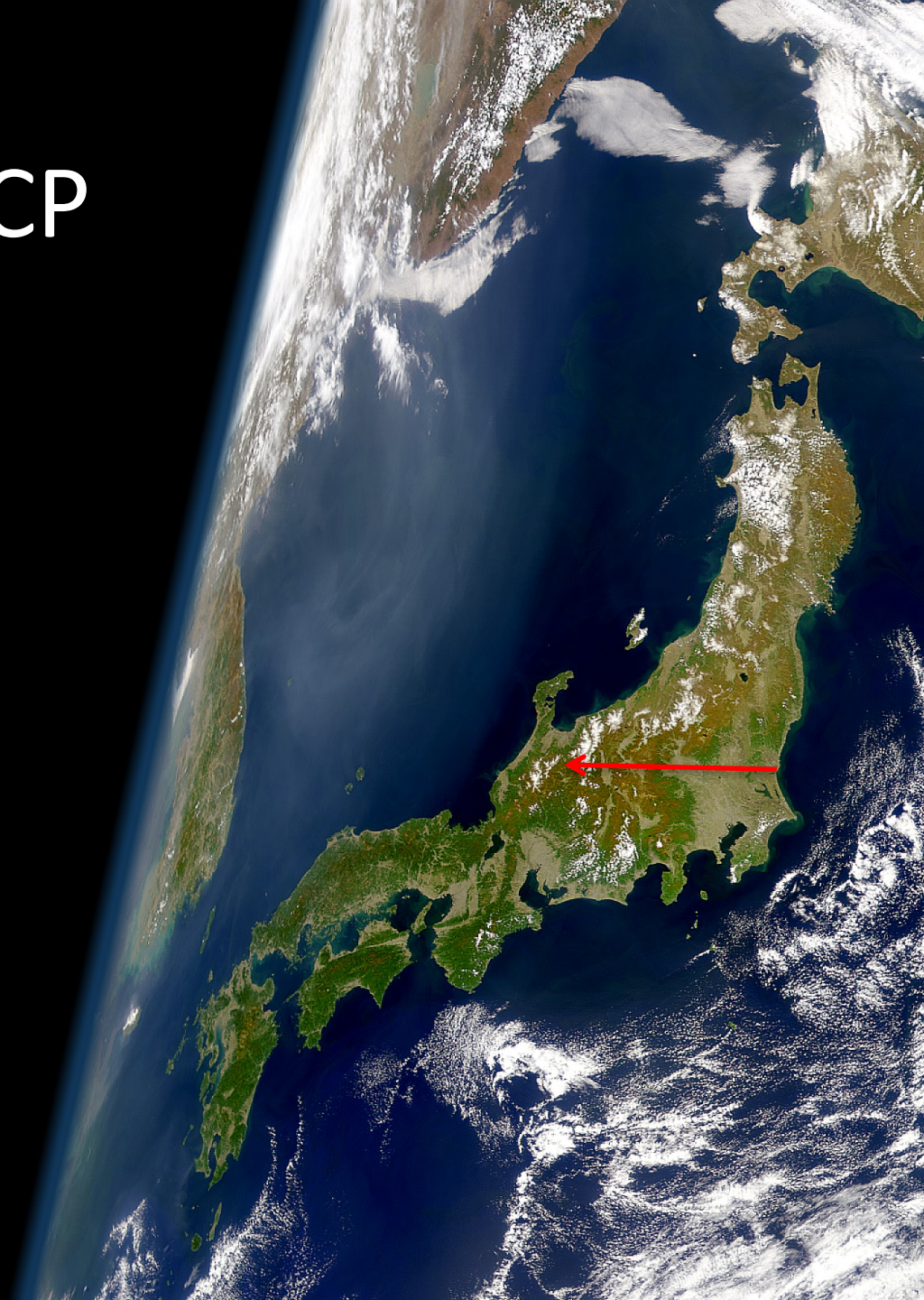
New results on CP from T2K

T. Nakadaira
(KEK IPNS/J-PARC)
for
the T2K collaboration



52nd **Rencontres de Moriond**
ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES
Mar. 18th - 25th, 2017

The T2K Collaboration

~500 members, 63 Institutes, 11 countries

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

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IPN Lyon
LLR E. Poly.
LPNHE Paris

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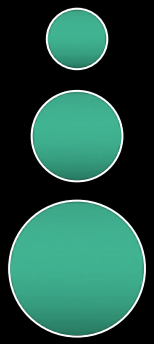
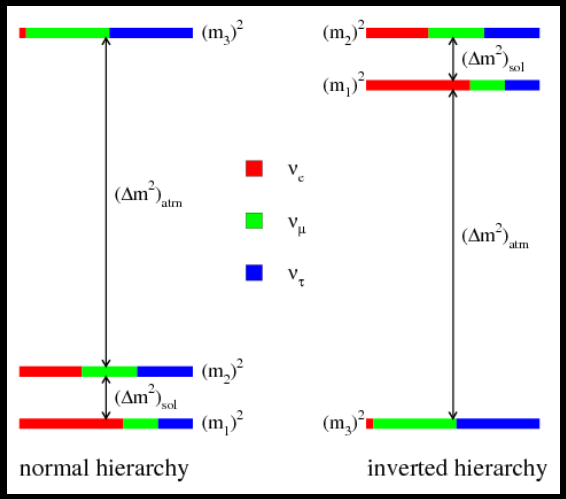
3-flavor neutrino oscillation

Weak eigenstates

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{\mathrm{PNMS}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mass eigenstates





$$U_{\mathrm{PNMS}} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{+i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix} \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

$$P(\nu_a \to \nu_b) = \delta_{ab} - 4\sum_{i>j}(U_{ai}U_{bi}U_{aj}U_{bj})\sin^2\left(\Delta m^2_{ij}L/4E\right) \qquad \Delta m^2_{ij} \equiv m^2_i - m^2_j$$

- 6 independent parameters in 3 mixing angles, 1 complex phases, 3 mass-squared differences.
  - Mass hierarchy (sign of Δm^2_{32}) and δ_{CP} are not determined yet. ← Accelerator-based Long baseline ν oscillation experiment can address.

Goal of T2K experiment

- Direct search for $\nu_\mu \rightarrow \nu_e$ oscillation: Discovered in 2013!
- Precise measurement θ_{23} of $\nu_\mu \rightarrow \nu_\mu$ disappearance
- Search for CP violation phenomena in the lepton sector
  - Difference between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

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

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)\left(1 + \frac{2a}{\Delta m^2_{31}}\left(1 - 2\sin^2\theta_{13}\right)\right)$$

$$- \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin\delta_{CP} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) \sin\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \cdots$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)\left(1 - \frac{2a}{\Delta m^2_{31}}\left(1 - 2\sin^2\theta_{13}\right)\right)$$

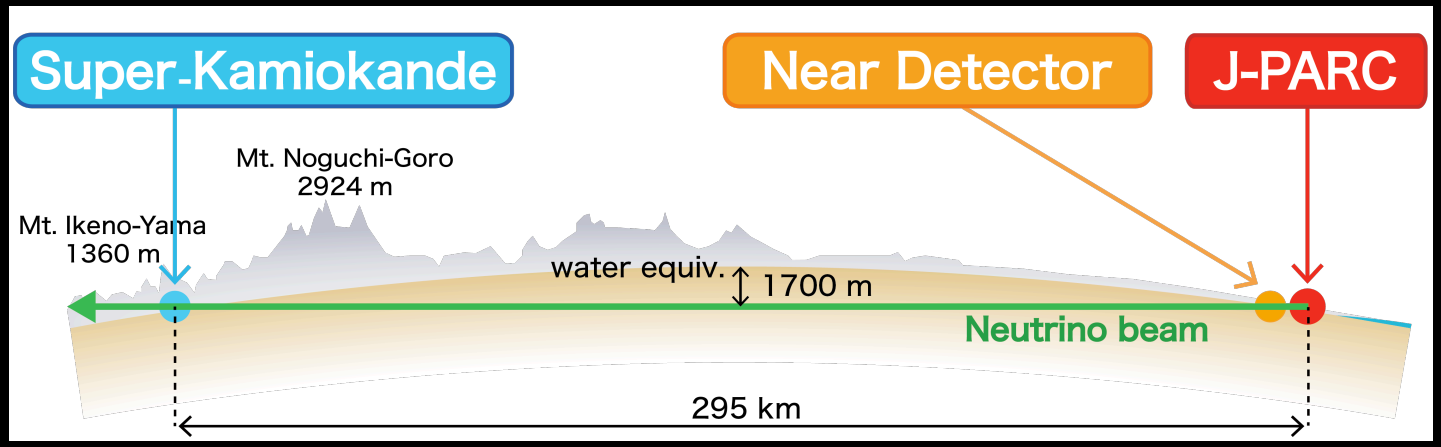
$$+ \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin\delta_{CP} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) \sin\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \cdots$$

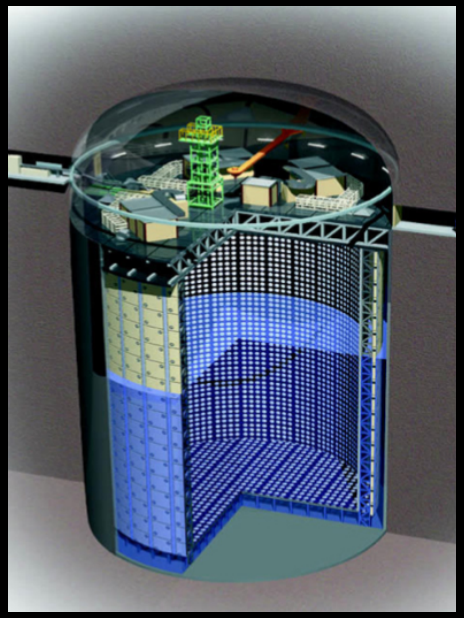
Approx. At around osci. max. L/E_ν

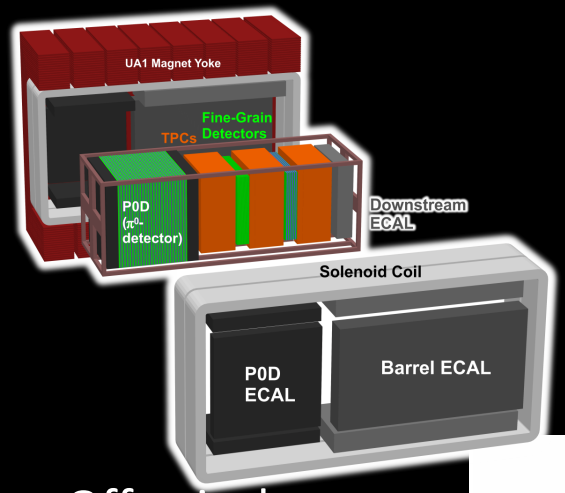
Matter effect is small for L=300km.

