Neutrino and anti-neutrino oscillation measurements at the T2K Experiment

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on behalf of the T2K Collaboration

Super-Kamiokande

J-PARC

Image NASA

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Outline

- Introduction
- T2K experiment
- Neutrino oscillation measurement results
- Outlook + Summary

Neutrino Oscillations

Neutrinos change flavor while propagating in vacuum/matter

➔ Neutrinos have mass = evidence for physics beyond the Standard Model

Flavor

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

Mass

ν_e

ν_μ

ν_τ

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

atmospheric & **accelerator**

$\theta_{23} = (45 \pm 3)^o$

$|\Delta m^2_{32}| = (2.52 \pm 0.04)\times 10^{-3}$ eV^2

reactor & **accelerator**

$\theta_{13} = (8.5 \pm 0.15)^o$

$|\Delta m^2_{31}| = (2.52 \pm 0.04)\times 10^{-3}$ eV^2

solar & reactor

$\theta_{12} = (33.6 \pm 0.8)^o$

$\Delta m^2_{21} = (7.50 \pm 0.18)\times 10^{-5}$ eV^2

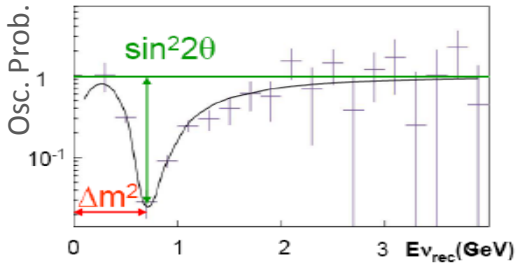
CP violation phase: $\delta_{CP} \approx -90^o$

PMNS (Pontecorvo, Maki, Nakagawa, Sakata) – matrix describes mixing between flavor and mass eigenstates

Neutrino Oscillation Probabilities

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\frac{\Delta m^2_{32} L}{4E_\nu}$$

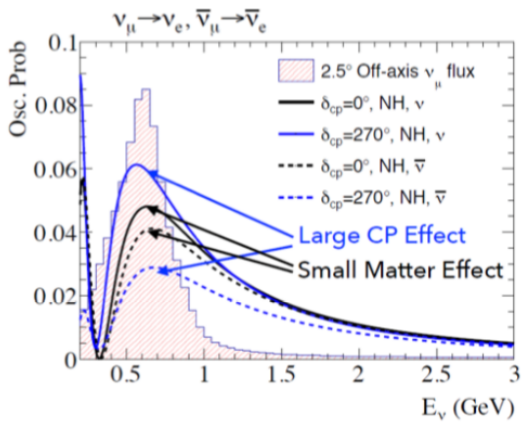


Leading term: ~ 0.95 next to leading term: ~ 0.05

yields sensitivity to θ_{23} octant

ν_e appearance:

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$
$$-\alpha \sin\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+\alpha\cos\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$
$$+\mathcal{O}(\alpha^2)$$



$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

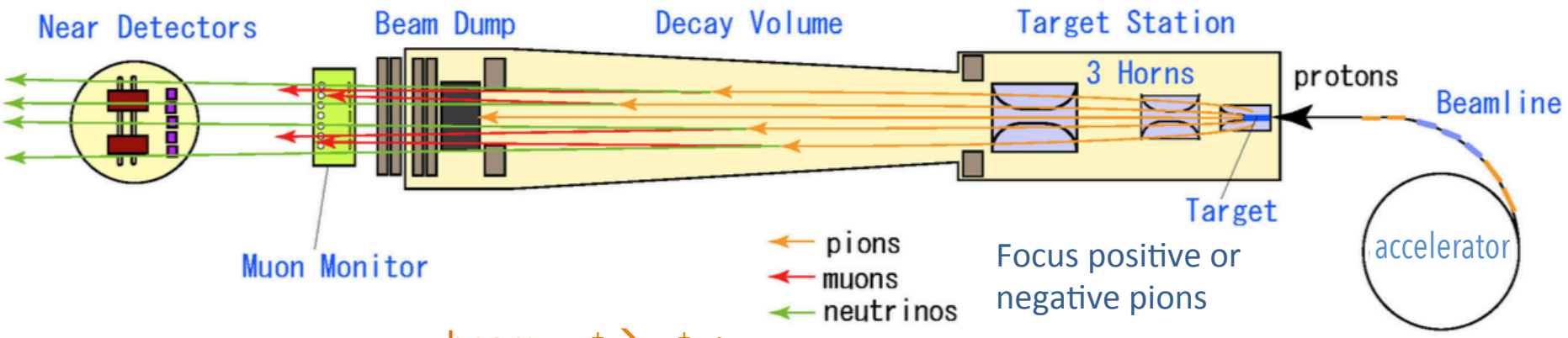
θ_{13} sensitivity

θ_{23} octant sensitivity (θ_{23} >,<,= 45°)

δ_{CP} phase sensitivity : $P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e}) \neq 0$ for $\sin\delta \neq 0$

