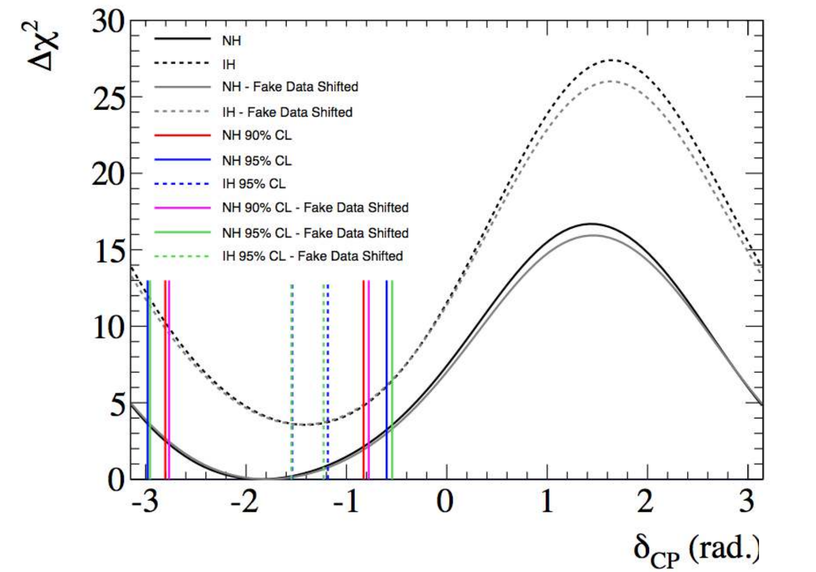


Impact of Fake data on δ_{CP}

- Maximum shift in the NH 2σ confidence interval mid-point is 1.7%
- Maximum change to the NH 2σ confidence interval is 2.3%
- **Impact on δ_{CP} confidence intervals is small!**







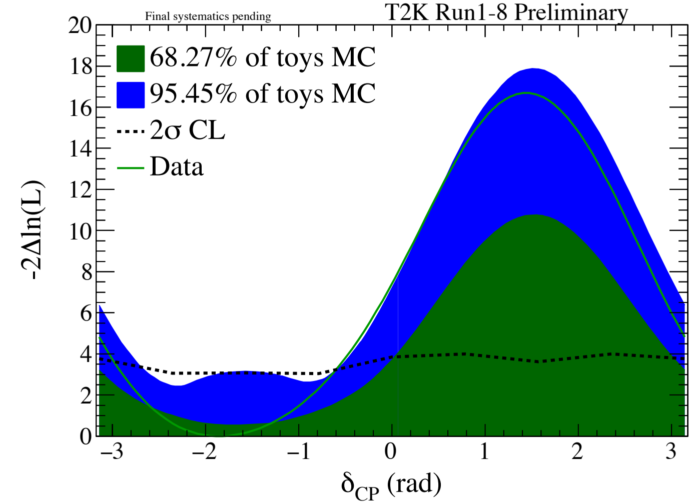
On δ_{CP} exclusion

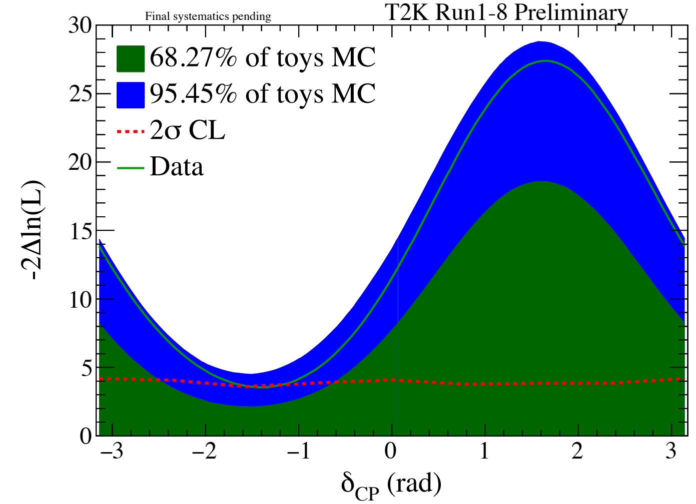
- The exclusion of δ_{CP} conserving values is stronger than our expected sensitivity. Is it reasonable?

- We throw 10^4 toy experiments in which normal mass hierarchy is assumed and δ_{CP} are fixed at $-\pi/2$, but other oscillation parameters, statistics, systematic parameters are varied

- **30% of experiments exclude δ_{CP} =0 at >2σ C.L.**

- **25% of experiments exclude δ_{CP} = π at >2σ C.L.**





Fitting methods

- Fit simultaneously 5 signal samples selected at Far Detector, Super-K
- A binned likelihood approach to fit data

$$-ln(L) = \sum_{i}^{N_{SK-bins}} N_i^{SK}(\vec{o},\vec{p}) - M_i^{SK} + M_i^{SK} ln\left[M_i^{SK}/N^{SK}(\vec{o},\vec{p})\right]$$

$$+\frac{1}{2}\sum_{i}^{N_o}\sum_{j}^{N_o}\Delta o_i (V_{ij}^{o})^{-1}\Delta o_j + \frac{1}{2}\sum_{i}^{N_p}\sum_{j}^{N_p}\Delta p_i (V_{ij}^{p})^{-1}\Delta p_j$$

N_i^{SK}/M_i^{SK} is the observed/predicted number of events in the i^{th}bin

$\vec{o}/\vec{p}$ are the oscillation/systematics parameters

V^o/V^p is the oscillation/systematics covariance matrix

- Perform both Frequentist approach (two analyses) and Bayesian approach (one analysis)

Aim to understand unoscillated ν beam: constrains flux and cross-section parameters

- ✧ **Tracker,** composed of Fine-Grained Detector (FGD) and Time Projection Chamber (TPC), is central part
  - o Two FGDs: active target w/ scintillator only (FGD1) or scintillator-water interleaved (FGD2)
  - o Three TPCs: mainly Argon (95%) filled, for momentum measurement and particle ID
- ✧ $\boldsymbol{\pi^0}$ **detector (POD)** for water-scintillator target and $\boldsymbol{\pi^0}$ tagging
- ✧ **Electromagnetic calorimeters (ECal)** to detect gamma rays and reconstruct $\boldsymbol{\pi^0}$
- ✧ **Side muon range detectors (SMRD)** to tag entering cosmic muons or side-exiting muons

Key features for cross-section:

- o Narrow flux spectrum , mean ~ 0.85 GeV
- o Multiple targets: scintillator, water, argon, lead
- o High final state ID resolution, charge separation