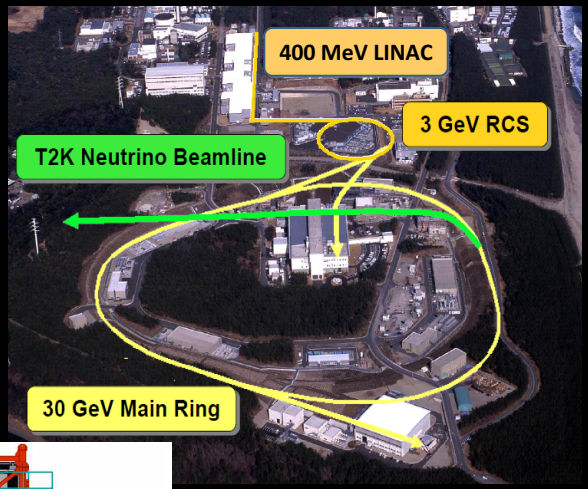
$$a \equiv 2\sqrt{2} G_F n_e E_\nu = 7.56 \times 10^{-5}\mathrm{eV}^2 \rho[g/cm^{-3}] E_\nu[\mathrm{GeV}]$$

T2K experiment



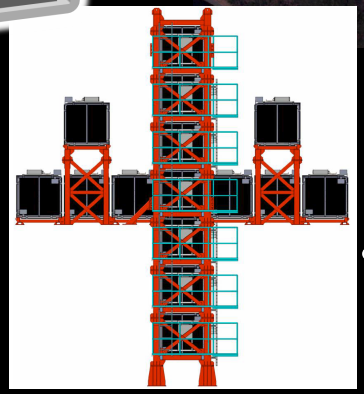






- 50 kt Water Cherenkov detector (Fiducial 22.5 kt) @ underground (2700 m water equivalent)
- Events on the beam timing are selected using GPS.

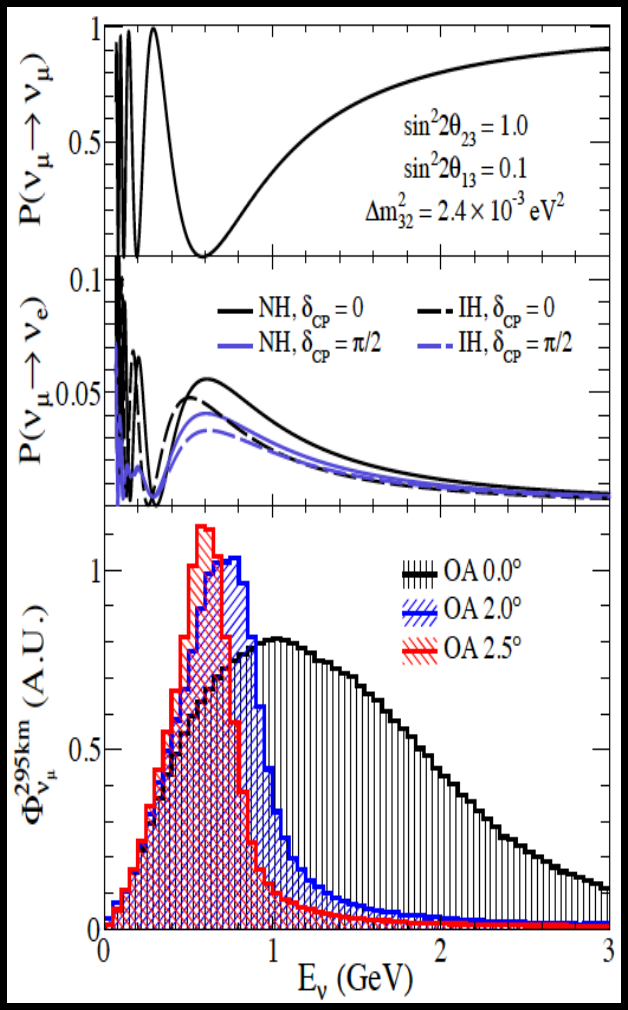
- Off-axis detector : ND280

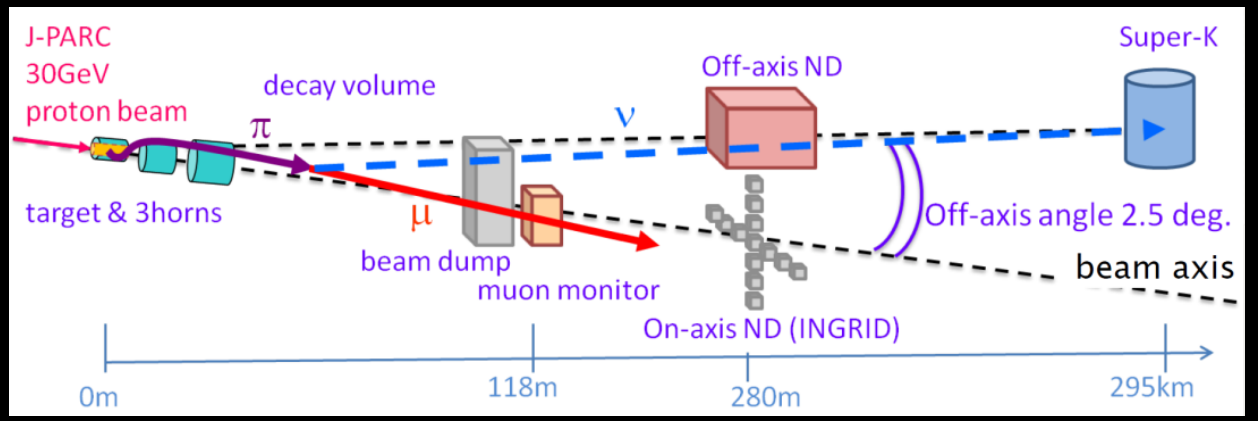


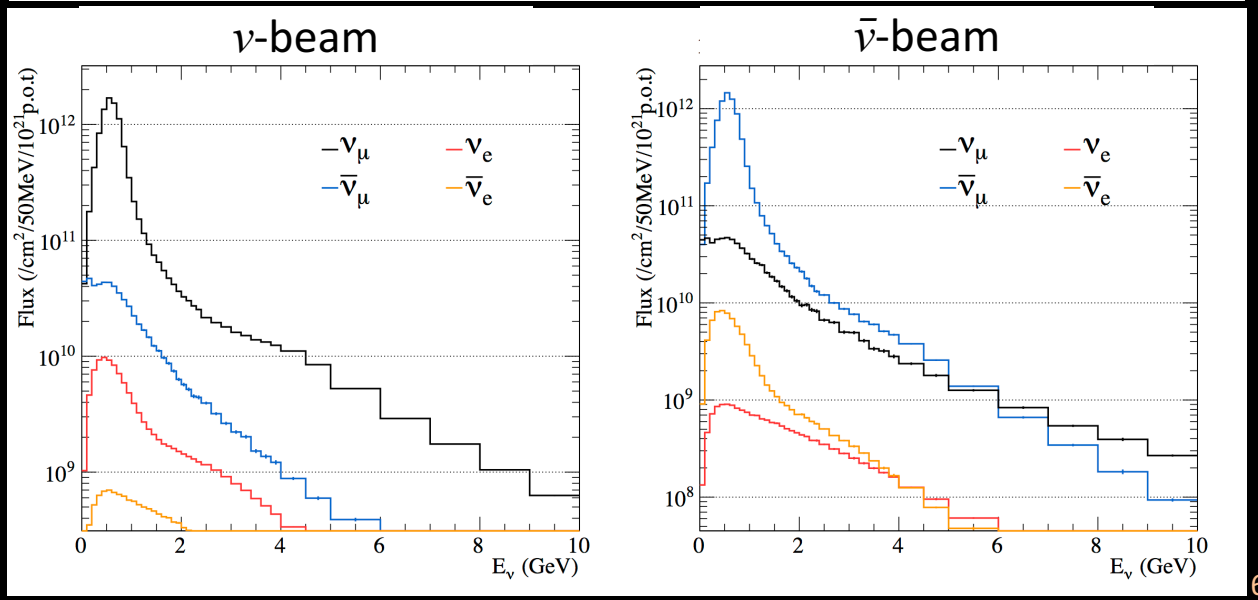
- On-axis detector : INGRID

J-PARC neutrino beam

- Narrow band beam by off-axis method.
- ν-beam and $\bar{\nu}$-beam can be switched by changing the field polarity of horns.
- Neutrino flux is estimated from beam MC using the hadron production of 30 GeV p-C measured by CERN NA61/SHINE experiment, etc.

