Latest T2K results and status

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Neutrino physics

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

- Neutrino flavor eigenstates are not identical to mass eigenstates, consequence ν oscillations and non zero ν masses
- Is CP conserved or violated?
- What is the ν mass ordering?
- Are there only 3 ν types?

θ_{23}=50.6+-1.7°

θ_{12}=33.6+-0.80°

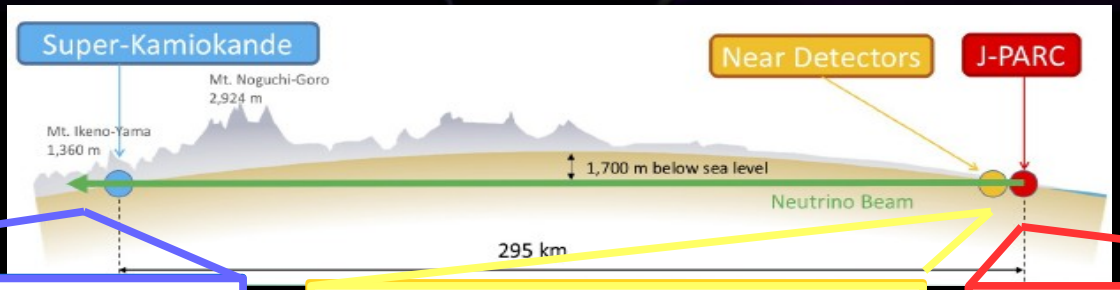
θ_{13}=8.37+-0.15°

Δm^2_{21}=7.53+-0.18 x 10^{-5}eV^2

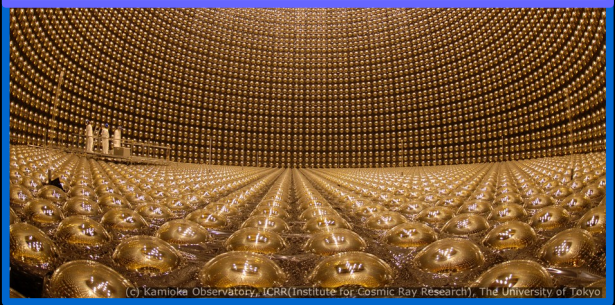
$|\Delta m^2_{32}|$=2.51+-0.05 x 10^{-3}eV^2

δ_{CP}=?