Matter effect sensitivity: ν_e enhanced in normal hierarchy

J-PARC accelerator and ν beam

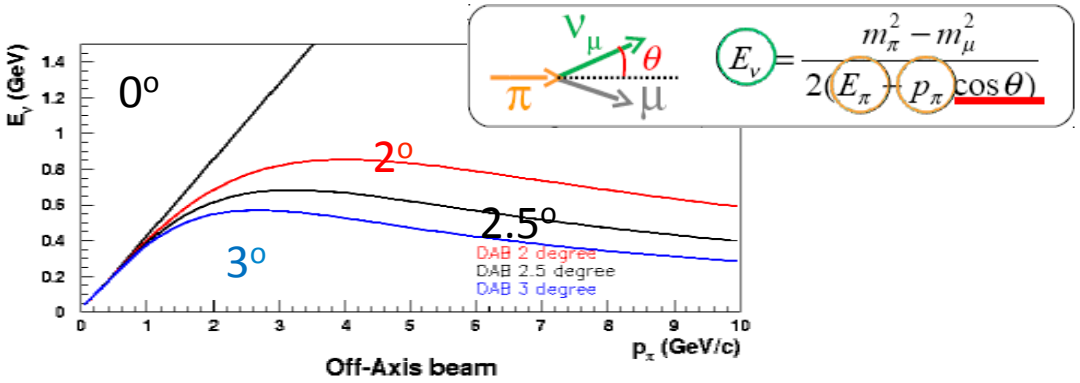


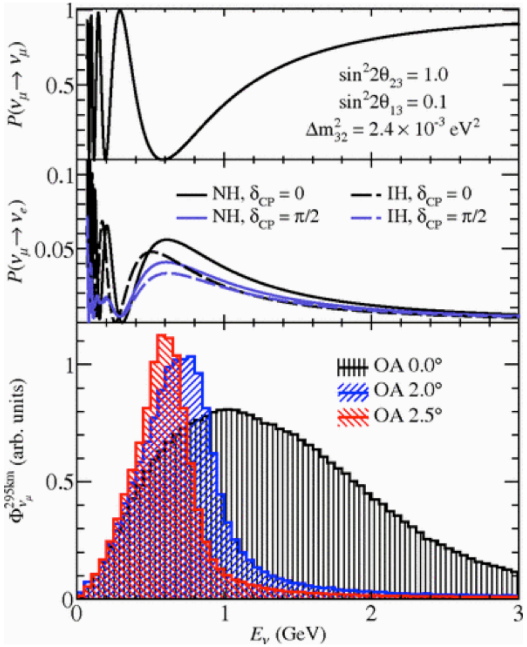
ν beam: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\bar{\nu}$ beam: $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

Muon monitors
Near ν detectors

to measure ν beam (composition), backgrounds and ν cross sections





Near detectors

Measures ν spectrum *before* oscillation:

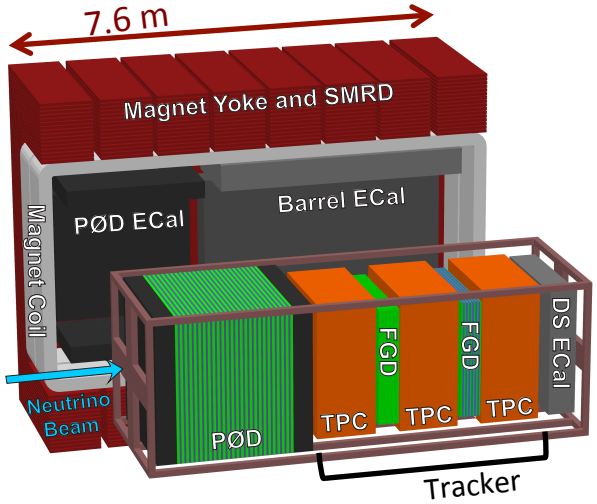
$$N_{ND} = \int dE\ \Phi(E) \times \sigma(E) \times \varepsilon_{ND}(E)$$

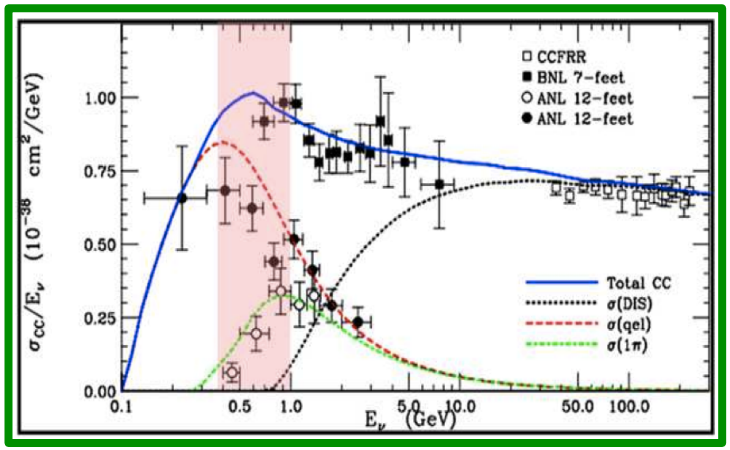
event no. | flux | cross section | efficiency

CC ν_μ events (normalization, spectrum)
NC π^0, CC ν_e events (backgrounds)
Neutrino interaction properties

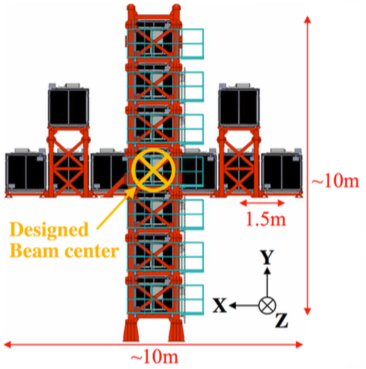
→ use to predict far detector ν flux spectrum
→ Reduces systematic uncertainties in oscillation analyses from 14% to 6%