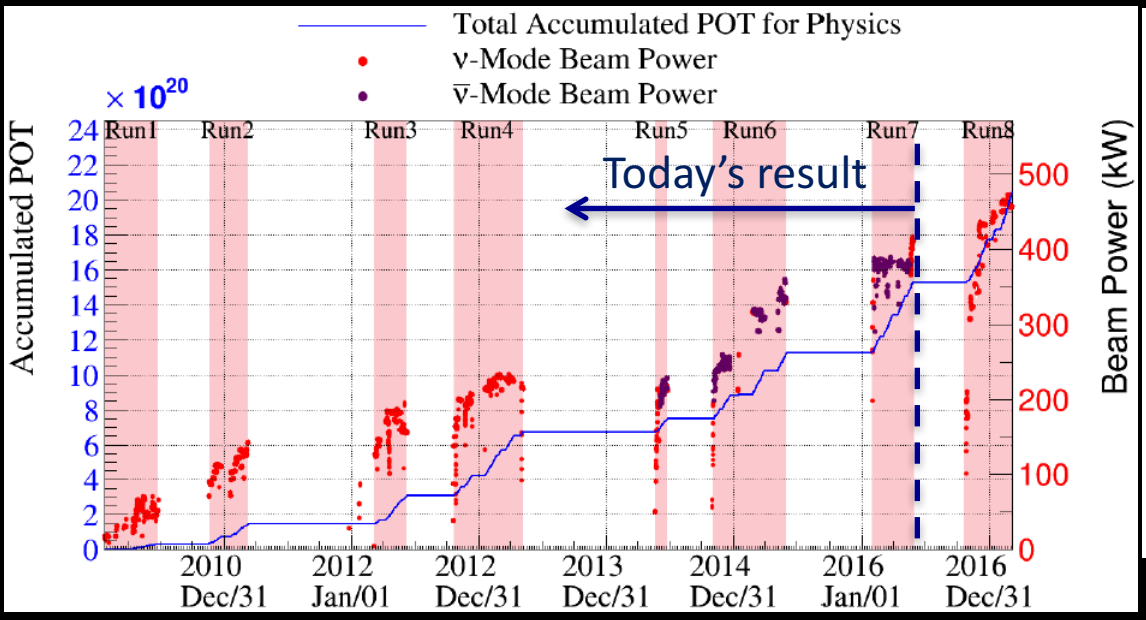


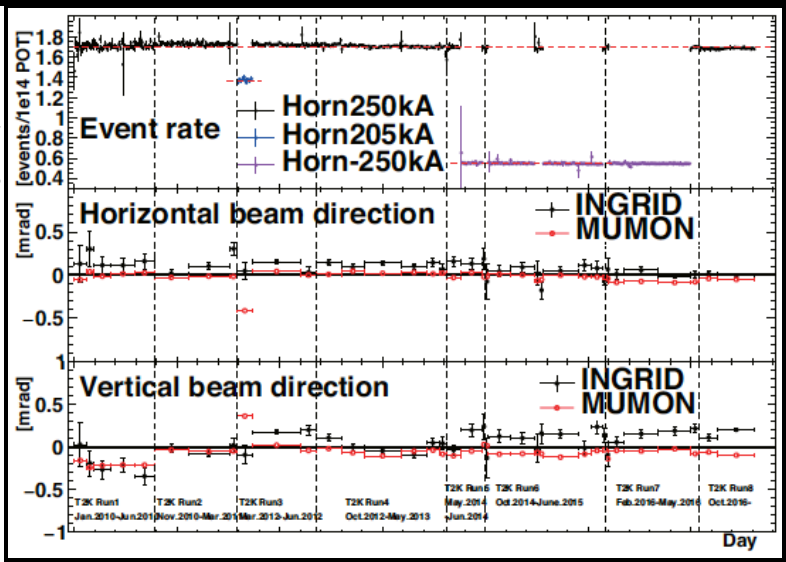




T2K data-taking status

- T2K has been taking physics data from Jan. 2010.
- From 2014, $\bar{\nu}$-beam data are also produced.
- Beam quality is stable for entire run period.
- Today's result is based on data up to May, 2016.
  - ν-beam data: 7.482×10^{20} POT (Protons-On-Target)
    $\bar{\nu}$-beam data: 7.471×10^{20} POT
- As of Mar 8th, beam power for physics run is ~470kW.
  Accumulated POT for T2K exceeds 2×10^{21} POT.



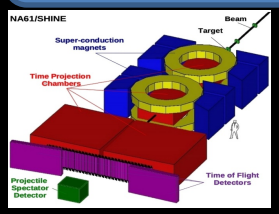


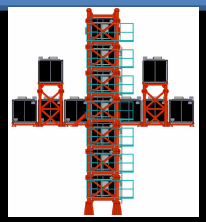
T2K oscillation analysis strategy

Proton beam data
INGRID data

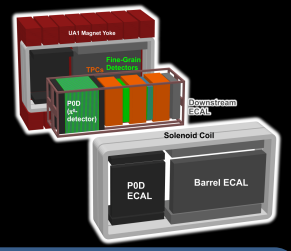
Neutrino beam-line simulation

Hadron production data
CERN NA61/SHINE, etc





Neutrino flux prediction

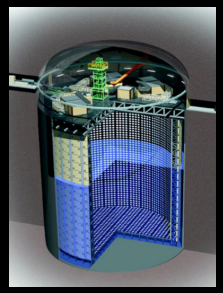


ND280 data

ND280 detector response

Predict
(flux & cross-section)@SK
by ND280 data fit

ν–nucleus interaction model



SK data

SK detector response

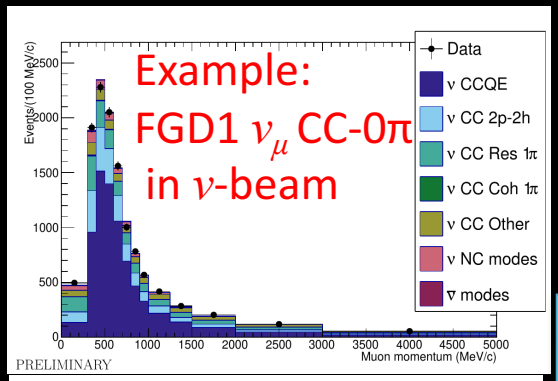
neutrino oscillation analysis by SK data fit

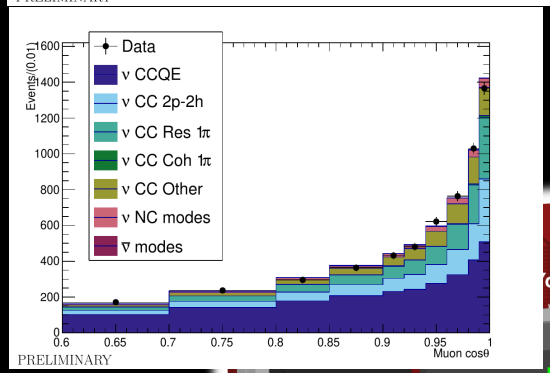
Results of oscillation parameters

θ_{13} results by Reactor experiments

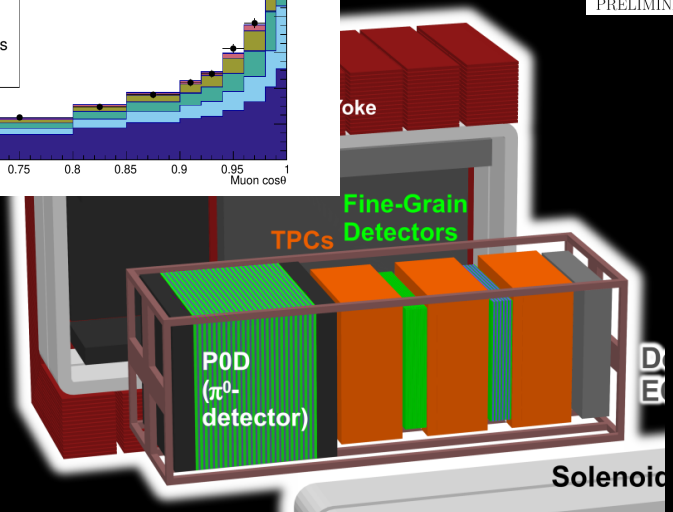
Near detector data fit

- Charged-current ν_μ / $\bar{\nu}_\mu$ interaction event sub-samples in FGD1(CH target) and FGD2(CH+H_2O target) that are categorized by final-state and beam-mode (ν/ $\bar{\nu}$) are fitted simultaneously.

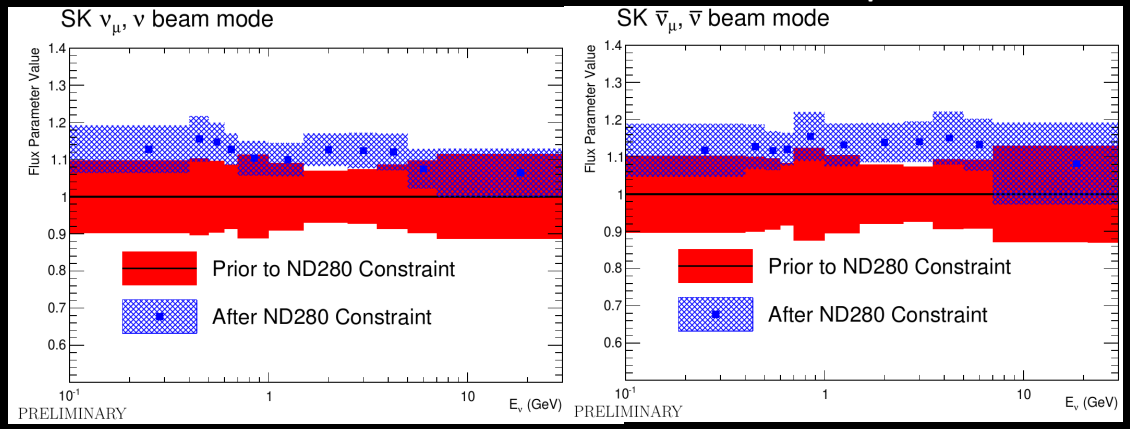




+ Other event samples



Estimated SK event normalization parameter / nominal flux parameters



Total systematic uncertainty of SK event rate prediction.