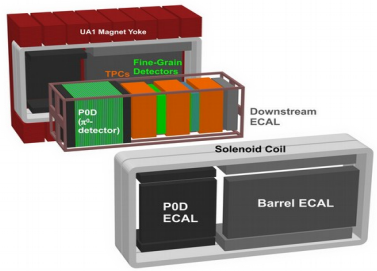
T2K experiment



Super-Kamiokande



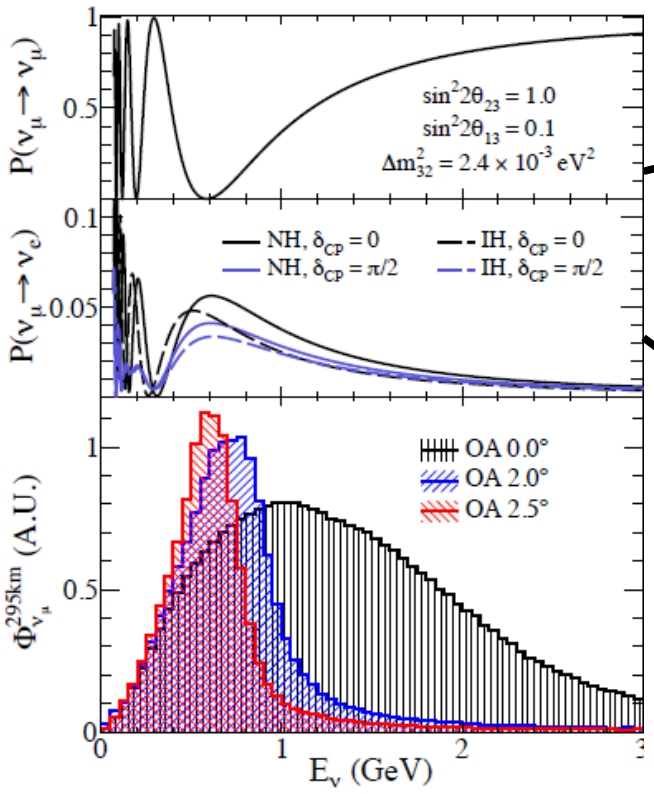
Near Detector ND280



J-PARC accelerator

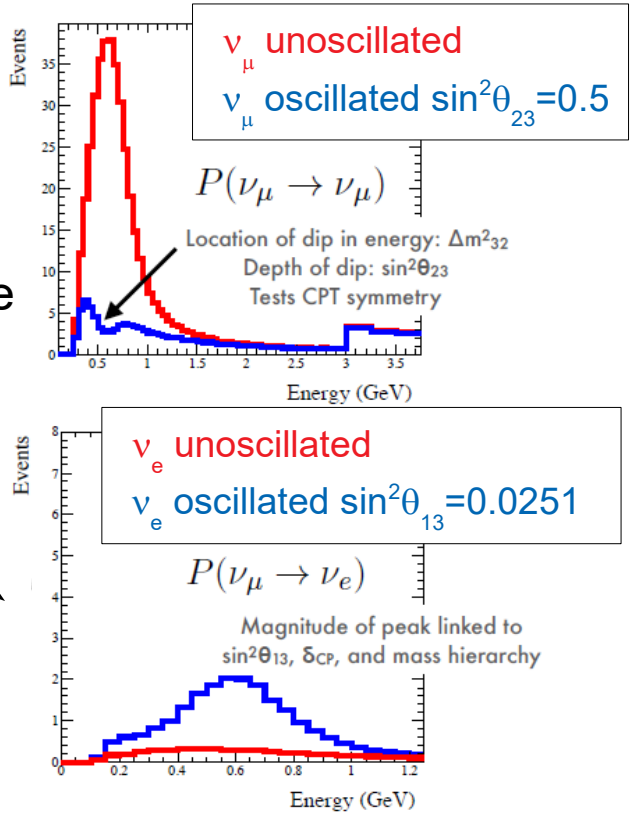
- 2.5° off-axis beam of ν_μ or $\bar{\nu}_\mu$ produced by J-PARC accelerator
- Near Detector located 280 m from ν source:
  - Constrains systematic errors for ν flux
  - Measures ν cross-sections
- Super-Kamiokande far detector located 295 km from J-PARC:
  - 50 kt water Cerenkov detector filled with ultra-pure water
  - Can distinguish ν_μ and ν_e interactions

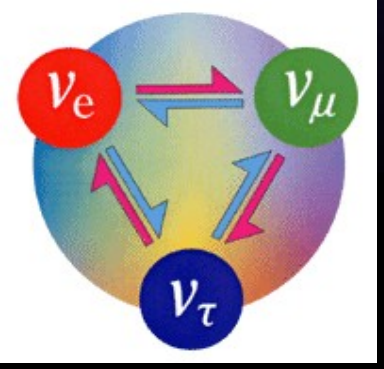
Principles of the T2K ν oscillations



ν_μ disappearance

ν_e appearance





What's new

- About 30% more $\bar{\nu}$ data

  $1.12 \times 10^{21} \rightarrow 1.63 \times 10^{21}$ POT

- Update reactor constraints to recent PDG2018 values:

  - Old PDG2016:

    $\sin^2\theta_{13} = 0.0219 +- 0.0012$

    $(\sin^2 2\theta_{13} = 0.086)$

  - New PDG2018:

    $\sin^2\theta_{13} = 0.0212 +- 0.008$

    $(\sin^2 2\theta_{13} = 0.083)$

Strategy of oscillation analysis

Predicted ν flux

Cross sections of ν interactions

Fit to near detector data

Near detector systematic uncertainties

Prediction for far detector

Fit to far detector data
Extraction of oscillation parameters

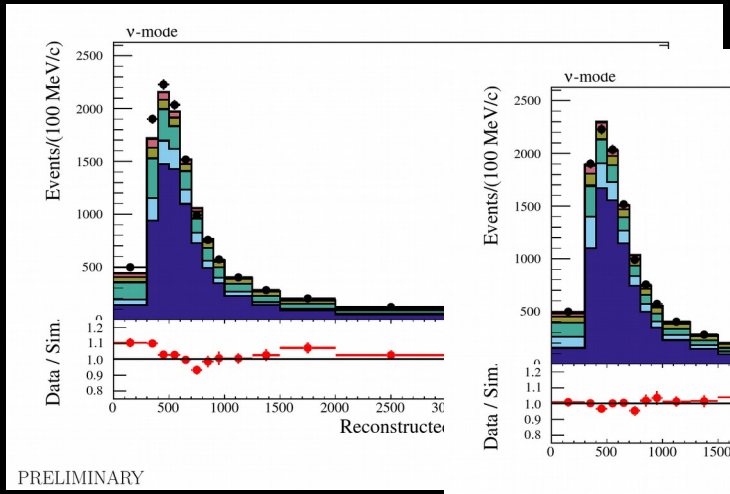
Far detector systematic uncertainties

Near Detector Measurement

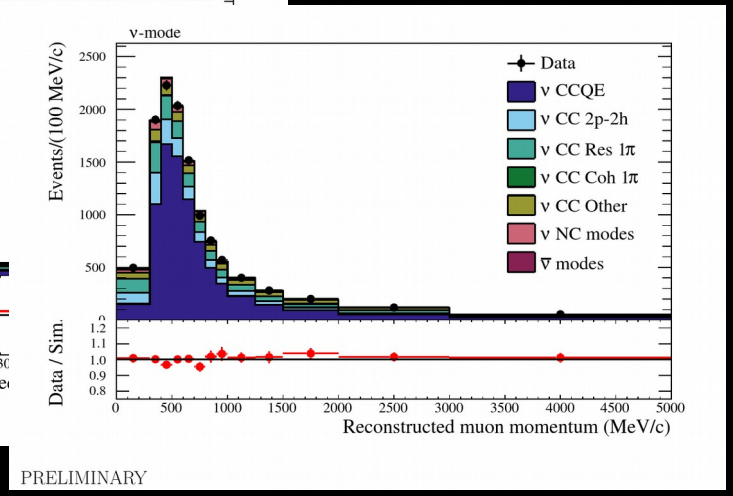
Fit to Near Detector data:

- ν data samples CC-0π, CC-1π, CC-Other
- $\bar{\nu}$ data sample CC-1Track, CC-Ntrack etc.
- Constrain flux and cross-section errors

Pre-fit CC-0π

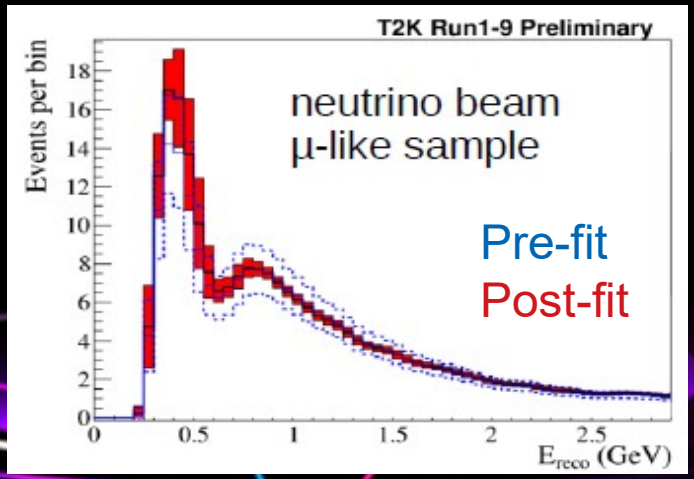


Post-fit CC-0π



Errors on SK event rate

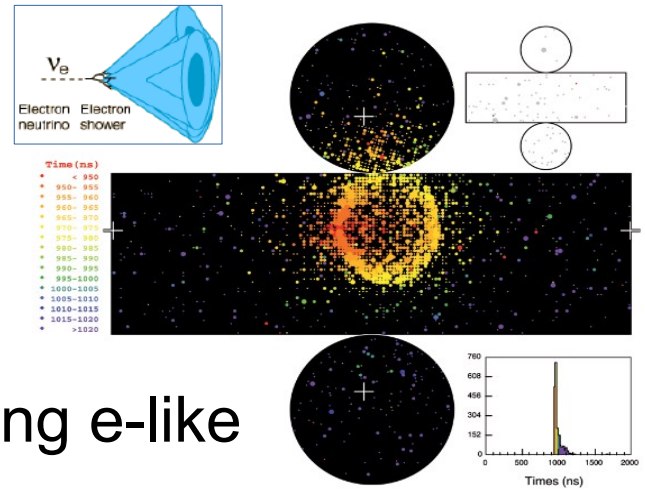
Sample	w/o ND280	W/ ND280
ν 1Rμ-like	14.6%	5.1%
ν 1Re-like	16.9%	8.8%
$\bar{\nu}$ 1Rμ-like	12.5%	4.5%
$\bar{\nu}$ 1Re-like	14.4%	7.1%



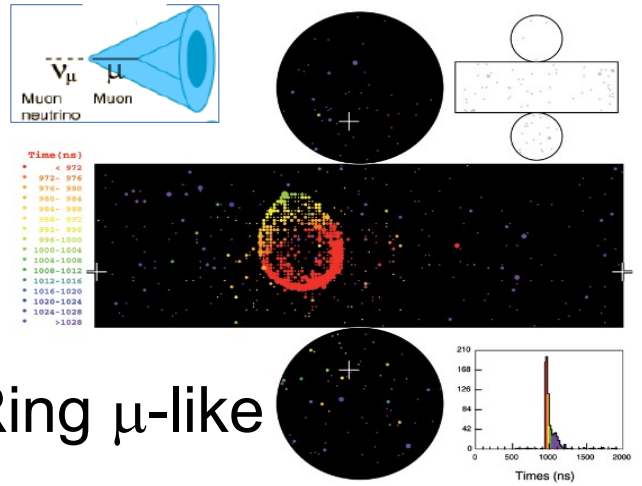
T2K data sample

Prediction with: $\sin^2\theta_{13}=0.0212$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.51\times10^{-3}\text{eV}^2$, NH