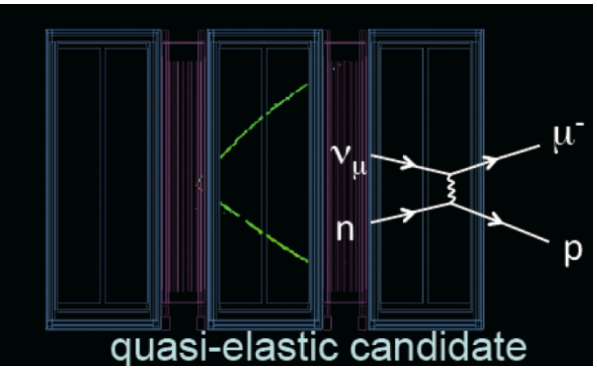
Off-axis near detector (ND280)



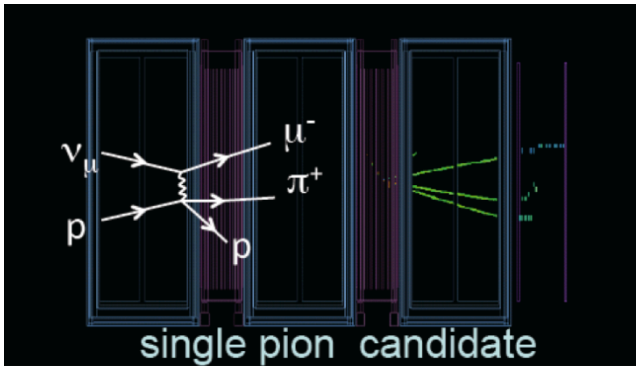


On-axis near detector

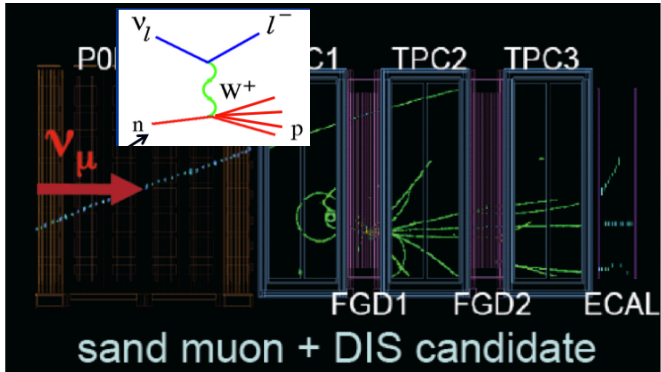




quasi-elastic candidate



single pion candidate



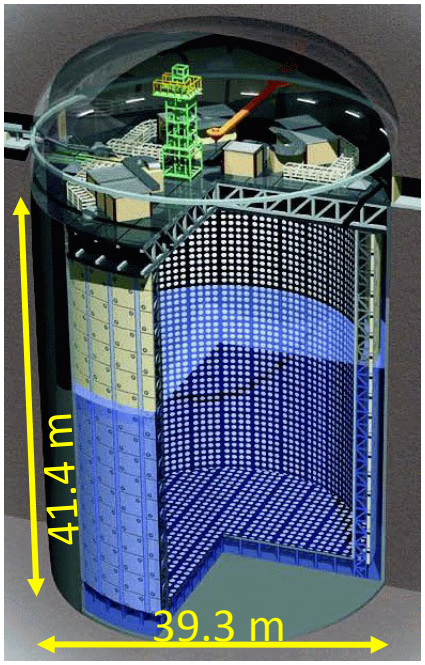
sand muon + DIS candidate

Far Detector: SK

Measure:

$$N_{FD} = \int dE\ \Phi_{FD}(E) \times \sigma(E) \times \varepsilon_{FD}(E) \times P(\nu_\alpha \rightarrow \nu_\beta; E; \theta_{ij}, \Delta m^2_{ij})$$

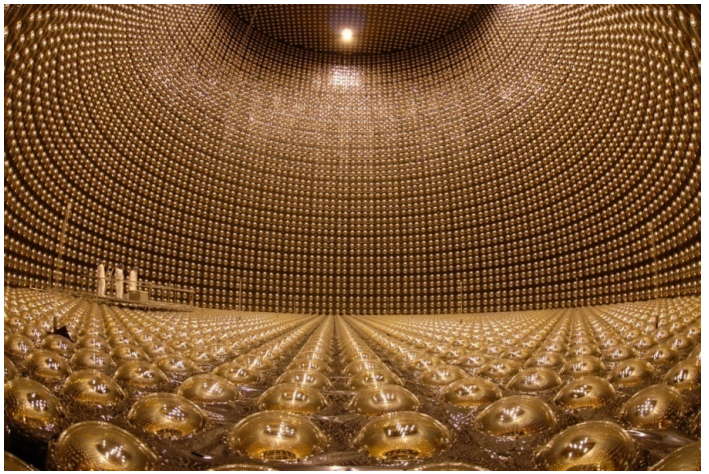
flux | Cross section | efficiency | Oscillation probability



50 kt Water-Cherenkov detector
(Fiducial : 22.5 kt)