SK event sample		w/o ND280	ND280 constrained
ν-beam	1-ring μ-like	12.0 %	5.1 %
	1-ring e-like	12.7 %	6.8 %
	CC-1π^+ like	21.9 %	15.3 %
$\bar{\nu}$-beam	1-ring μ-like	17.9 %	11.7 %
	1-ring e-like	14.5 %	7.4%

Far detector (SK) event selection

Fully contained at beam-timing + vertex inside fiducial volume

Only one-ring reconstructed

PID: μ-like

PID: e-like

μ momentum p_μ > 200MeV

Visible energy E_{vis} > 100MeV

# of decay-e $\leqq$ 1

No decay-e

Only 1 decay-e

Reconstructed E_ν < 1250MeV

Reconstructed E_ν < 1250MeV

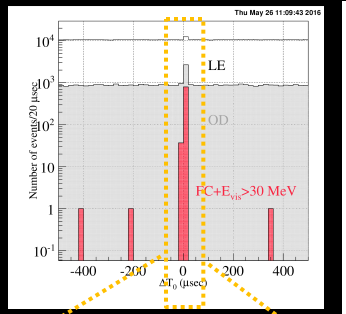
NC-π^0 rejection

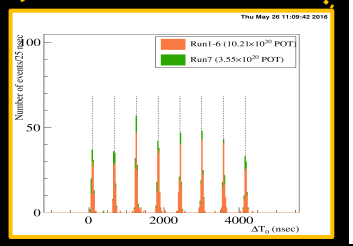
NC-π^0 rejection

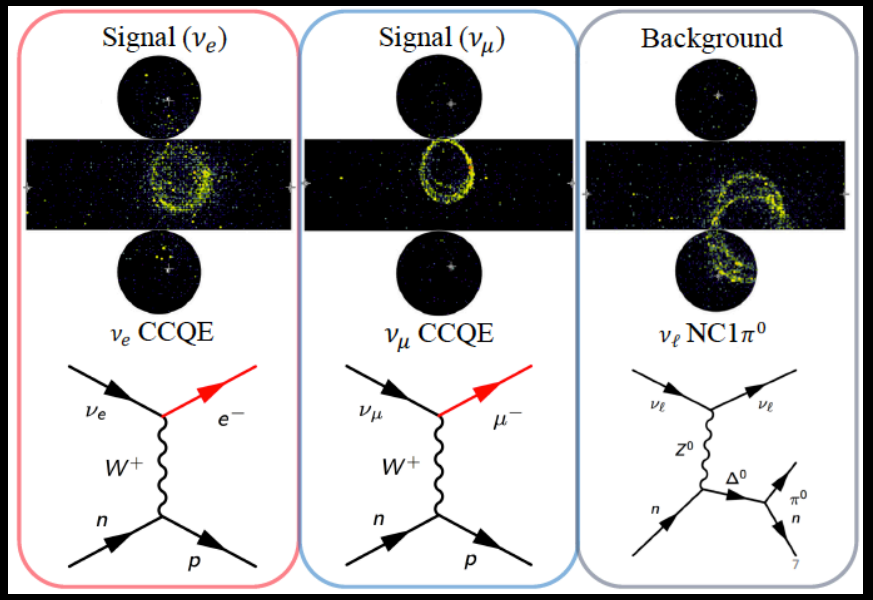
$\nu_\mu/\bar{\nu}_\mu$ CC-QE candidate

$\nu_e/\bar{\nu}_e$ CC-QE candidate

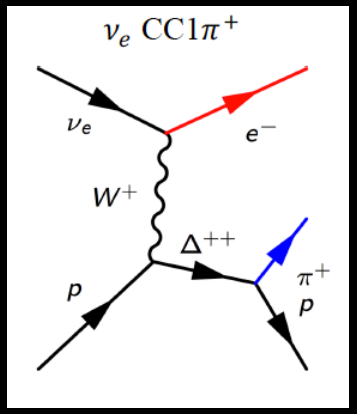
$\nu_e/\bar{\nu}_e$ CC-1π candidate







A new event sample become available for oscillation analysis!



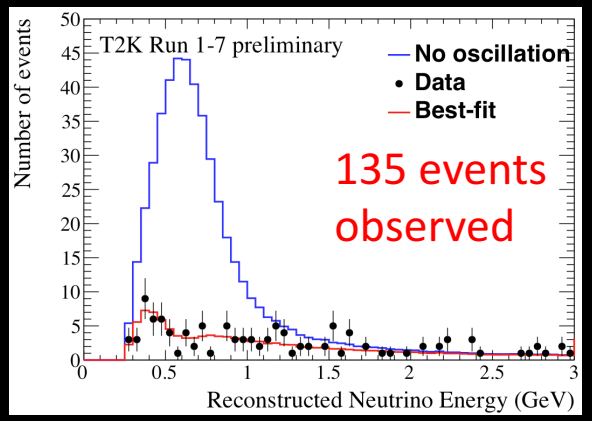
Neutrino energy is reconstructed assuming π-production via Δ-resonance

Observed SK neutrino event candidates

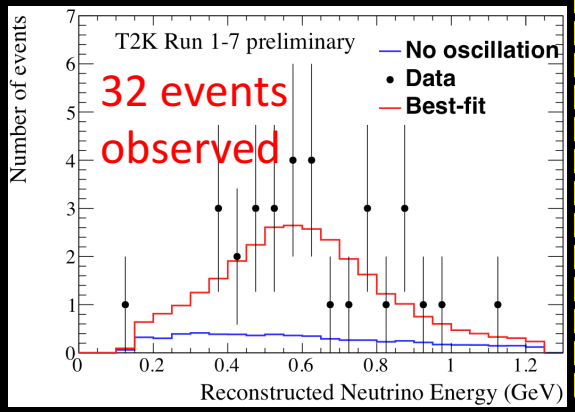
- Oscillation parameter is determined by fitting 5 event categories simultaneously.