Sample	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Observed
ν 1Rμ-like	272.4	272.0	272.4	272.8	243
$\bar{\nu}$ 1Rμ-like	139.5	139.2	139.5	139.9	140
ν 1Re-like	74.4	62.2	50.6	62.7	75
$\bar{\nu}$ 1Re-like	17.1	19.4	21.7	19.3	15
ν 1Re decay e	7.0	6.1	4.9	5.9	15



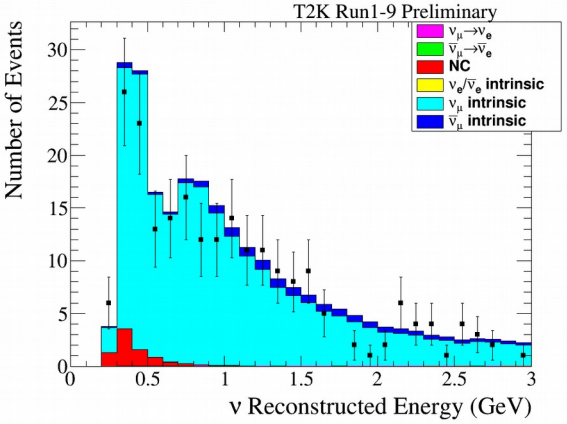
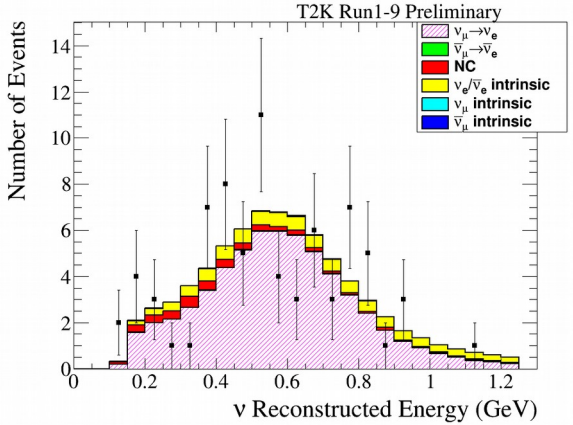
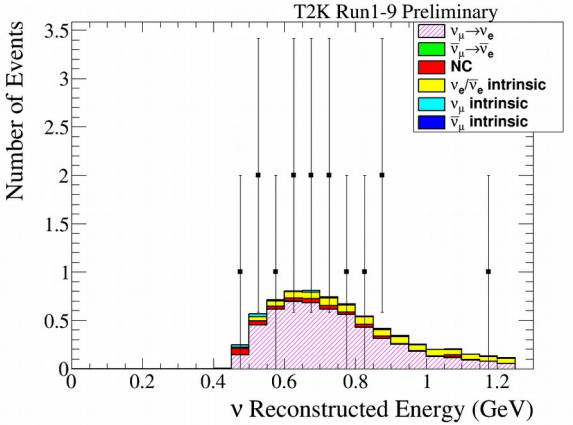
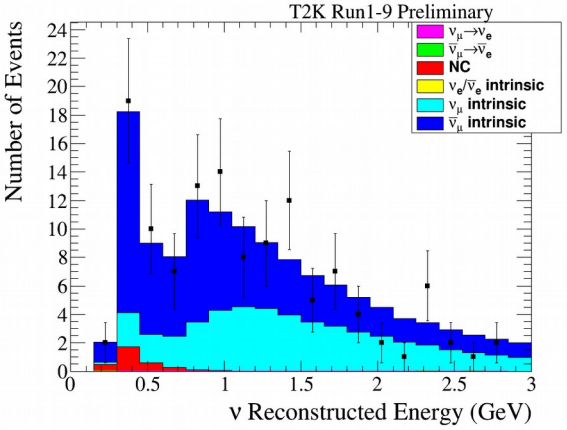
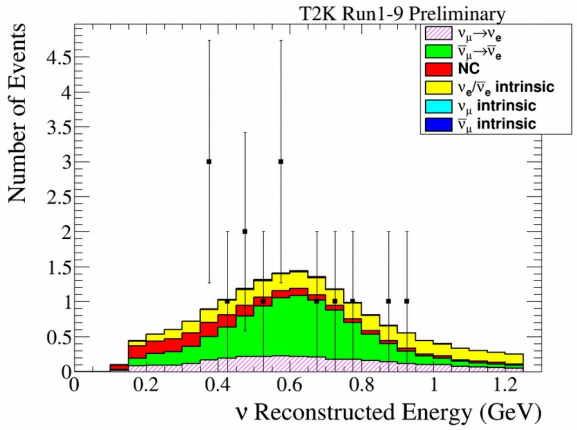
1Ring e-like



