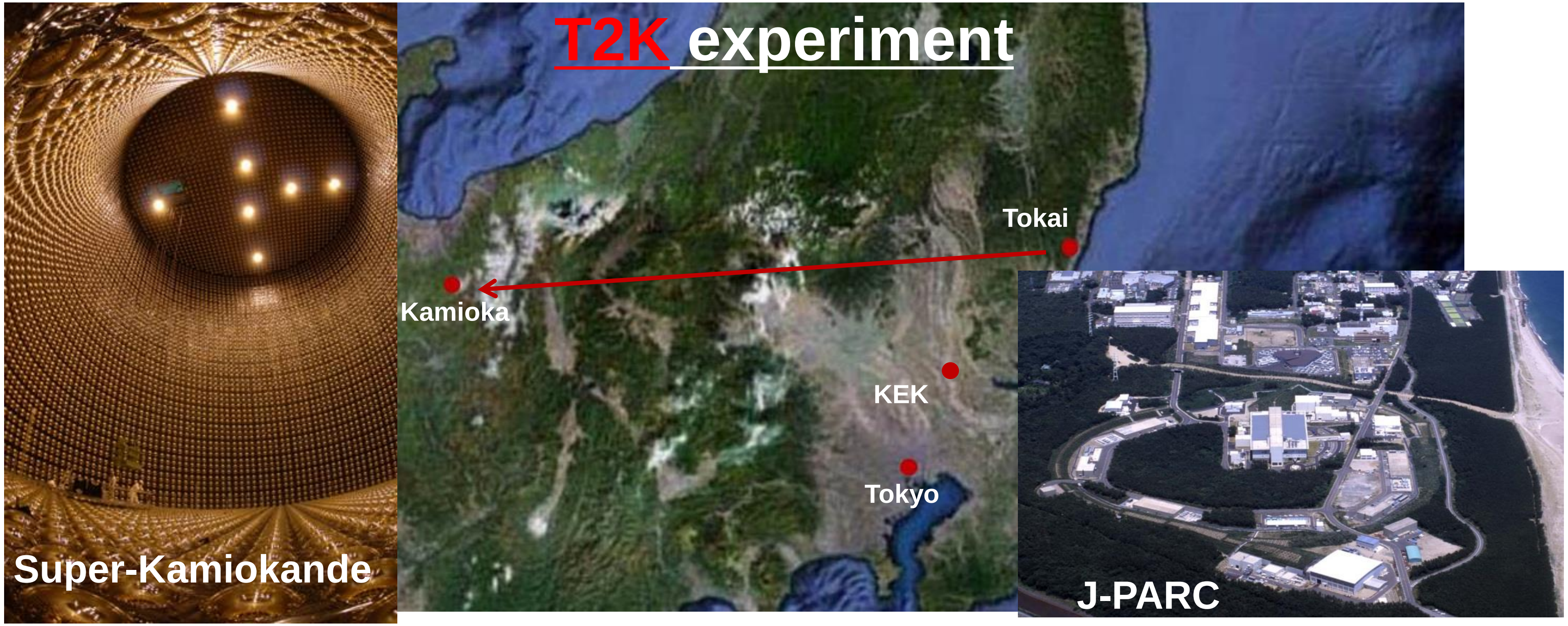
Search for CP violation in Neutrino and Antineutrino Oscillations by the T2K experiment with 2.2×10^{21} protons on target

arXiv:1807.07891v3

JC82 , 10/26/2018

T2K experiment (a few slide I found via web)

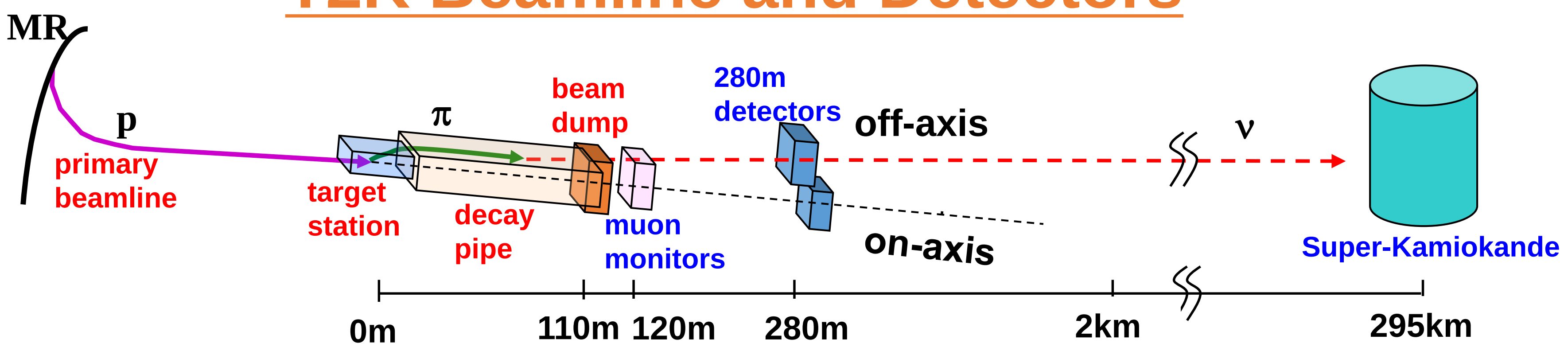
T2K experiment



- **Second generation long-baseline neutrino-oscillation experiment; from Tokai to Kamioka**
- **High intensity almost pure ν_μ beam from Main Ring in J-PARC is shot toward the Super-Kamiokande detector 295km away.**
- **Nominal beam intensity is much larger than K2K.**
- **The physics data-taking started in Jan. 2010, and stopped in March 2011 by the earthquake.**

From Yuichi Oyama (KEK)

T2K Beamline and Detectors



Beamline

- Primary beamline
- Target Station
- Decay pipe
- Beam dump @ ~110m downstream

Off axis beam
The center of the beam direction is adjusted to be 2.5^o off from the SK direction.