New event sample

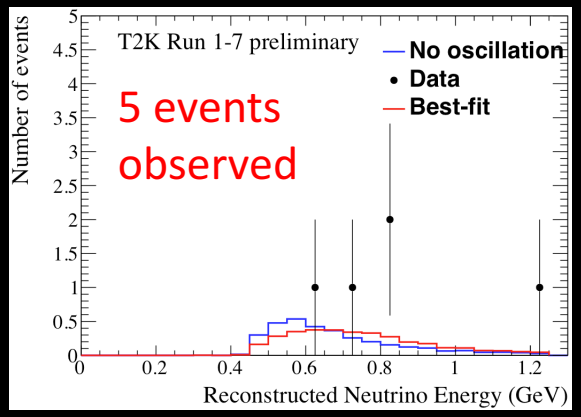
$\nu_\mu/\bar{\nu}_\mu$ CC-QE in ν-beam



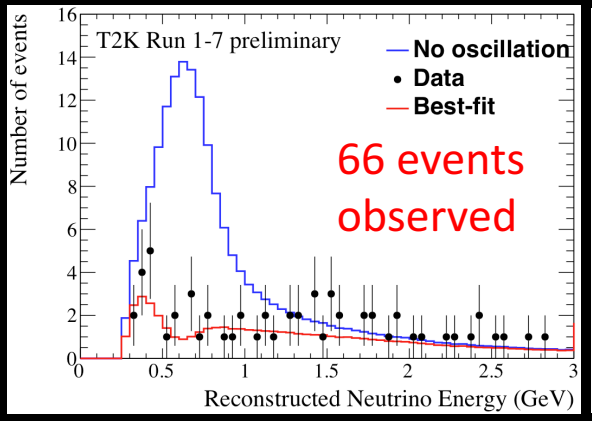
$\nu_e/\bar{\nu}_e$ CC-QE in ν-beam



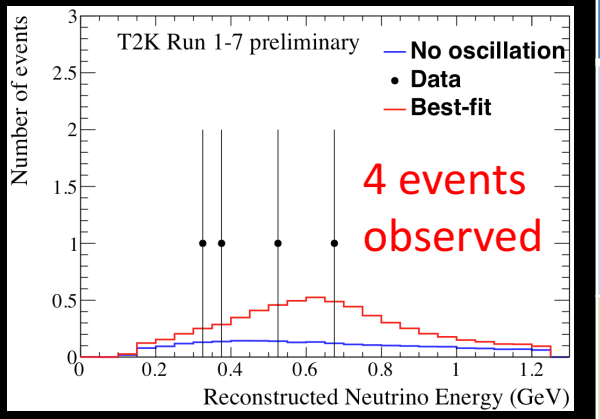
$\nu_e/\bar{\nu}_e$ CC-1π in ν-beam



$\nu_\mu/\bar{\nu}_\mu$ CC-QE in $\bar{\nu}$-beam



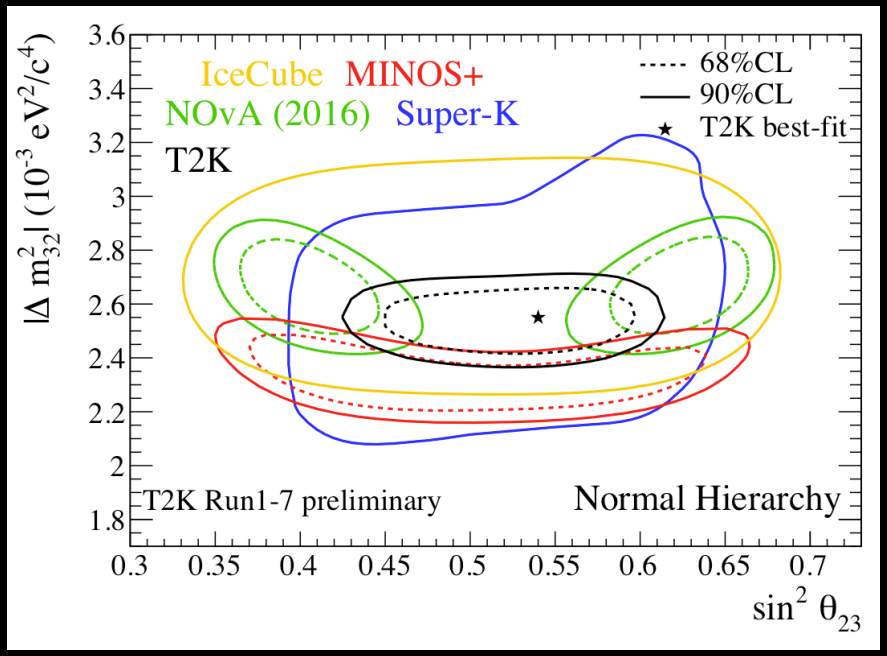
$\nu_e/\bar{\nu}_e$ CC-QE in $\bar{\nu}$-beam

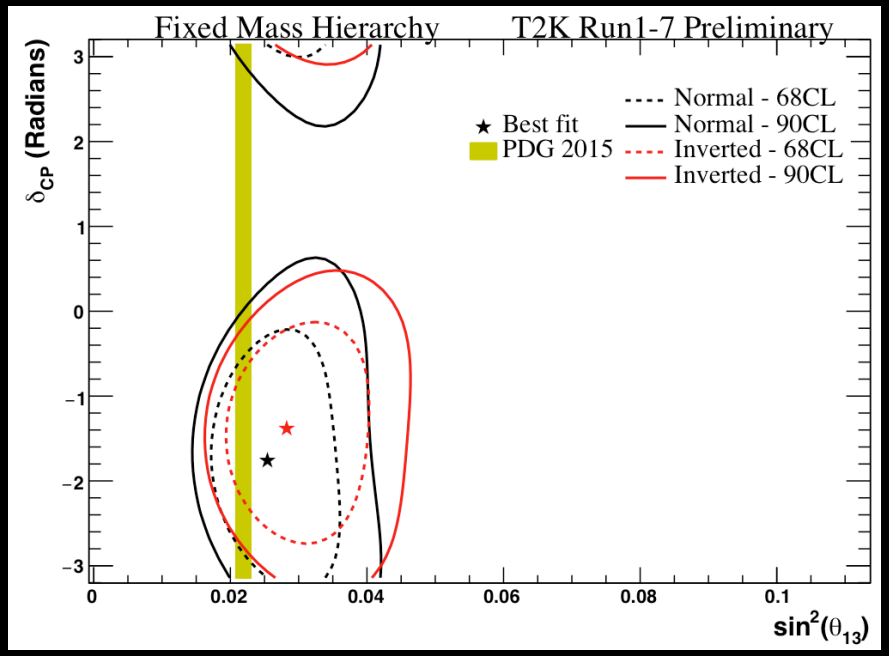


Expected # of events		δ_{CP} -1.6	δ_{CP} 0
ν-beam	$\nu_\mu/\bar{\nu}_\mu$ CC-QE	135.8	135.5
	$\nu_e/\bar{\nu}_e$ CC-QE	28.7	24.2
	$\nu_e/\bar{\nu}_e$ CC-1π	3.1	2.7
$\bar{\nu}$-beam	$\nu_\mu/\bar{\nu}_\mu$ CC-QE	64.2	64.1
	$\nu_e/\bar{\nu}_e$ CC-QE	6.0	6.9

Results on oscillation parameters

- T2K results consistent with the max. oscillation ($\sin^2\theta_{23}$=0.5).

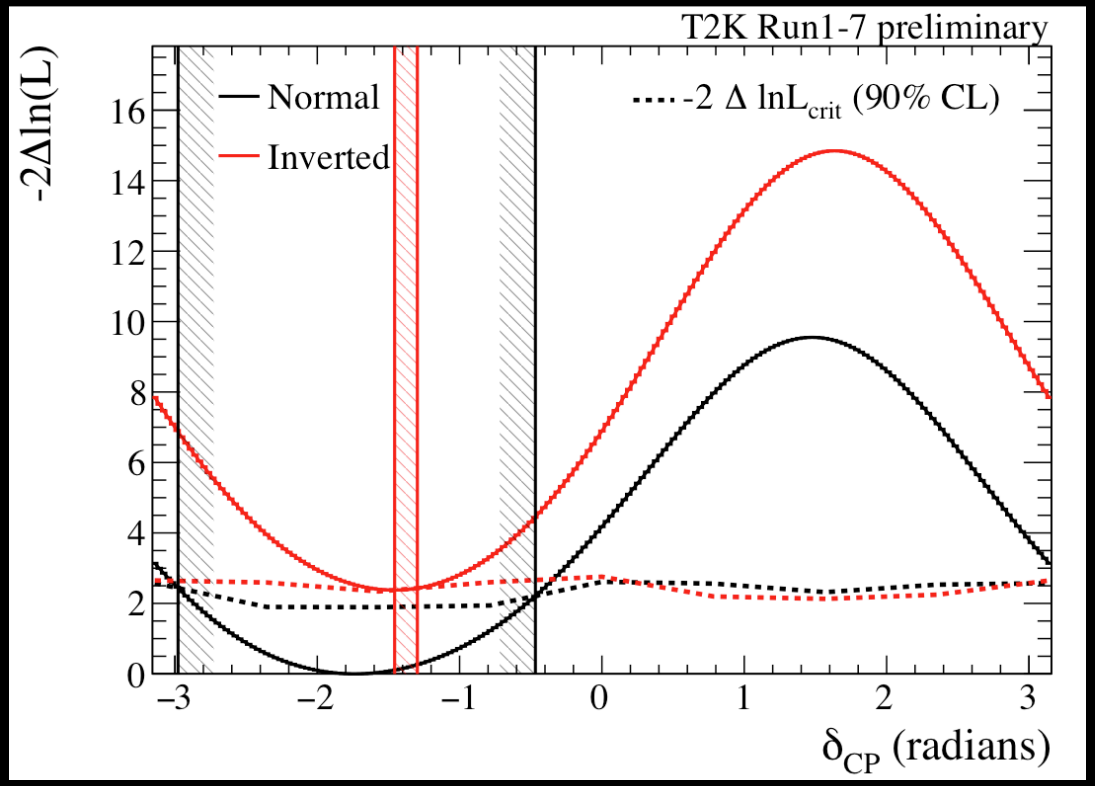




Super-K: PoS ICRC2015 (2015) 1062
Minos+: Neutrino 2014
NOvA : ICHEP2016
IceCube DeepCore: Phys.Rev. D91 (2015) 072004

Obtained results on CP

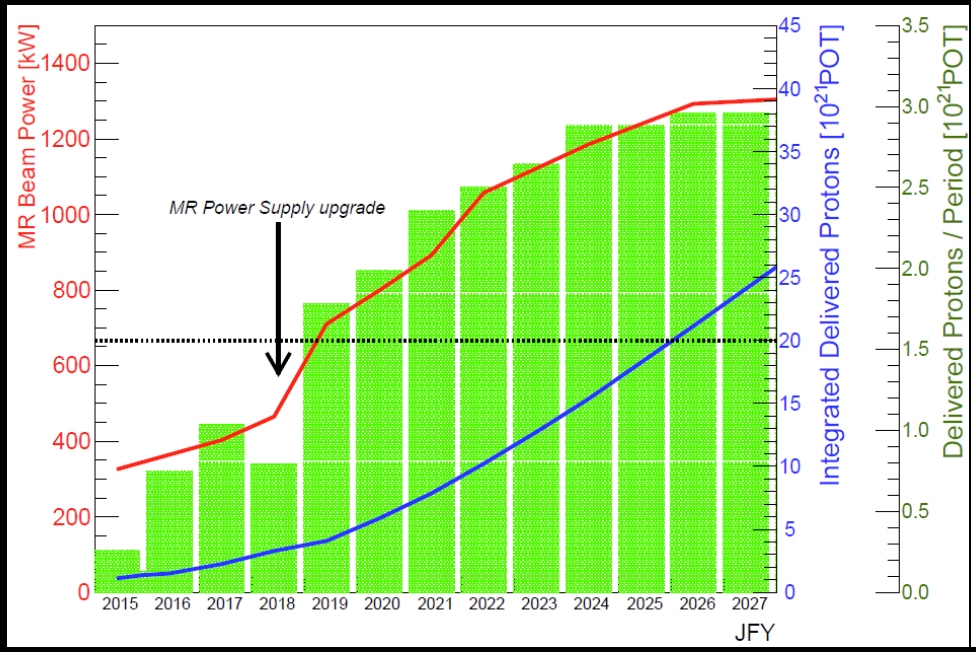
- Constrain θ_{13} with the results by reactor exp.
- *CP*-conservation hypothesis ($\sin\delta_{CP}=0$) is excluded with 90% CL.
- Confidence interval (90 %CL): NH -2.978 ~ -0.467 [rad]
  IH -1.466 ~ -1.272 [rad]