1Ring μ-like

T2K data sample

1.49×10^{21} ν + 1.63×10^{21} $\bar{\nu}$ POT

	1-ring CCQE μ-like	1-ring CCQE e-like	1-ring CC-1π e-like
ν			
$\bar{\nu}$			

Assuming:

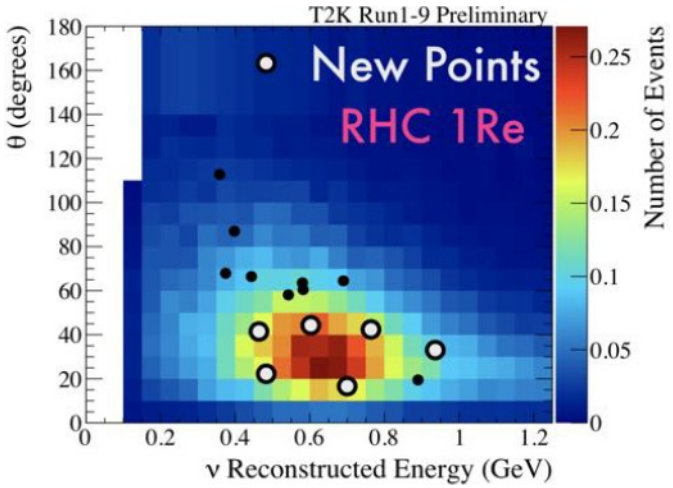
$\delta_{CP} = -\pi/2$

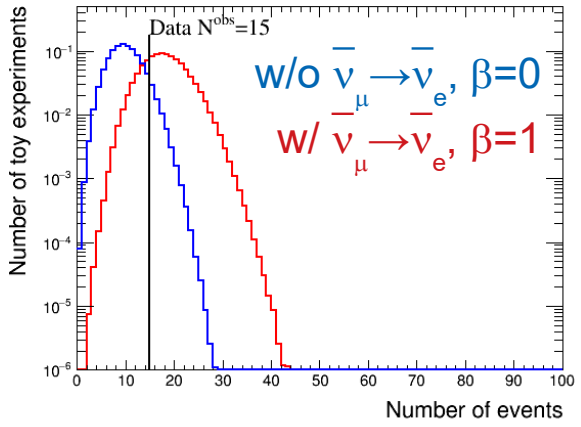
Normal Hierarchy

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

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

New T2K $\bar{\nu}_e$ appearance results



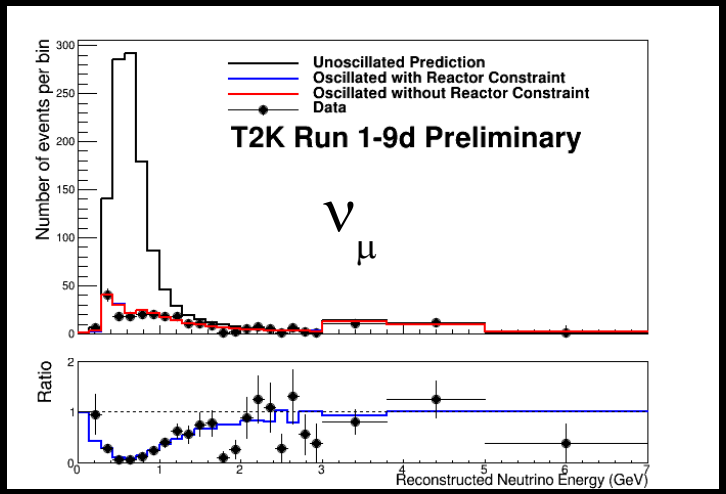


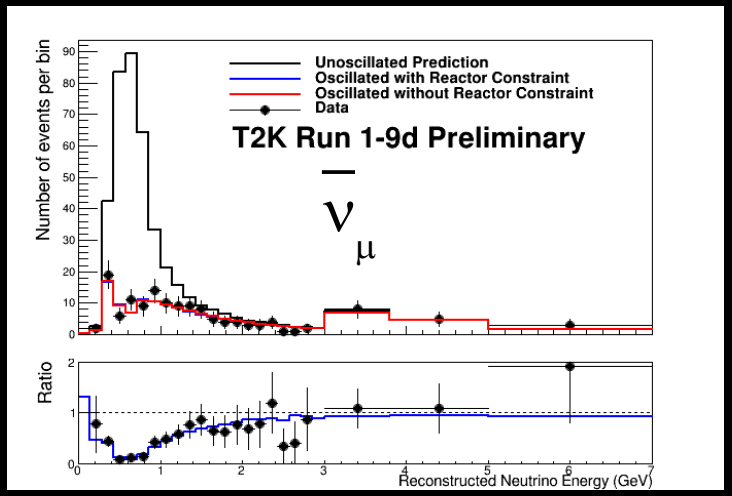
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{PNMS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Analysis	P-value β=0 (σ excluded)	P-value β=1 (σ excluded)
Rate only	0.0686 (1.82σ)	0.246 (1.16σ)
Rate+Shape	0.0224 (2.25σ)	0.261 (1.12σ)