40% Photo coverage

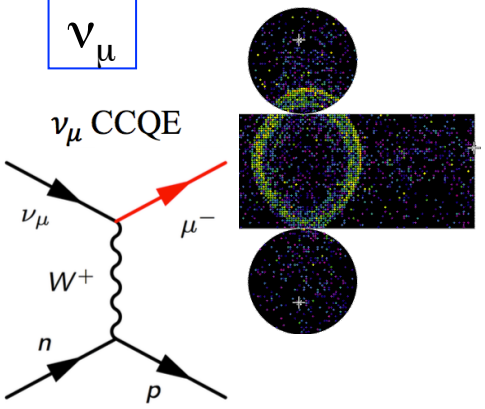
Good energy resolution (~ 10%)



20' ID PMT×11,129
8' OD PMT×1885

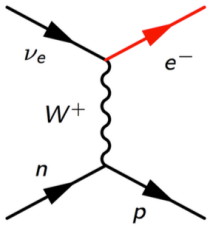
ν_μ

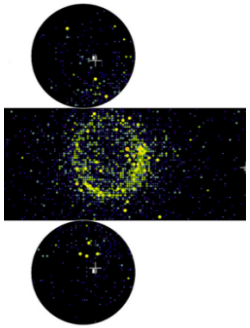
ν_μ CCQE



ν_e

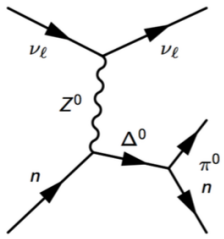
ν_e CCQE

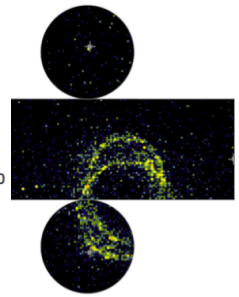