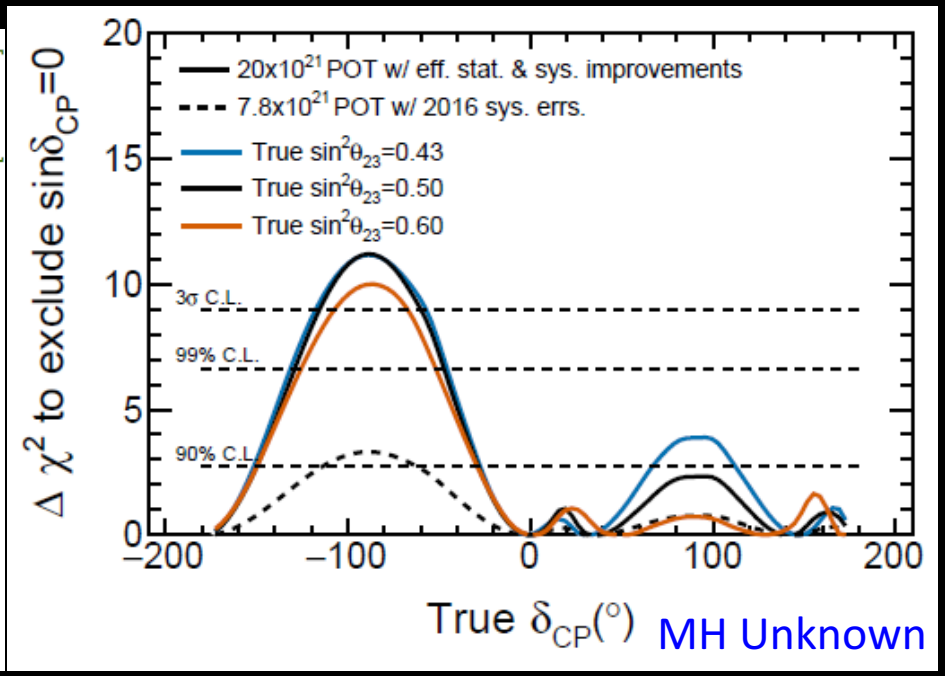


Future prospects

T2K-II (Running time extension)

- T2K proposes to collect 20×10^{21} POT data to search for evidence of CP violation in the lepton sector with 3σ sensitivity. (arXiv:1609.04111 [hep-ex])
  - J-PARC PAC recognizes the scientific merit and gave stage-1 status in 2016.





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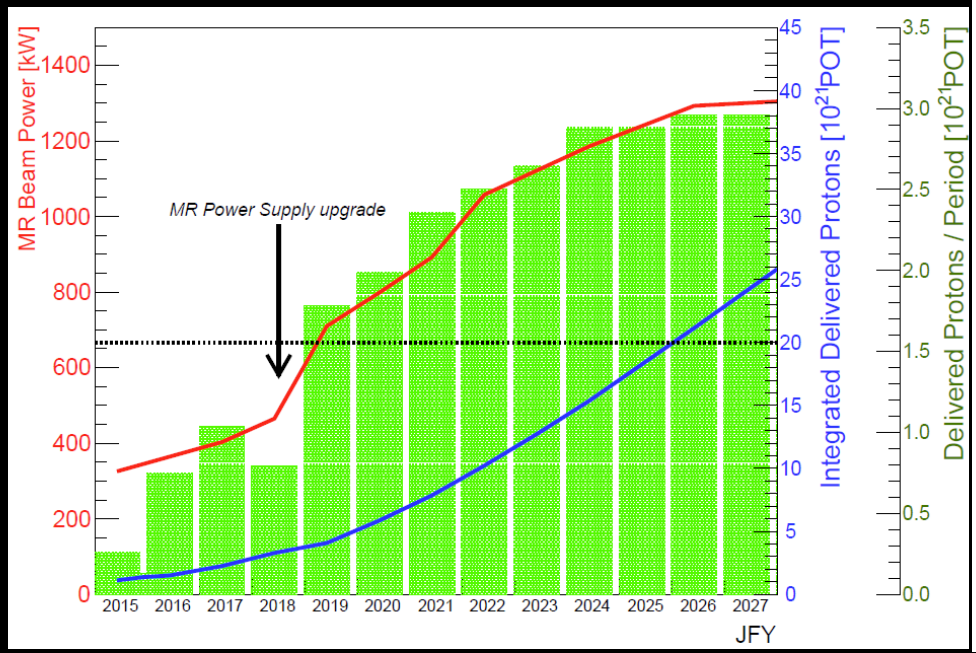
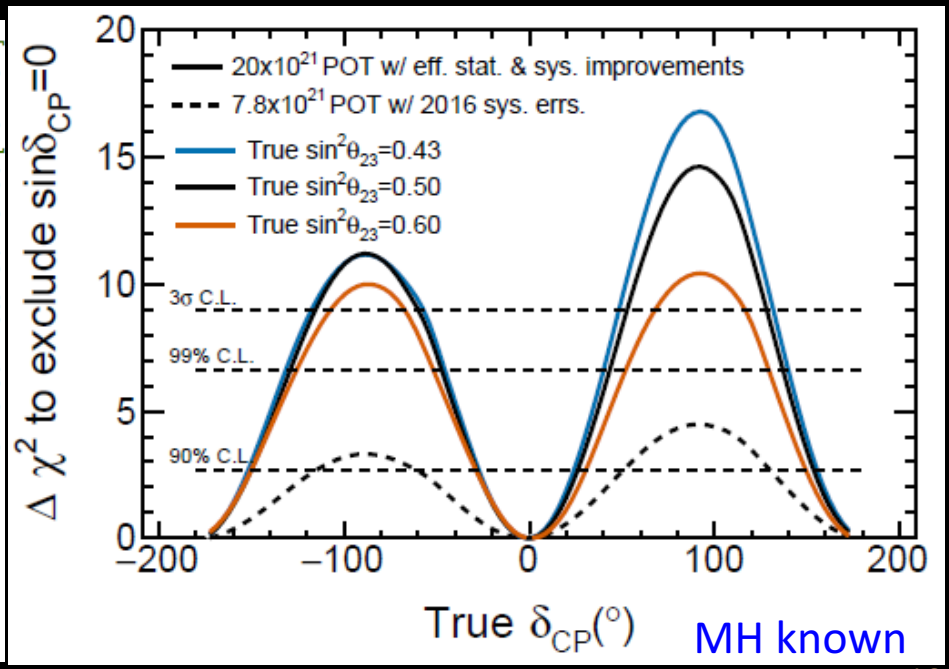




Upgrade: T2K → T2K-II

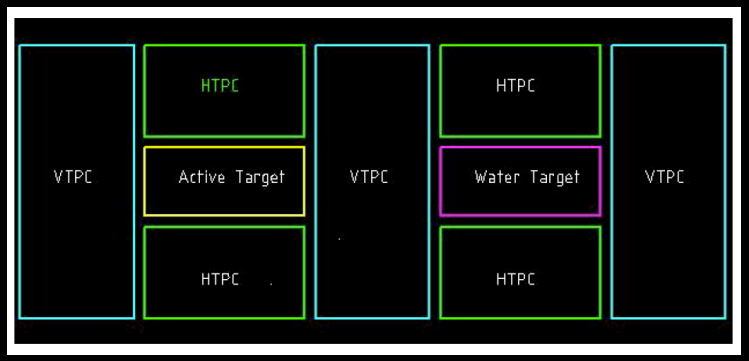
- Beam Improvement:
  - 750 kW → 1.3 MW by HW upgrade of J-PARC MR accelerator and ν-beamline
  - Improve ν-flux/POT by horn current 250 kA→320 kA
- Far detector (SK) analysis improvement:
  - Enlarge fiducial volume, etc

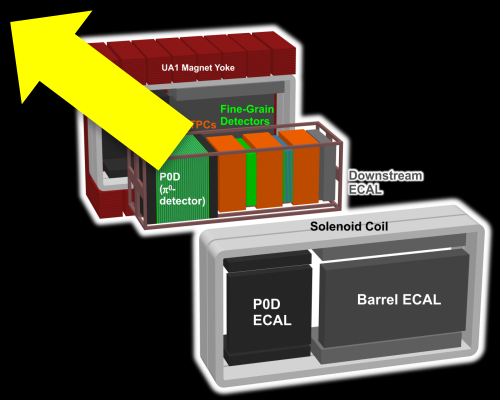
→Aiming ×1.5 signal/POT

- 356.3 $\nu_\mu \rightarrow \nu_e$ sig. expected in ν-beam
- 73.6 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal expected in $\bar{\nu}$-beam (ν-beam:$\bar{\nu}$-beam=50:50, NH, δ_{CP}=0 is assumed)

- Near detector upgrade
  - Covering more phase space, etc
  - LOI was submitted to CERN SPSC.

→ Aiming to improve syst. error: ~6% → ~4%





New collaborators are very welcome!

Summary

- Latest T2K results on neutrino oscillation by adding new event sample (ν_e CC1π) is reported.
  - CP conservation hypothesis ($\sin\delta_{CP} = 0$) is disfavored with 90% CL.
  - Neutrino oscillation via mixing angle θ_{23} is consistent with Max. oscillation ($\sin^2\theta_{23}=0.5$).
- T2K propose to collect 2×10^{22} POT with aim to search for CPV with 3σ sensitivity.
  - Scientific merit is recognized by J-PARC PAC (stage-1 status)
  - Near detector upgrade has been started.
  - Effort to beam-power improvement is also on-going.
    New collaborators are very welcome!