- For Rate+Shape no oscillation hypothesis is excluded at 2.25σ
- More data are needed

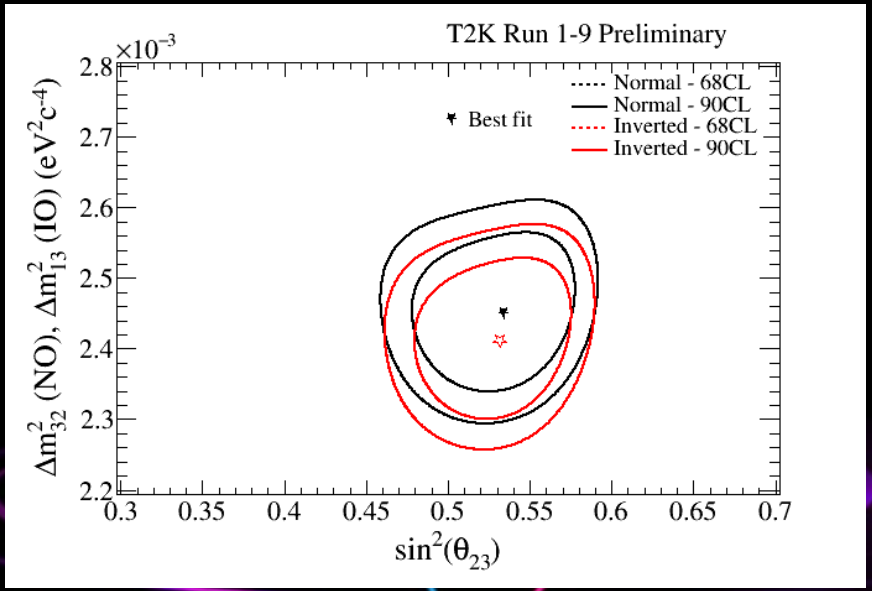
The ν_μ disappearance results





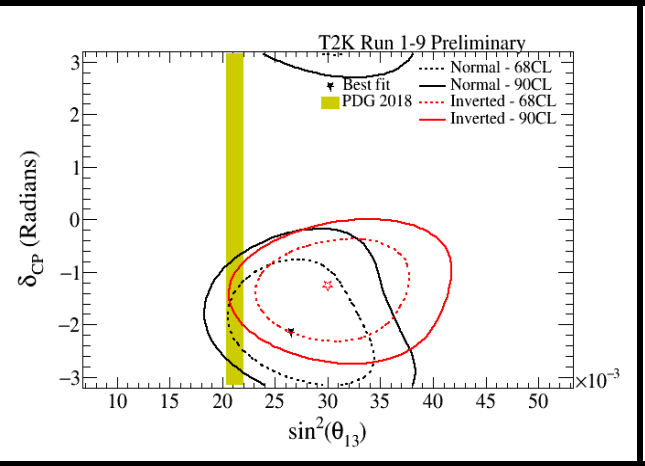
- The best fit point:
  $\sin^2\theta_{23} = 0.532$
  $\Delta m^2_{32} = 2.452 \times 10^{-3} eV^2$

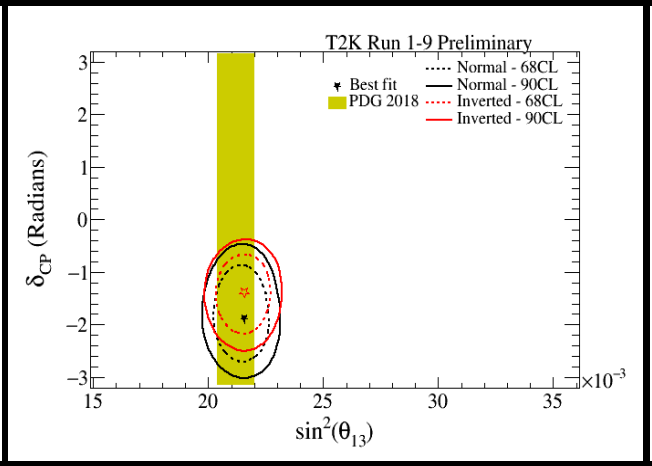
- T2K data are compatible with maximal mixing

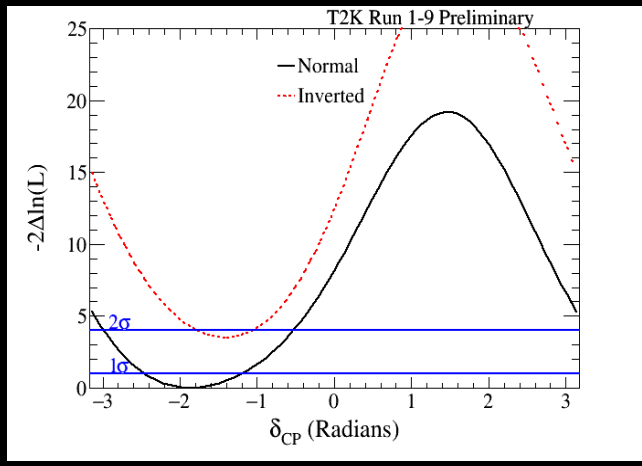


The T2K CP Violation Results

w/o reactor const. w/ reactor const.