Detectors

- Muon monitors @ ~120m downstream
- Near detector@ ~280m downstream, called ND280.
- Far detector@ 295km downstream (Super-Kamiokande)

From Yuichi Oyama (KEK)

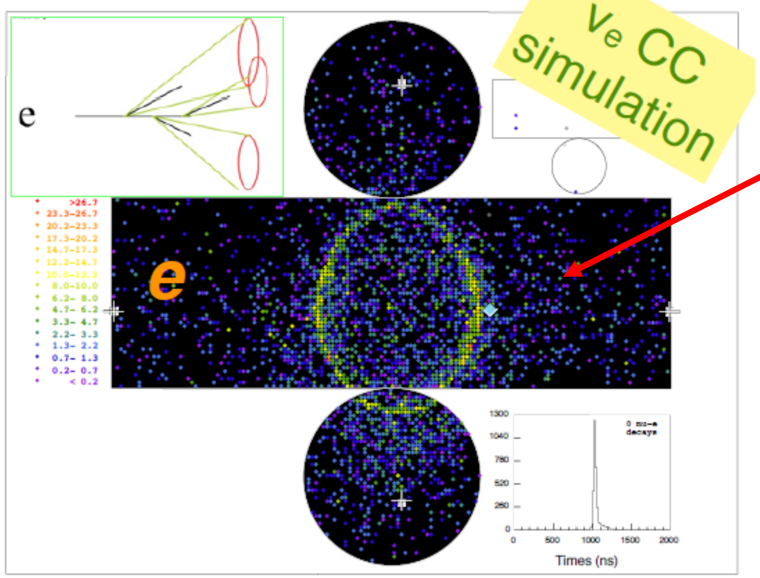
Water Cherenkov technique

- For νe appearance in T2K (J-PARC beam)
  - νe signal efficiency ~60%
  - BG ν_μ+antiν_μCC<0.1%, NCπ^0~1%

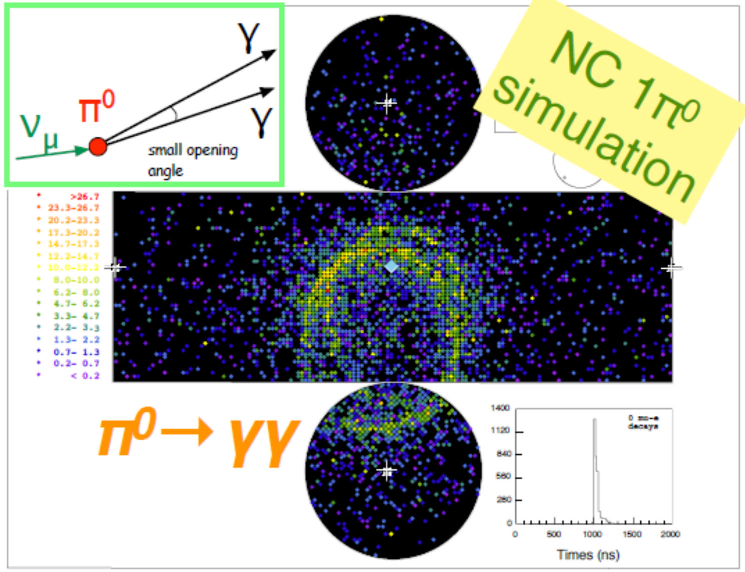
  (0.1<E^{rec}_ν<1.25GeV, can be optimized in future)

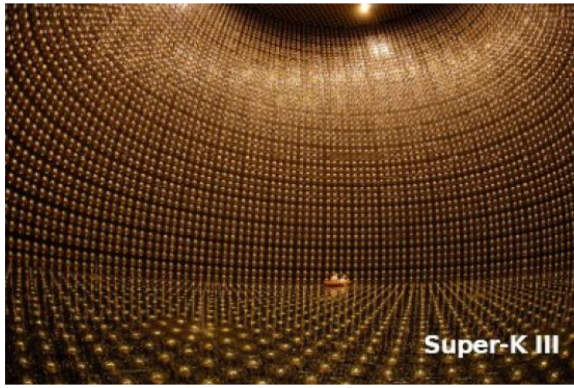
- Excellent particle ID capability > 99%
- Energy resolution for e and μ ~3%
- Energy threshold ~5MeV
  - Supernova ν, solar ν...
- Stable operation
  - energy scale stability ~1%
  - livetime for physics analyses > 90%

Excellent detector performance
&
Scalablity



Analyze this ring image





From Prof. Shiozawa

Neutrino Oscillation

Eigenstates of the flavor (e, μ, τ) and the eigenstates of the mass (1, 2, 3) is different

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

if $\delta_{CP} = 0$ or π, there is no CP violation,
otherwise, CP violation happens at neutrino sector

My consideration : we could push the dCP term at the other matrix, but it is combined with the s_{13} , which represents the mixing of e-neutrino with the τ-neutrino, for the ease of the (12) or (23) calculation.

From the paper

Data set. — The results presented here are based on data collected from Jan 2010 to May 2017. The data sets include a beam exposure of 14.7×10^{20} protons on target (POT) in neutrino mode and 7.6×10^{20} POT in antineutrino mode for the far-detector (SK) analysis, and an exposure of 5.8×10^{20} POT in neutrino mode and 3.9×10^{20} POT in antineutrino mode for the near-detector (ND280) analysis.