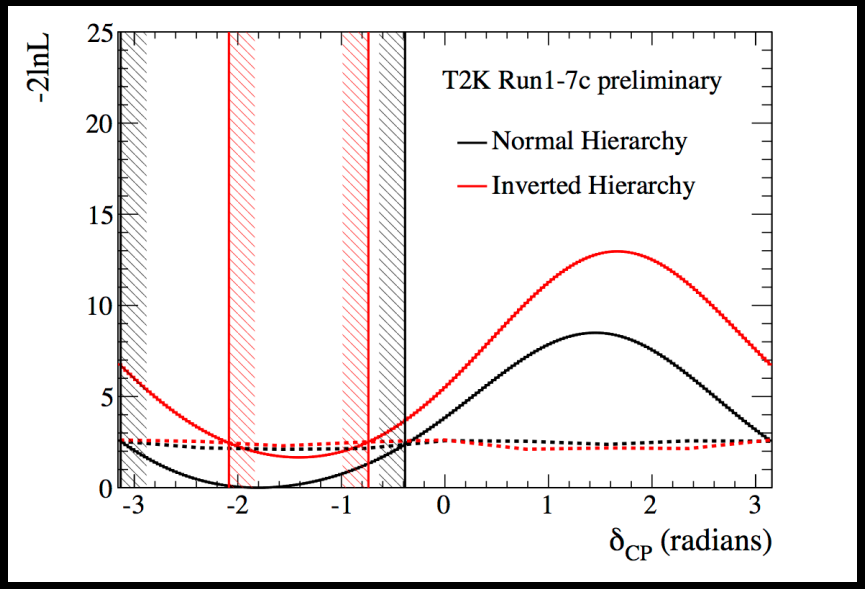
Backup

Systematic uncertainty of expected # events at SK

Source of Uncertainties			SK event sample: $\Delta N_{SK}/N_{SK}$ (1σ error)				
			ν-beam			$\bar{\nu}$-beam	
			1-ring μ-like	1-ring e-like	CC-1π^+ e-like	1-ring μ-like	1-ring e-like
SK: Detector + Final State Int. + 2ndary int.			4.2%	3.5%	14.0%	11.1%	4.0%
Beam + Near detectors	Neutrino Beam flux		3.6%	3.7%	3.6%	3.8%	3.8%
	ν-interaction cross-section	*MEC (corr)*	*3.5%*	*3.9%*	*0.5%*	*3.0%*	*3.0%*
		MEC bar (corr)	*0.2%*	*0.1%*	*0.0%*	*1.8%*	*2.3%*
		NC 1γ (uncorr)	*0.0%*	*1.5%*	*0.4%*	*0.0%*	*3.0%*
		$\sigma(\nu_e)$ / $\sigma(\nu_\mu)$	*0.0%*	*2.6%*	*2.4%*	*0.0%*	*1.5%*
		(Cross-section: sub total)	4.0%	5.1%	4.8%	4.2%	5.5%
	(Flux + Cross-section Sub total)		2.9%	4.2%	5.0%	3.5%	4.7%
Oscillation parameters: $\sin^2\theta_{13}$, $\sin^2\theta_{12}$, Δm^2_{21}			0.0%	4.2%	3.8%	0.0%	4.0%
Total			5.1%	6.8%	15.3%	11.7%	7.4%

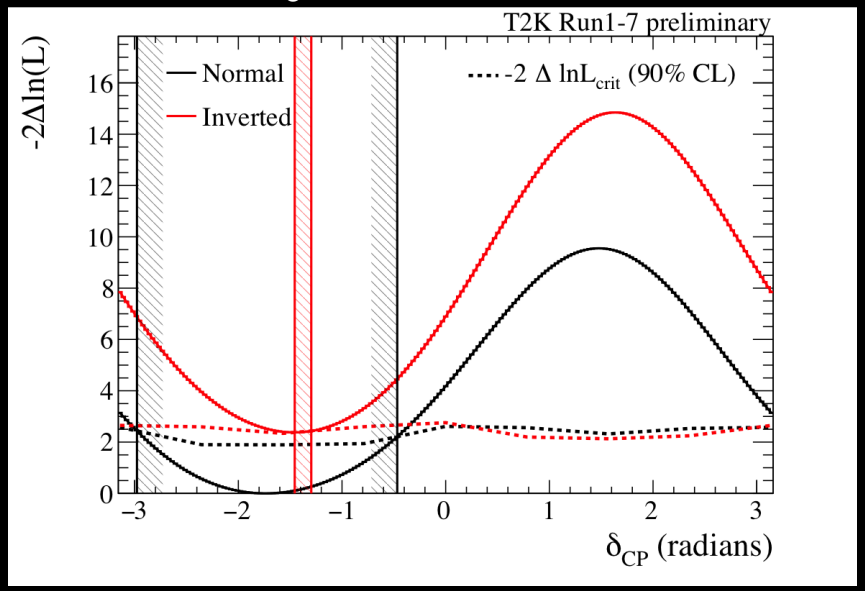
Improvement by SK ν_e CC-1π sample

Previous results, arXiv:1701.00432 (Accepted by PRL)



90%CL Confidence intervals
NH: -3.13 ~ -0.39
IH: -2.09 ~ -0.74

With SK ν_e CC-1π e sample



90%CL Confidence intervals
NH: -2.98 ~ -0.47
IH: -1.47 ~ -1.27

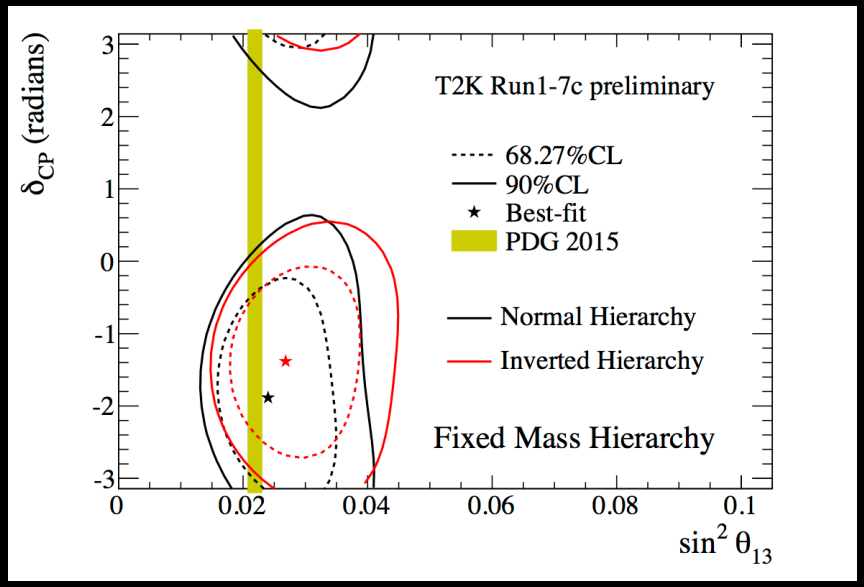
Bayesian analysis :Posterior probability for different mass hierarchies and octants.

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
IH ($\Delta m^2_{32} < 0$)	0.116	0.254	0.370
NH ($\Delta m^2_{32} > 0$)	0.210	0.420	0.630
Sum	0.326	0.674	1

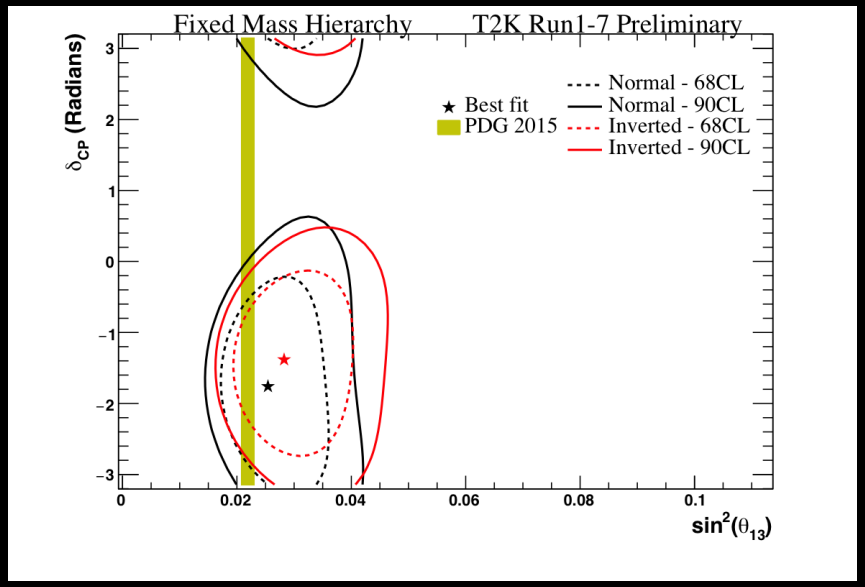
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line Total
Inverted Hierarchy	0.055	0.150	0.205
Normal Hierarchy	0.232	0.563	0.795
Column Total	0.287	0.713	1

Improvement by SK ν_e CC-1π sample

Previous results, arXiv:1701.00432 (Accepted by PRL)