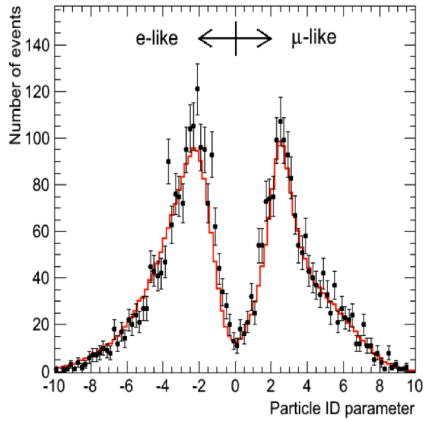


Background

ν_ℓ NC1π^0

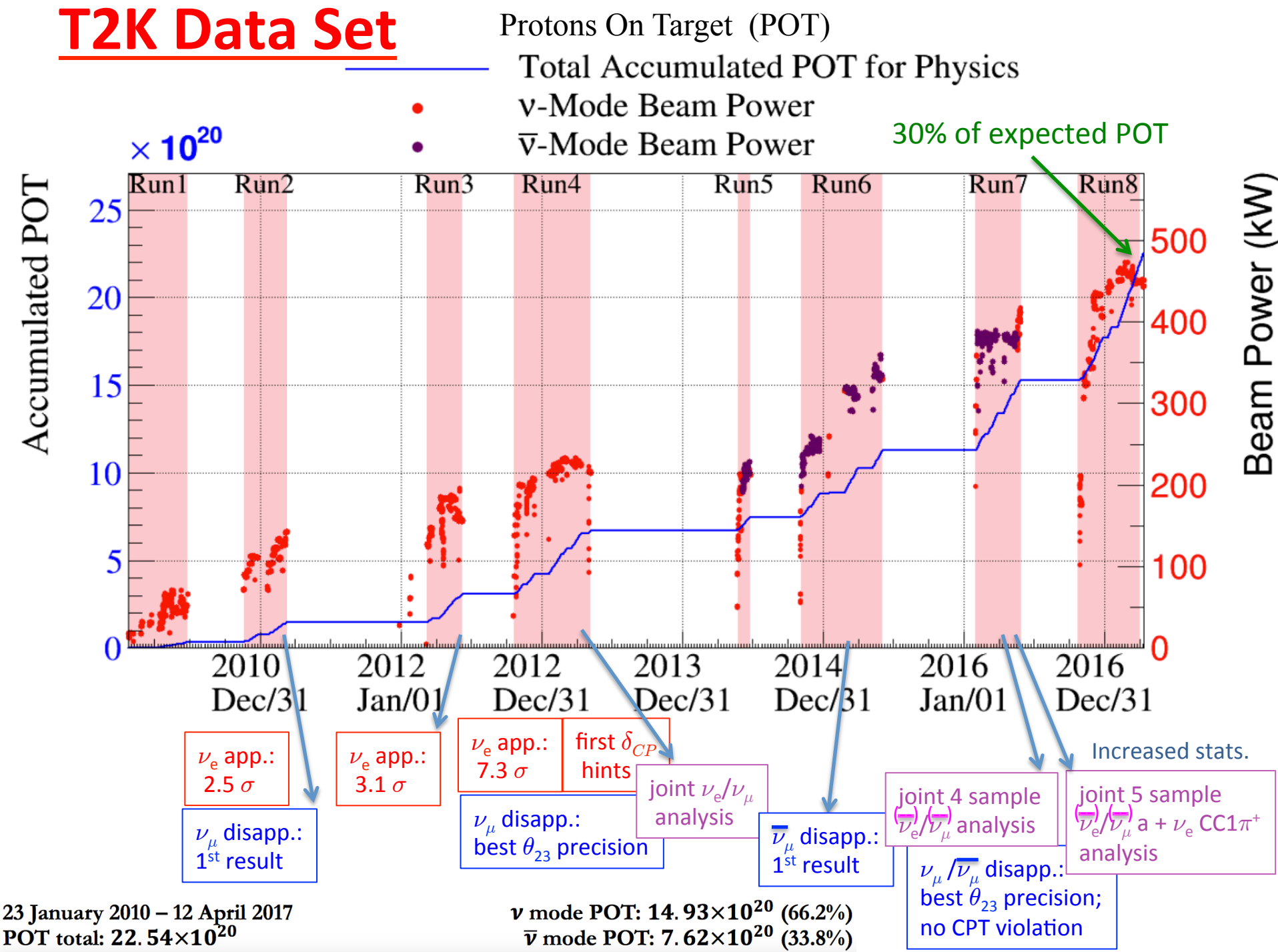






Good e/μ separation:
mis-idendification < 1%

T2K Data Set

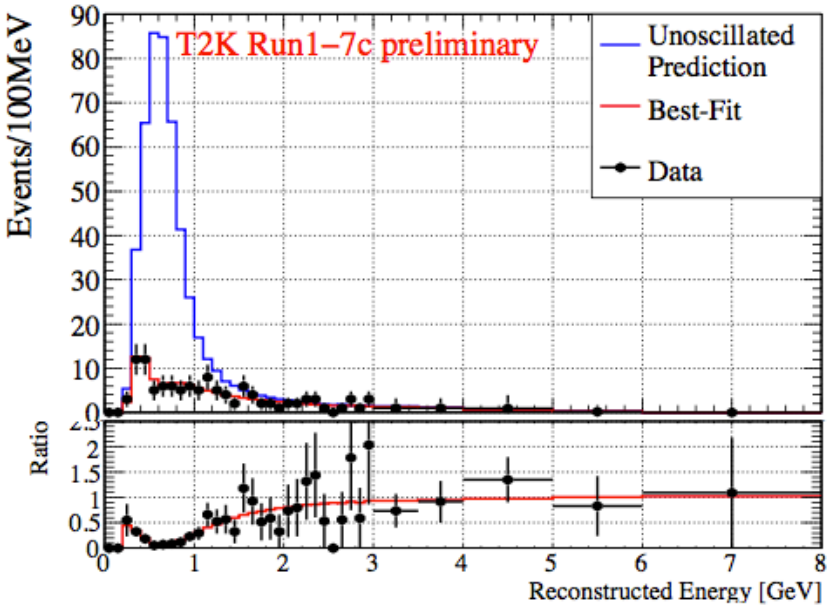


23 January 2010 – 12 April 2017
POT total: 22.54×10^{20}

ν mode POT: 14.93×10^{20} (66.2%)
$\bar{\nu}$ mode POT: 7.62×10^{20} (33.8%)