Event Category

- Analysis for the far detector

5 categories :

ν_μ

ν_e

$\nu_e + \pi$

$\overline{\nu_\mu}$

$\overline{\nu_e}$

TABLE I. Systematic uncertainty on far detector event yields.

Source [%]	ν_μ	ν_e	$\nu_e\pi^+$	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	2.4	7.8	4.1	1.7	4.8
Flux & ND280-constrained cross sec.	3.3	3.2	4.1	2.7	2.9
SK detector systematics	2.4	2.9	13.3	2.0	3.8
Hadronic re-interactions	2.2	3.0	11.5	2.0	2.3
Total	5.1	8.8	18.4	4.3	7.1

TABLE II. Number of events expected in the ν_e and $\bar{\nu}_e$ enriched samples for various values of δ_{CP} and both mass orderings compared to the observed numbers. The θ_{12} and Δm^2_{21} parameters are assumed to be at the values in the PDG. The other oscillation parameters have been set to: $\sin^2\theta_{23} = 0.528$, $\sin^2\theta_{13} = 0.0219$, $|\Delta m^2| = 2.509 \times 10^{-3}\mathrm{eV}^2\mathrm{c}^{-4}$.

	δ_{CP}	ν_e CCQE	ν_eCC $1\pi^+$	$\bar{\nu}_e$ CCQE
	$-\pi/2$	73.5	6.9	7.9
Normal	0	61.4	6.0	9.0
ordering	$\pi/2$	49.9	4.9	10.0
	π	61.9	5.8	8.9
	$-\pi/2$	64.9	6.2	8.5
Inverted	0	54.4	5.1	9.8
ordering	$\pi/2$	43.5	4.3	10.9
	π	54.0	5.3	9.7
Observed		74	15	7

Reconstructed neutrino energy

-- comparison between with/without the oscillation --

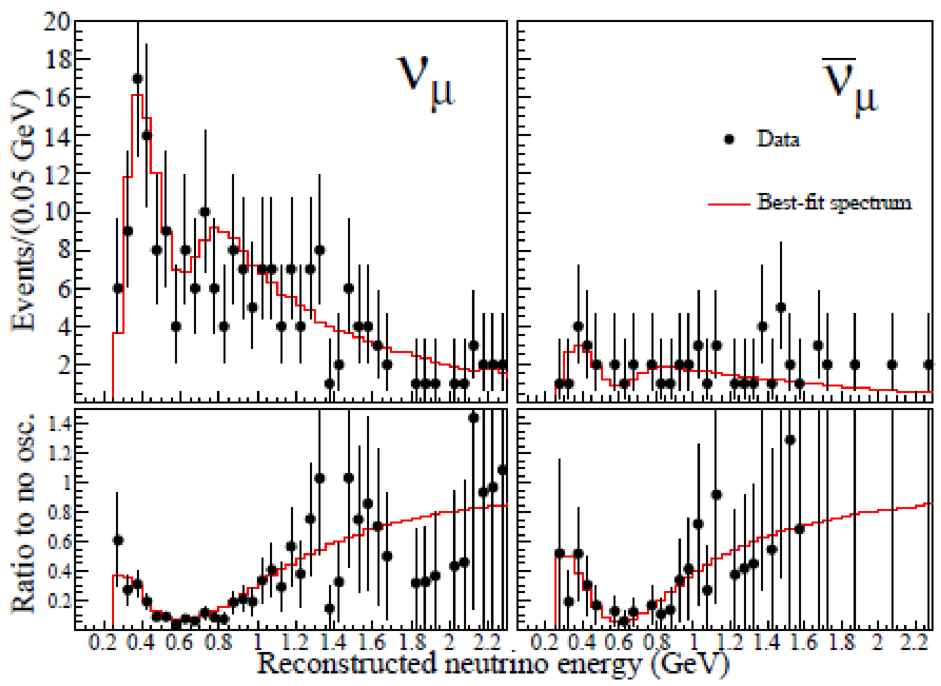


FIG. 2. Reconstructed neutrino energy distributions at the far detector for the ν_μ CCQE (left) and $\bar{\nu}_\mu$ CCQE (right) enriched samples with total predicted event rate shown in red. Ratios to the predictions under the no oscillation hypothesis are shown in the bottom figures.