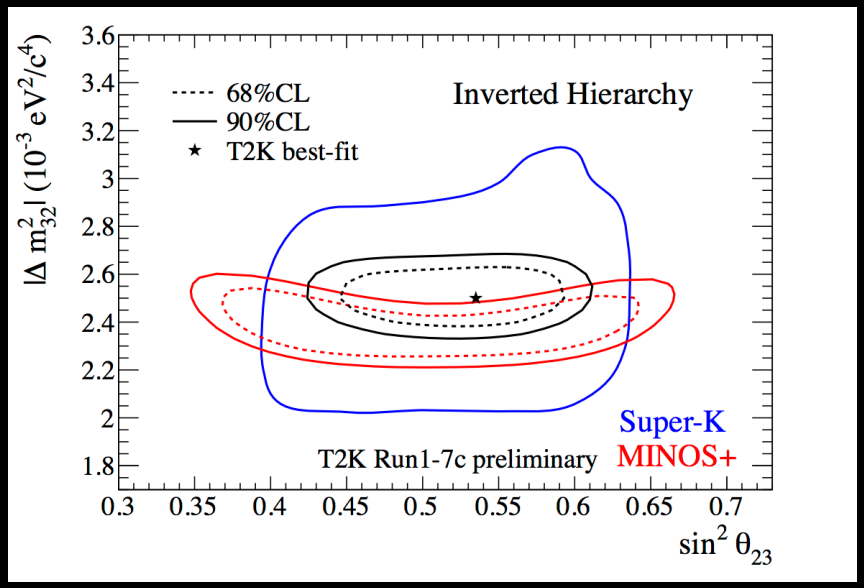


With SK ν_e CC-1π e sample

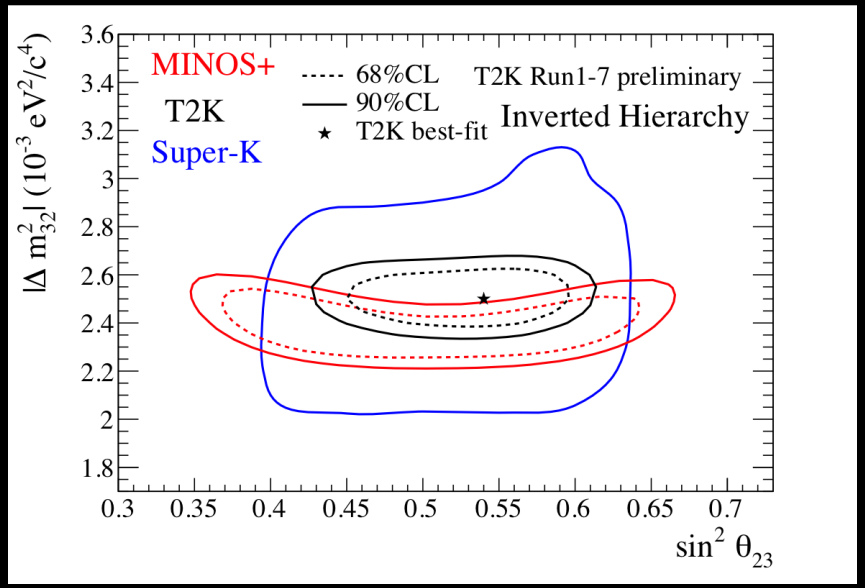


Improvement by SK ν_e CC-1π sample

Previous results, arXiv:1701.00432 (Accepted by PRL)

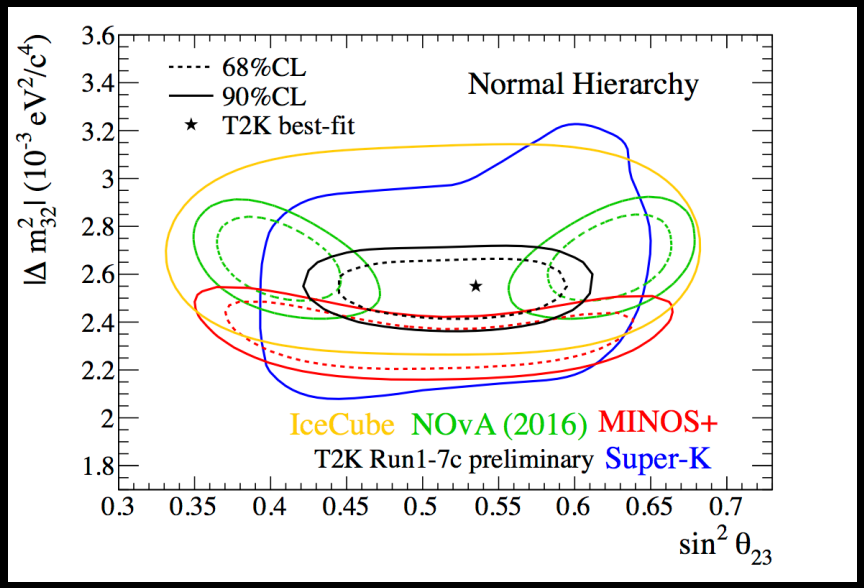


With SK ν_e CC-1π e sample

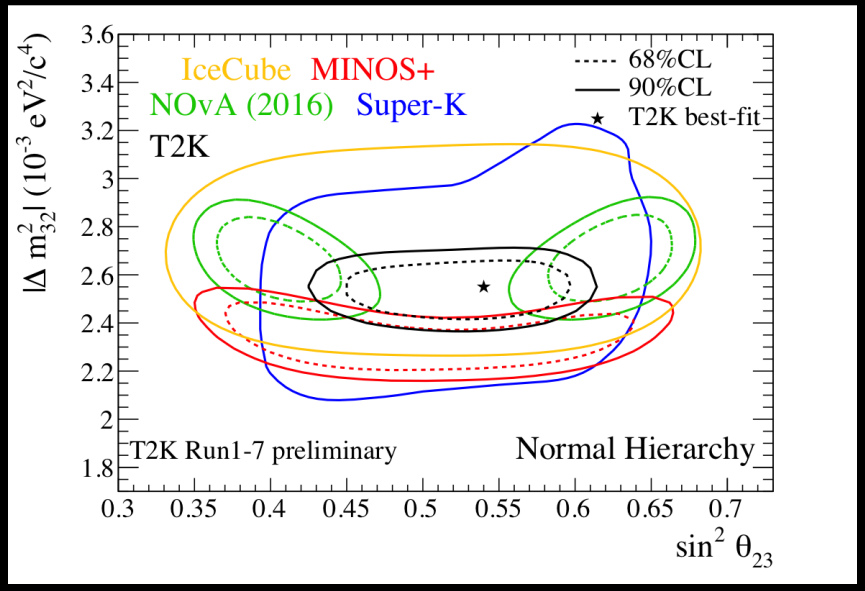


Improvement by SK ν_e CC-1π sample

Previous results, arXiv:1701.00432 (Accepted by PRL)



With SK ν_e CC-1π e sample



Near detector upgrade project

- CERN-SPSC-2017-002 ; SPSC-EOI-015 "Near Detectors based on gas TPCs for neutrino long baseline experiments"
  - T2K plans to establish the detector design and prepare the Technical Design Report (TDR) by the end of 2017.

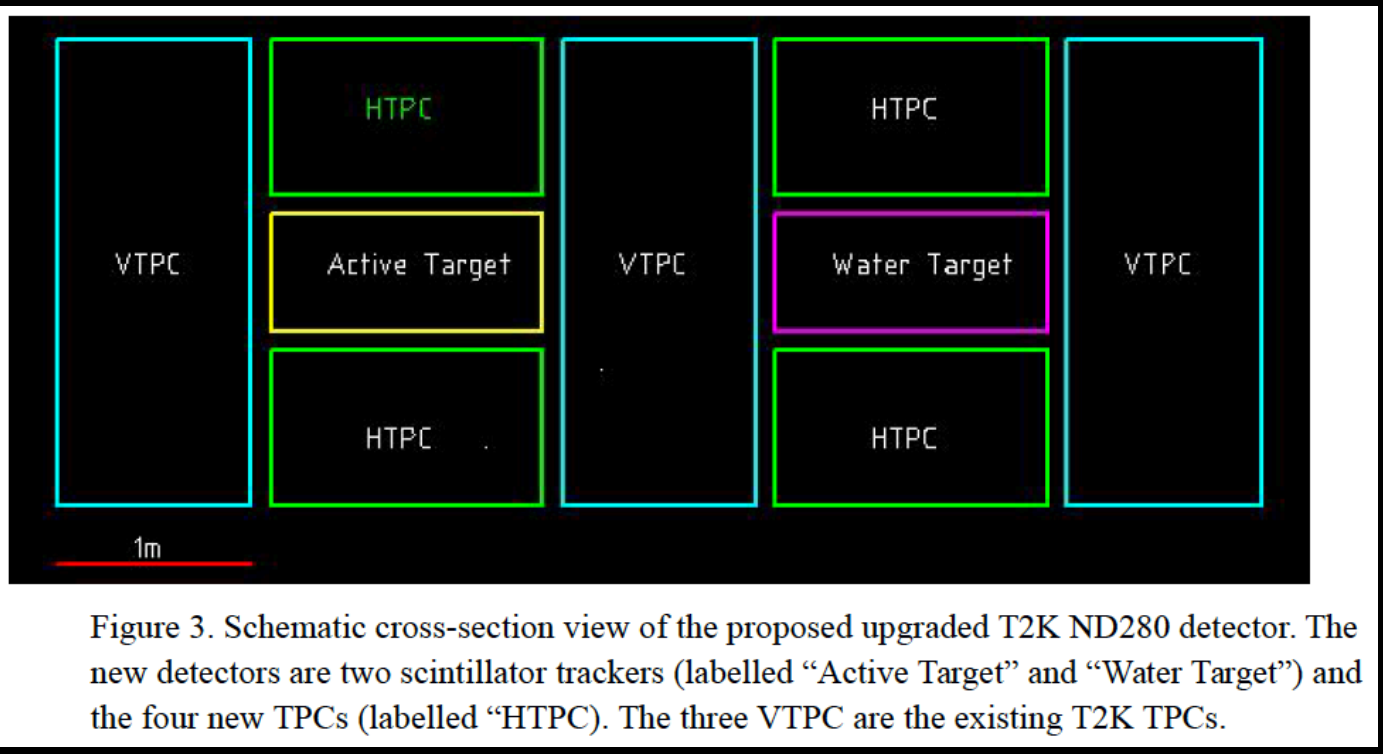


Figure 3. Schematic cross-section view of the proposed upgraded T2K ND280 detector. The new detectors are two scintillator trackers (labelled "Active Target" and "Water Target") and the four new TPCs (labelled "HTPC). The three VTPC are the existing T2K TPCs.