$\nu_\mu / \overline{\nu}_\mu$ disappearance results

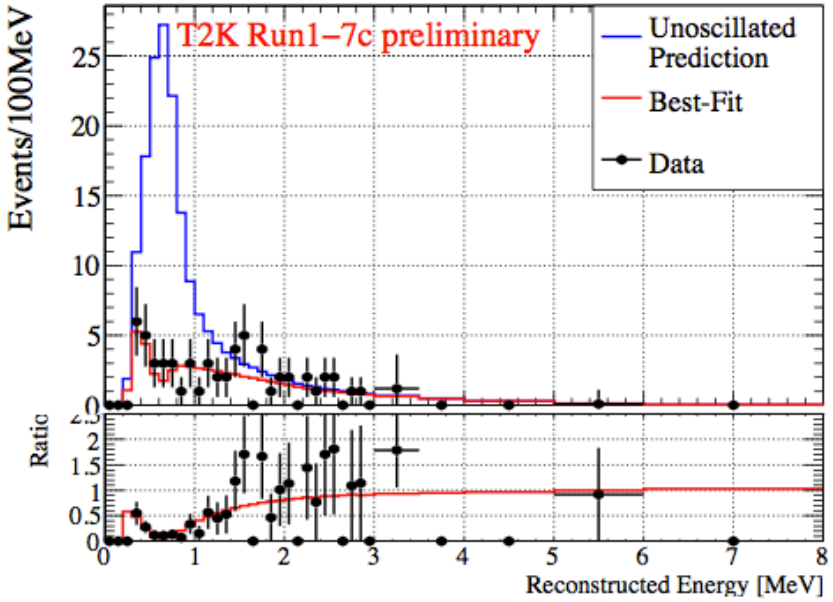
ν_μ



135 events observed

7.482×10^{20} POT

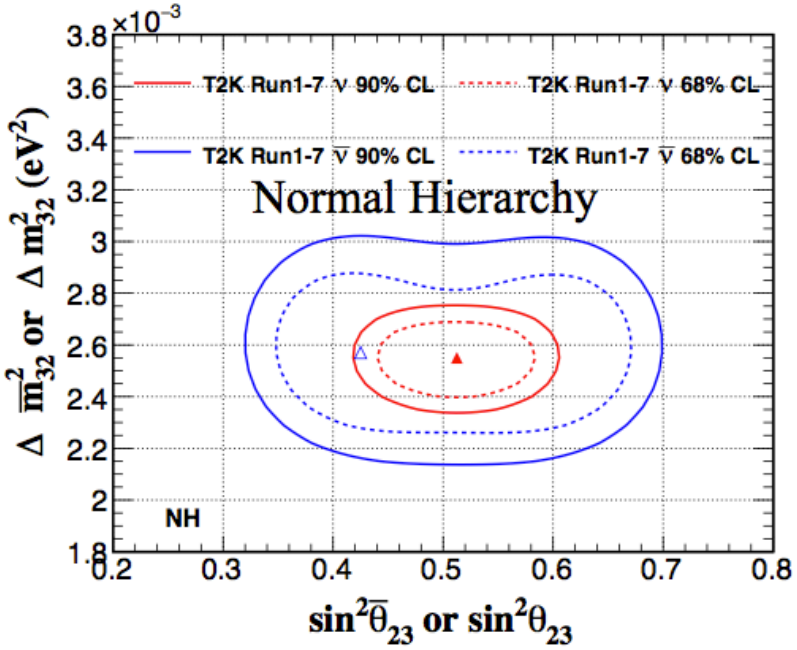
$\overline{\nu}_\mu$

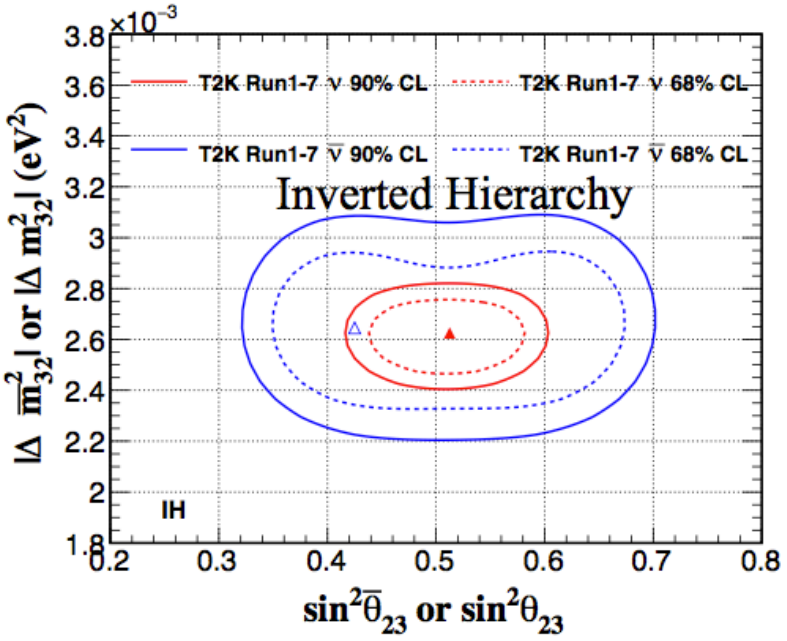


66 events observed

7.471×10^{20} POT

$\overline{\theta}_{23}$ and $\Delta\overline{m}^2_{32}$

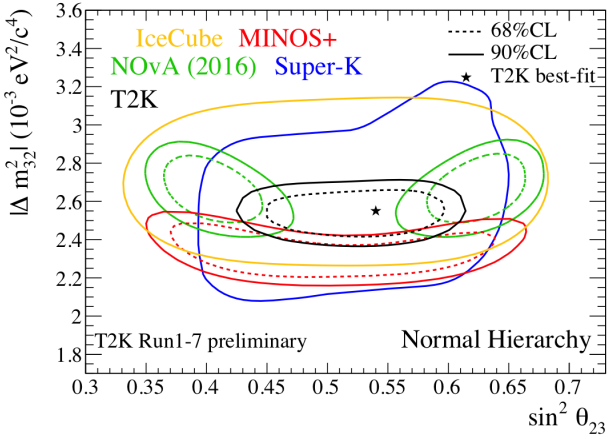




	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\lvert\Delta m^2_{32}\rvert[10^{-3}\mathrm{eV}^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

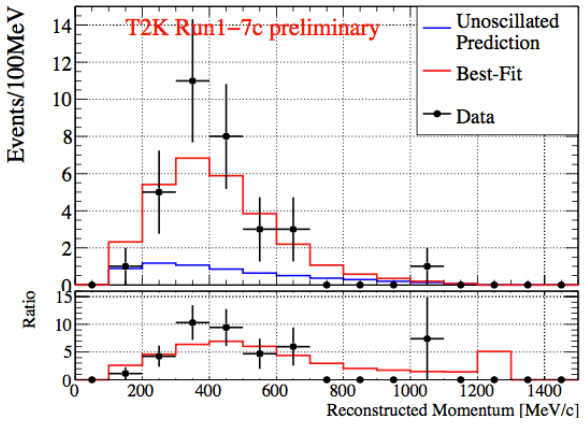
→ No hint of CPT violation

→ T2K results consistent with maximal mixing (θ_{23} = 45°)