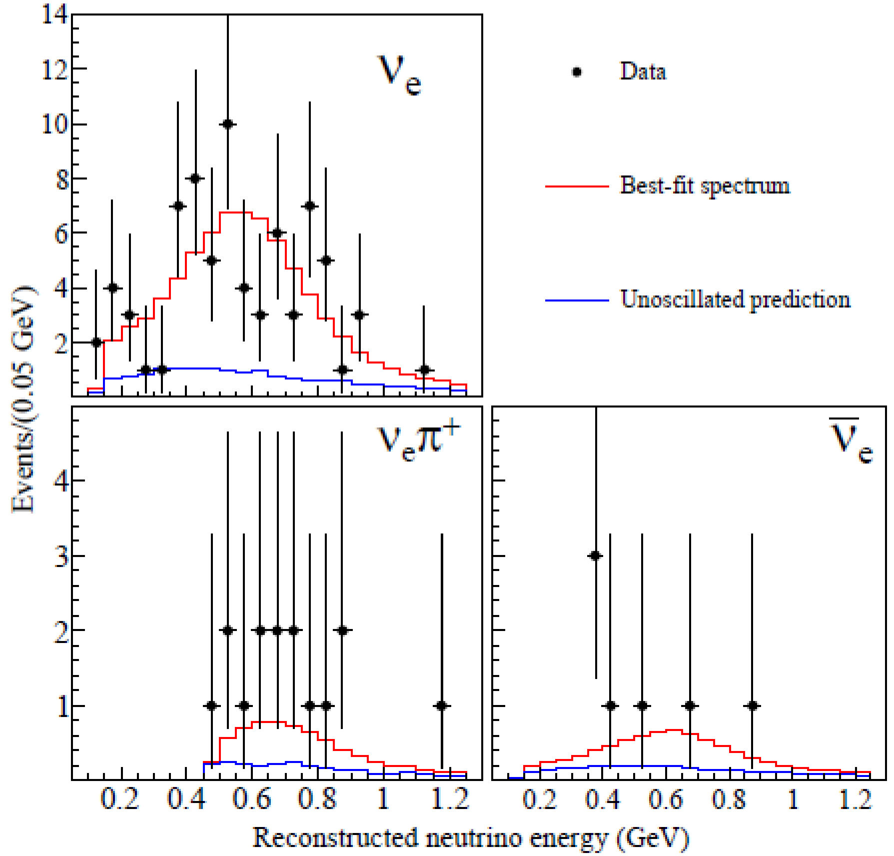


FIG. 3. Reconstructed neutrino energy distributions at the far detector for the ν_e CCQE (top left), ν_e CC1π^+ (bottom left) and $\bar{\nu}_e$ CCQE (bottom right) enriched samples. Predictions under the no oscillation hypothesis are shown in blue and best-fit spectra in red.

Results I.

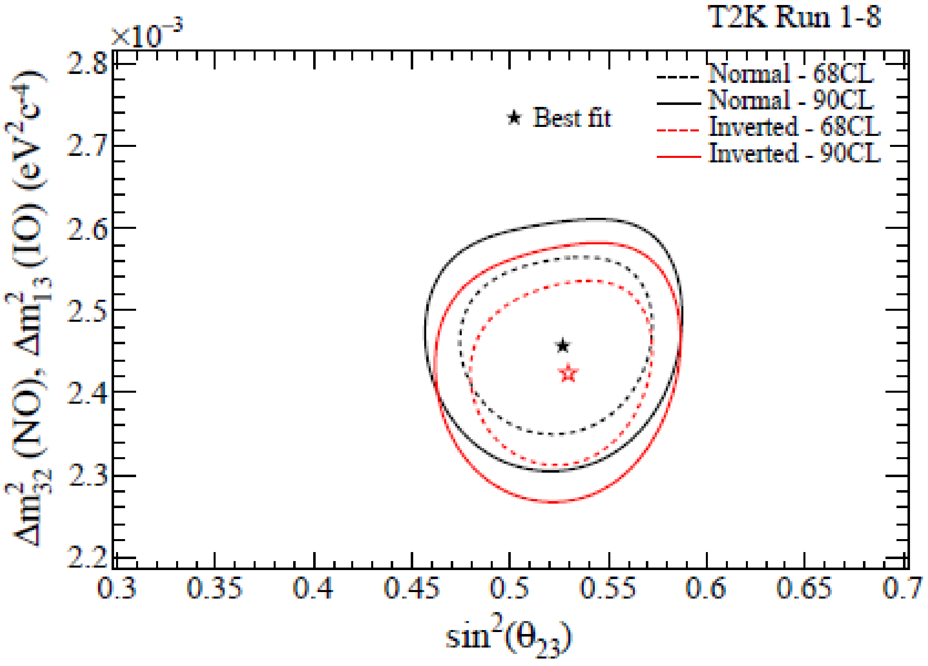


FIG. 4. The 68% (90%) constant $-2\Delta\ln\mathcal{L}$ confidence regions in the $|\Delta m^2|$-$\sin^2\theta_{23}$ plane for normal (black) and inverted (red) ordering using the reactor measurement prior on $\sin^2(2\theta_{13})$.