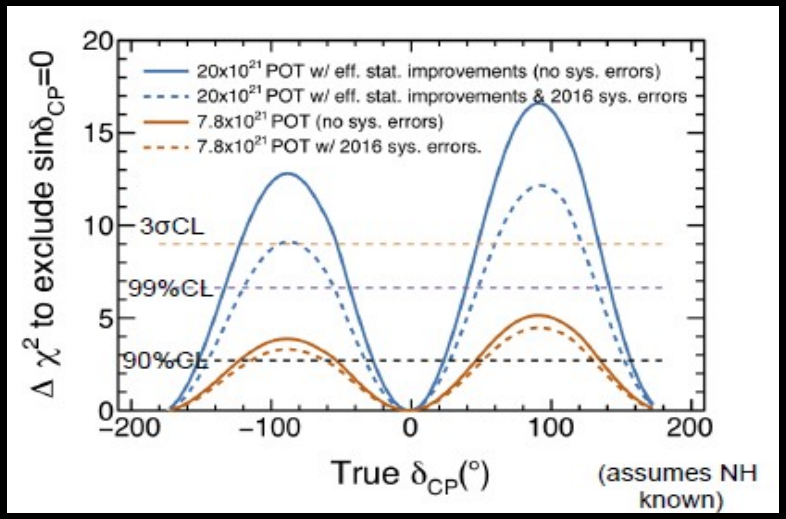


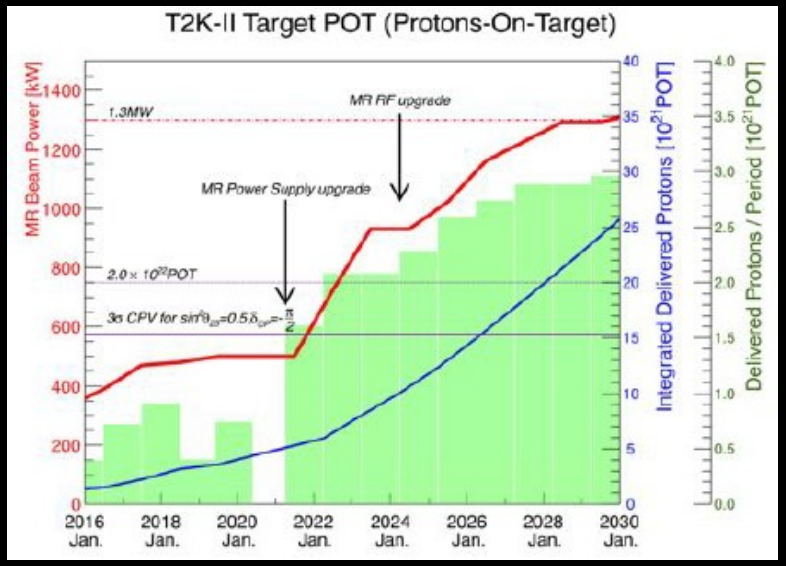




- Preferred value around δ_{CP}=-π/2 with the best fit point of δ_{CP}=-1.885
- δ_{CP} 2σ intervals:
  - Normal Hierarchy [-2.966, -0.628] radians
  - Inverted Hierarchy [-1.799, -0.979] radians
- CP conserving values (δ_{CP}=0 or π) disfavored at 2σ level
- Need more data to reach 3σ result