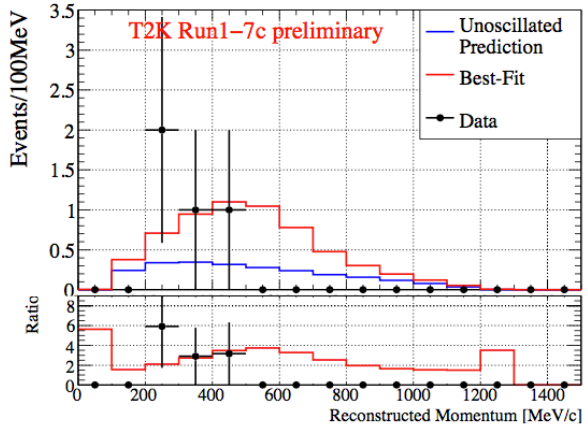
ν_e / $\bar{\nu}_e$ appearance results

ν_e



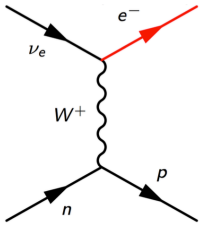
32 events observed

$\bar{\nu}_e$

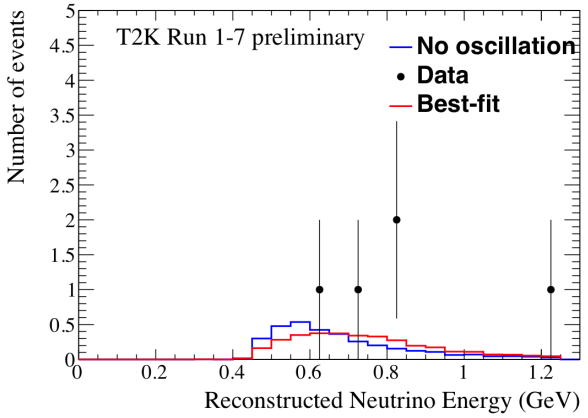


4 events observed

ν_e CCQE

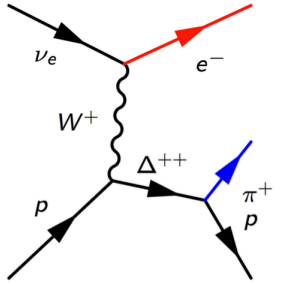


New sample: ν_e single ring electron-like + Michel electron



5 events observed

ν_e CC1π^+

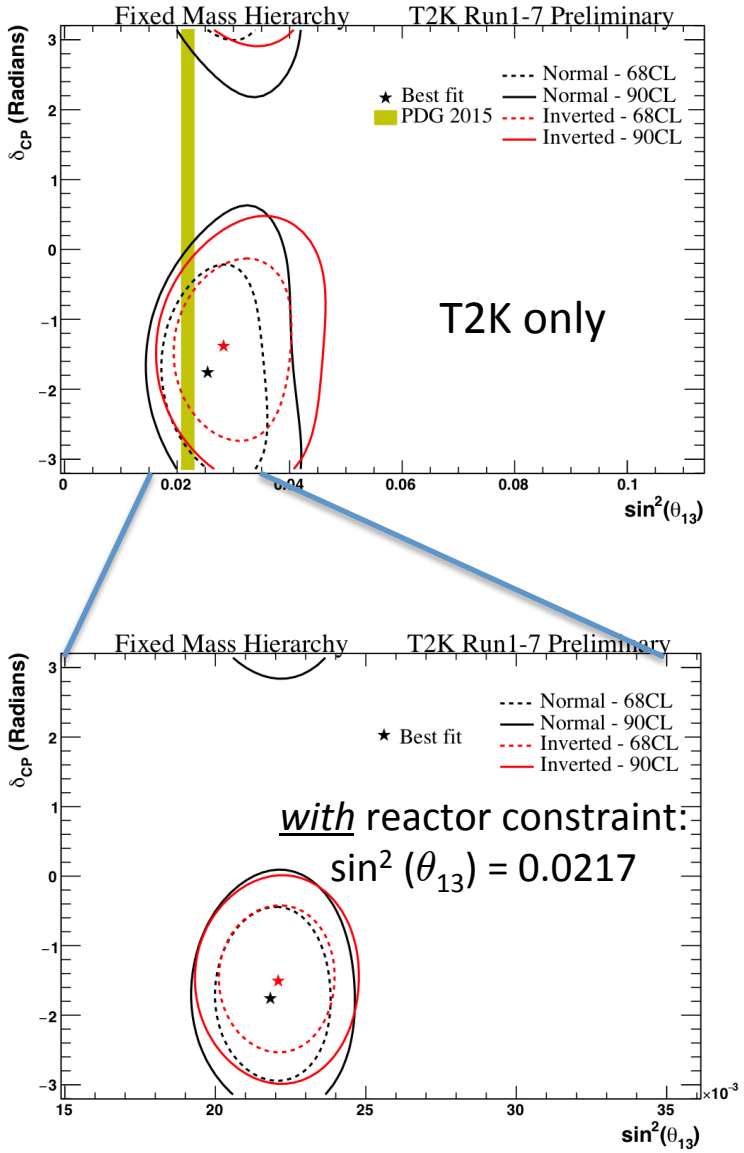


Expected events:

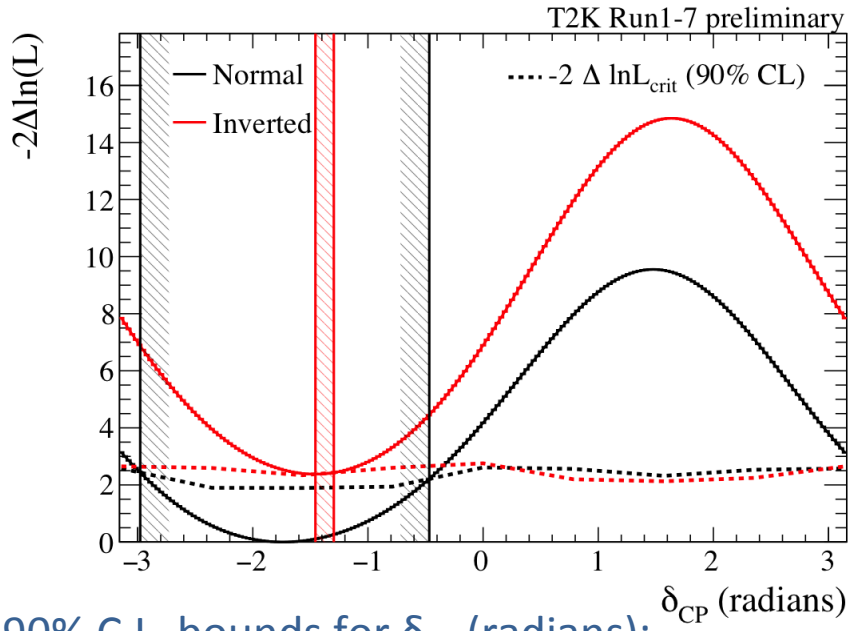
	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4
ν_eCC1π^+	3.1	2.8	2.3	2.7	5

→ T2K observed more ν_e and fewer $\bar{\nu}_e$ candidate events than expected

θ_{13} and δ_{CP}



→ **T2K results consistent with reactor measurements**



90% C.L. bounds for δ_{CP} (radians):

- Normal mass hierarchy: [-2.948,-0.467]
- Inverted mass hierarchy: [-1.466,-1.272]

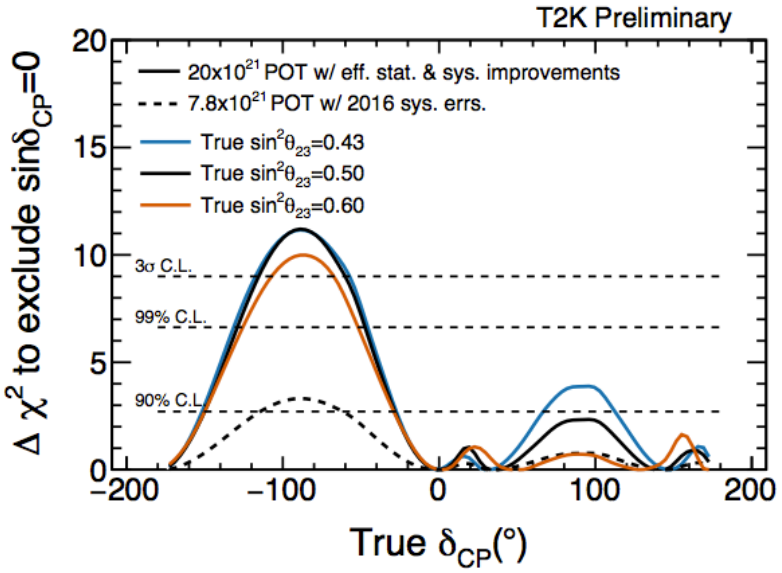
→ **2σ and 90% exclusion of δ_{CP} = 0 and π, respectively**

→ **Measurements to date favor δ_{CP} = - π/2 and normal hierarchy**

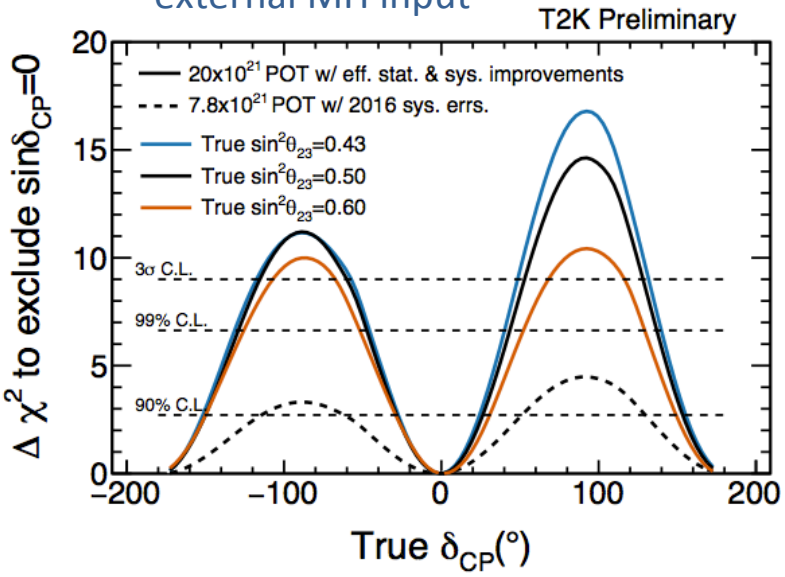
Prospects for T2K II

T2K II (extension of T2K to collect 20×10^{21} POT by $\sim$2026)
T2K approved for 7.8×10^{21} POT by $\sim$2021
→ Accelerator and beamline upgrades to reach **1.3 MW**

MH unknown



external MH input



→ $\sim 3\sigma$ sensitivity to δ_{CP} for currently favored parameters
→ Measure θ_{23} to $\sim$1.7° or better

Summary/Outlook

- Gave overview of neutrino oscillations and measurements of long-baseline neutrino oscillations with T2K

- Fast progress and many new results:
  - **Data seem to prefer $\delta_{CP} \approx -\pi/2$ and NH**
  - **ν and anti-ν running → no hint of CPT violation**
  - **T2K measurements point towards maximal θ_{23}**

http://t2k-experiment.org/publications/

- More data and excitement ahead

- Additionally T2K addresses physics topics not discussed here (see talk on T2K cross sections)