$\mathrm{Sin}\theta_{23}$ vs Δm_{23}

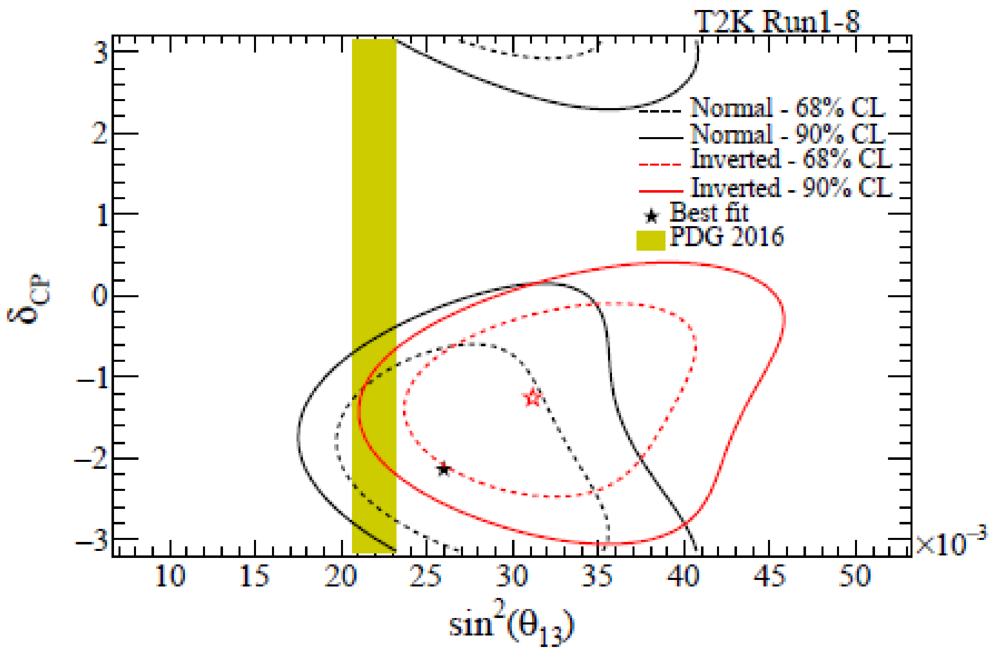


FIG. 5. The 68% (90%) constant $-2\Delta\ln\mathcal{L}$ confidence regions in the $\sin^2\theta_{13}$-δ_{CP} plane using a flat prior on $\sin^2(2\theta_{13})$, assuming normal (black) and inverted (red) mass ordering. The 68% confidence region from reactor experiments on $\sin^2\theta_{13}$ is shown by the yellow vertical band.

δ_{CP} vs $\mathrm{Sin}\theta_{13}$

Results II.

δ_{CP} range,
if the sin13 is fixed

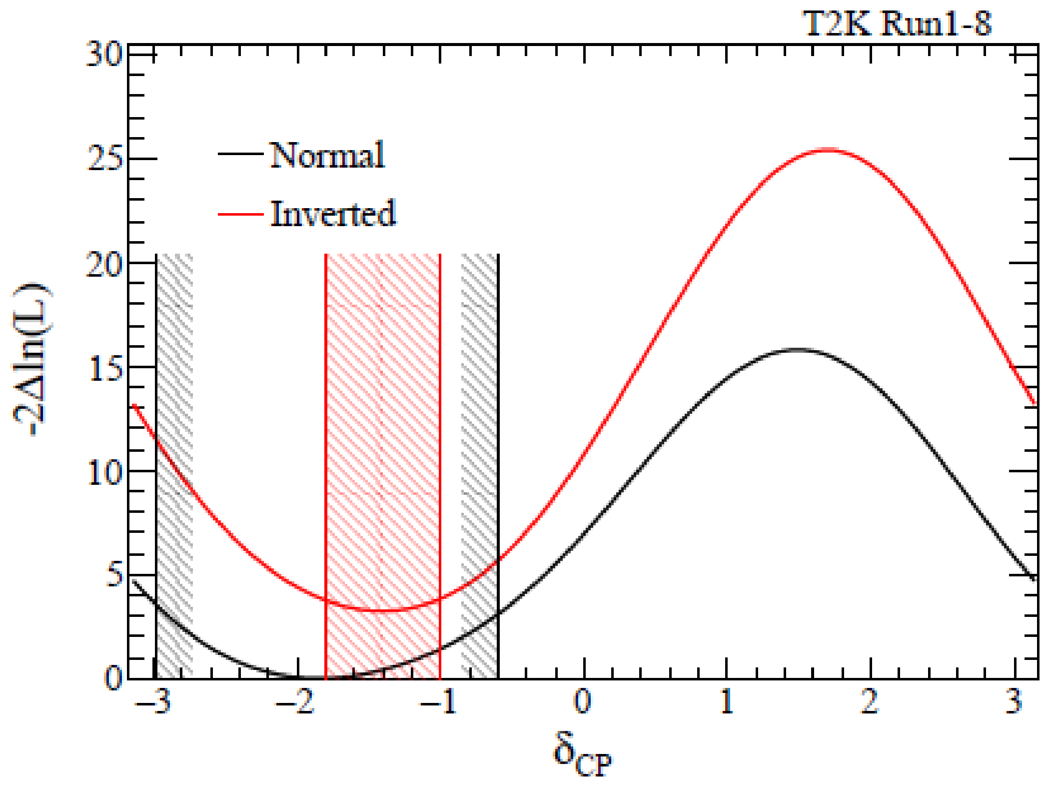


FIG. 6. 1D $-2\Delta\ln\mathcal{L}$ as a function of δ_{CP} for normal (black) and inverted (red) mass ordering using the reactor measurement prior on $\sin^2(2\theta_{13})$. The vertical lines show the corresponding allowed 2σ confidence intervals, calculated using the Feldman-Cousins method instead of the constant -2Δ $\ln\mathcal{L}$ method.

Conclusion

Conclusions. — T2K has constrained the leptonic CP violation phase (δ_{CP}), $\sin^2\theta_{23}$, Δm^2 and the posterior probability for the mass orderings with additional data and with an improved event selection efficiency. The 2σ (95.45%) confidence interval for δ_{CP} does not contain the CP-conserving values of $\delta_{CP} = 0, \pi$ for either of the mass orderings. The current result is predominantly limited by statistics. T2K will accumulate 2.5 times more data, thereby improving sensitivity for the relevant oscillation parameters. The data related to the measurement and results presented in this Letter can be found in [46].

For the questions

Question (from Yuzhen)

Why the author can get sin2(Θ**23**) and Δ(m32)2 from the observed number of e neutrino and anti-e neutrino?

A.

"Fits to determine either one or two of the oscillation parameters are performed, while the other parameters are marginalized"

m_{23} & $\sin\theta_{23}$ are the free parameters

$\sin\theta_{13}$ is fixed for this fitting, though I could clearly confirm that the δ_{CP} is fixed, (or less effect ?)