T2K future prospects

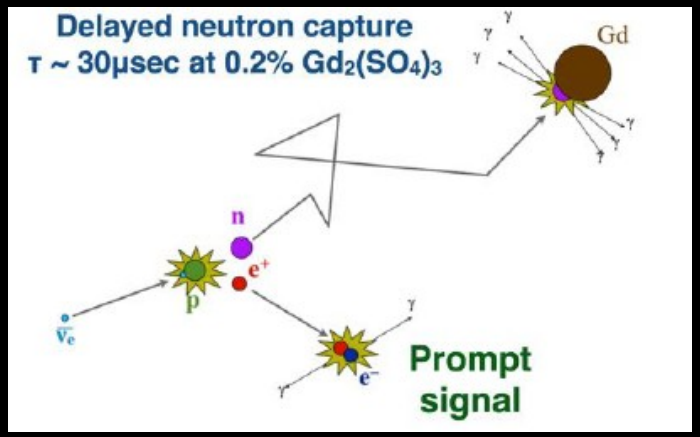




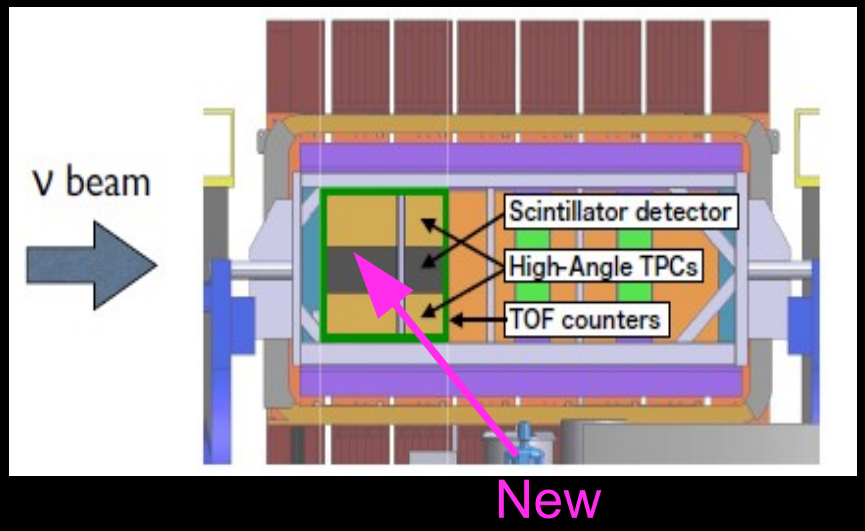
- T2K-II plans to collect 20 x 10^{21} POT by 2027~2028
- May reach 3σ sensitivity to δ_{CP}=0 by ~2026
- Beam line upgrade - expected beam power 1.3 MW
  - -reduce repetition rate 2.48 s→ 1.16 s
  - - more protons per pulse 2.4 → 3.2 x 10^{14}
  - - 320 kA horn current
- Super-K Gadolinium upgrade
- Near Detector upgrade

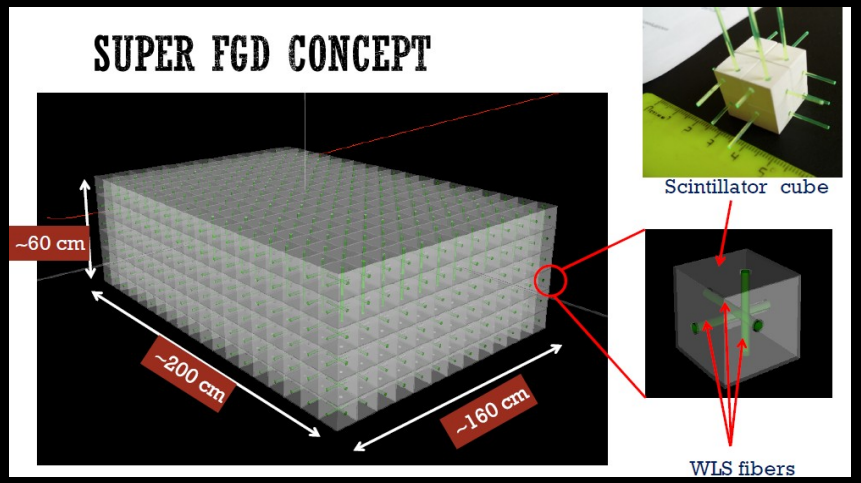
Super-K Gd upgrade

- Super-Kamiokande plans to load Gadolinium to the water tank,
  0.02% $Gd_2(SO_4)_3$ by 2019/2020
  0.2% later
- Gd can capture thermal neutrons providing delayed gamma signal, so it can tag $\bar{\nu}_e$
- May help $\nu/\bar{\nu}$ discrimination for T2K analysis
- SK tank was drained and opened in summer 2018
- Repairs were done: cleaning, water sealing, tank piping, replacement of dead PMTs
- Tank filling begun in Oct 2018 now tank is almost full.



Near Detector upgrade





- New part composed of scintillator target – SuperFGD, 2 horizontal TPC and TOF detector
- Designed to reduce Near Detector systematic <4%
- Will provide:

  4π coverage for μ tracks, better short track recon. and good timing
- Beam test were performed at CERN during summer 2018
- Planned to be installed in 2021

Summary

- T2k has provided many interesting results
- The analysis of $\bar{\nu}_\mu$ data gives 2σ hint for $\bar{\nu}_e$ appearance
- The CP conserving values of $\delta_{CP} = 0$ and π lie outside of 2σ interval
- Need more data for precise measurements
- It has been proposed to extend T2K run
- Upgrades of various parts of the experiment are underway

Backup slides

Probability of $\bar{\nu}_e$ appearance versus ν_e appearance