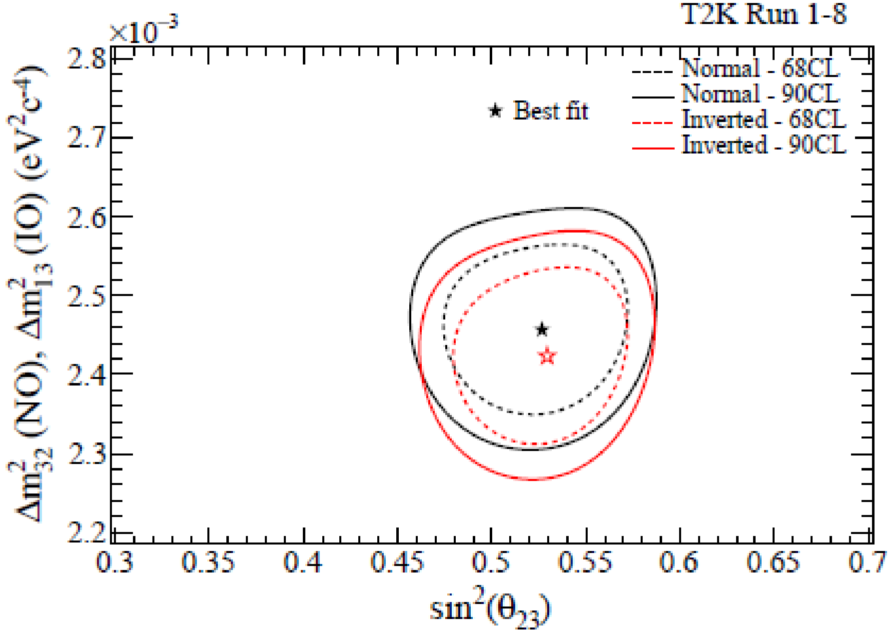


FIG. 4. The 68% (90%) constant $-2\Delta\ln\mathcal{L}$ confidence regions in the $|\Delta m^2|$-$\sin^2\theta_{23}$ plane for normal (black) and inverted (red) ordering using the reactor measurement prior on $\sin^2(2\theta_{13})$.

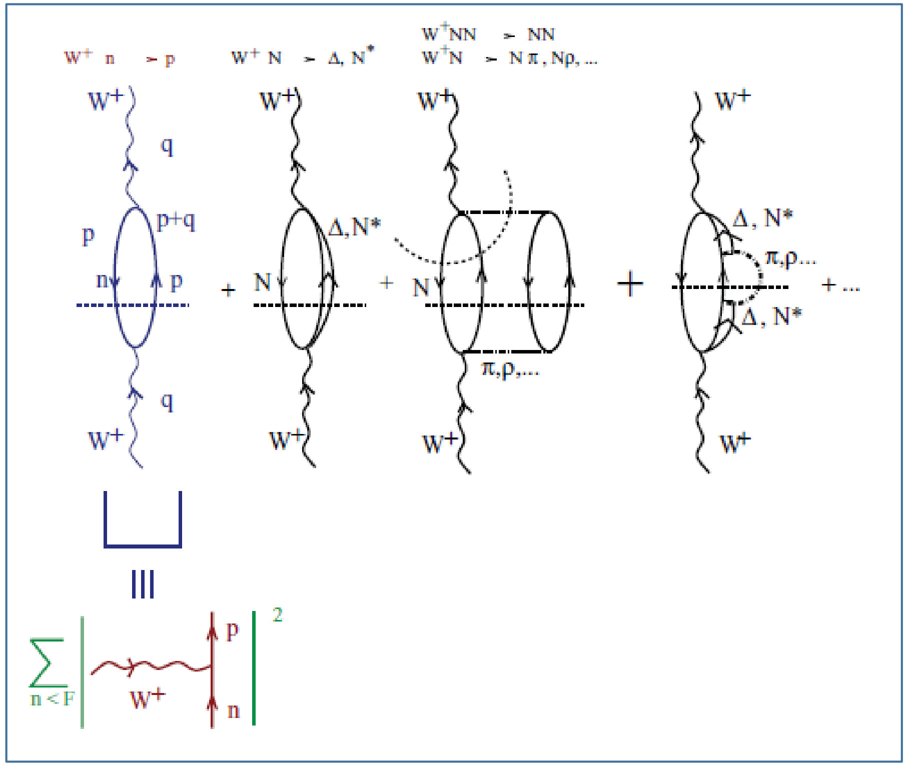
Question (from Shan)

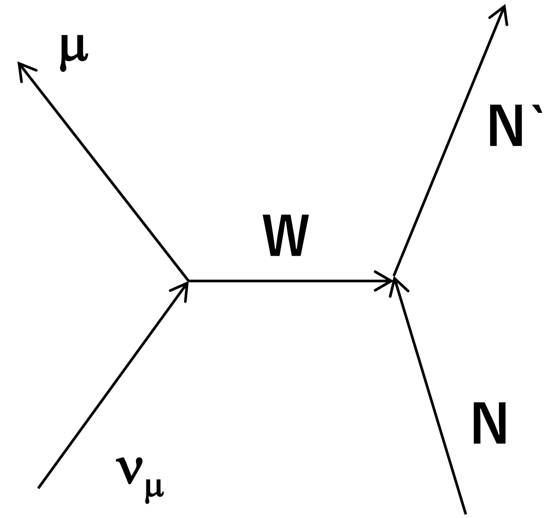
What's the "2p-2h" model, also the 1p-1h, Δ-like 2p-2h and non-Δ-like 2p-2h ？

A.

"2p-2h" model is the scattering of W boson with two nuclei.

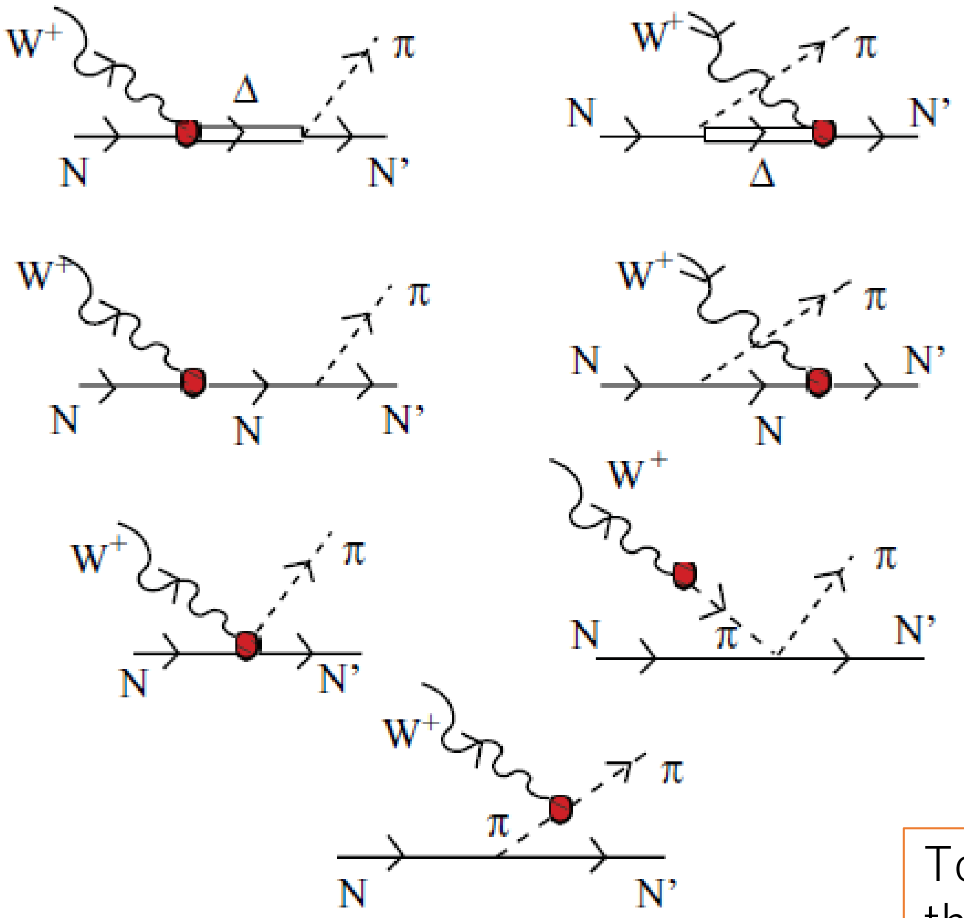
Model to consider the interaction of W boson with the nuclei in higher order.





"Normal" reaction

For those diagram, pion is emitted where the δ particle can intermediate those channel



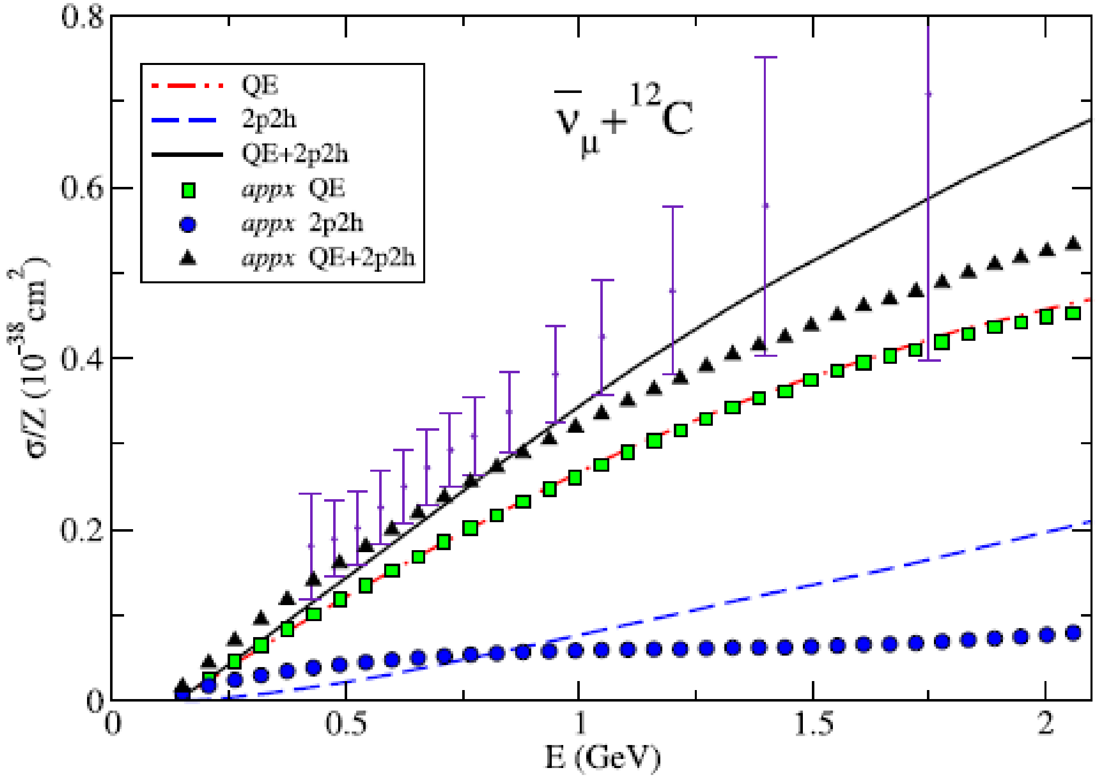


Fig. 1. Cross section contributions divided by the number of protons for $\bar{\nu} + {}^{12}C$ scattering as a function of the antineutrino energy. Curves labeled *appx* correspond to the approximated unfolded cross section for the MiniBooNE flux. Experimental points and flux from Ref. [29].

To explain experimental results of neutrino scattering, those small ? corrections are introduced within 20years.

J. Nieves et. al., PLB 721 (2013) 90-93

Question (from Amit)

What is the meaning for delta-Like and Non-Delta Like?

A.

cesses. These can be divided into meson exchange current (Δ-like) contributions, which include both diagrams with an intermediate Δ and contributions from pion in-flight and pion contact terms (see Ref. [17] for details), and contributions from interactions with correlated nucleonnucleon pairs (non-Δ-like), which introduce different biases in the reconstructed neutrino energy, E_{rec}, cal-

Difference is the model of those reactions . (though I do not cover them well)

Question (from Xin)

At the end of paper, it says:

"Sensitivity studies show that, if the true value of δCP is −π/2 and the mass ordering is normal, 22% of simulated experiments exclude δCP = 0 and π at 2σ C.L.".

How to extract the 22% value? And why use 2-sigma C.L. ?

A. This sentence is not clear for me, especially what parameters they changed in the simulation and/or they want to express that there exists systematic terms not well implemented ?

Page 4, they excuse that some of systematics from model parameters are not easy to be implemented well.

But I do not know it is related to that statement.

Some systematic uncertainties are not easily implemented by varying model parameters. These are the subjects of "simulated data" studies, where simulated data generated from a variant model is analyzed under the assumptions of the default model. Studies include varying E_b, replacing the RFG model with a local Fermi gas model [17] or a spectral function model [31], changing the 2p-2h model to an alternate one [32] or fixing the 2p-2h model to be fully "Δ-like" or "non-Δ-like", varying the axial nucleon form factor to allow more realistic high Q^2 uncertainties [33, 34], and using an alternative single pion production model described in [35]. Additional simulated data studies, based on an excess observed at low muon momentum ($p_\mu \leq 400$ MeV) and moderate angle ($0.6 \leq \cos\theta_\mu \leq 0.8$) in the near detector, quantified possible biases in neutrino energy reconstruction by modeling this as an additional *ad hoc* interaction under hypotheses that it had 1p-1h, Δ-like 2p-2h or non-Δ-like 2p-2h kinematics. Finally, a discrepancy in the pion kinematic spectrum observed at the near detector motivated a simulated data study to check the impact on the signal samples at SK.

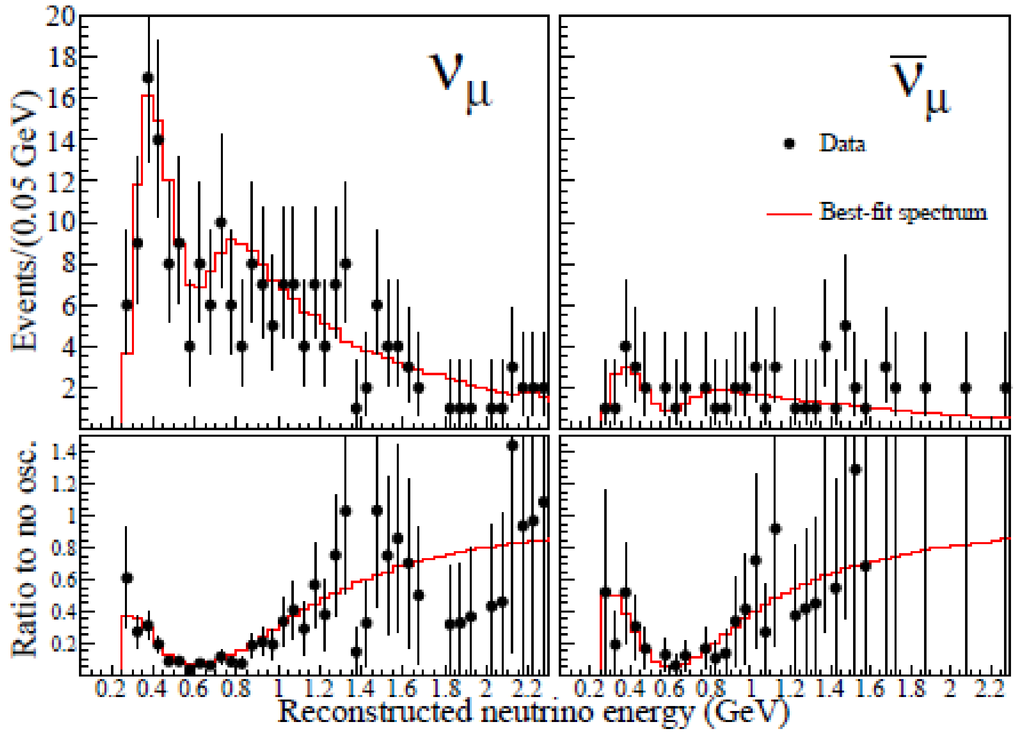
Question (from Yuhang)

In fig 2. Ratios to the predictions under the no oscillation hypothesis are shown in the bottom figures. How to understand the ratio?

A.

ν_μ/anti-ν_μ disappears due to the oscillation (ν_μ flavor is mainly changed to ν_τ)

The energy of ν_μ is about 600MeV, therefore, it would be rare to create τ from ν_τ .



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Question (from Kai)

Mass ordering is important parameter in CP violating phase determination, and in the paper, they indeed considered two assumptions on the mass orderings, normal ordering, inverted ordering.

But why they only report results of normal ordering in the abstract, do you know the reason?

A.

Actually, I do not know...

As pointed out, the derived values for both normal/inverted ordering are described in the contents/conclusion .