Measurement of the Leptonic CP Violation Phase With a New Parameterization Using T2K Neutrino Oscillation Data

X. Y. Zhao, on behalf of the T2K Collaboration

Eidgenössische Technische Hochschule Zürich (ETHZ), 8046 Zürich, Schweiz

1 The T2K experiment

The T2K experiment is a long baseline neutrino oscillation experiment in which a muon neutrino or anti-neutrino beam is directed over a 295 km baseline from the J-PARC facility to the Super-Kamiokande (SK) detector.
The configuration allows neutrino oscillation to be studied in two channels: disappearance of ν_μ ($\overline{\nu}_\mu$) and appearance of ν_e ($\overline{\nu}_e$).

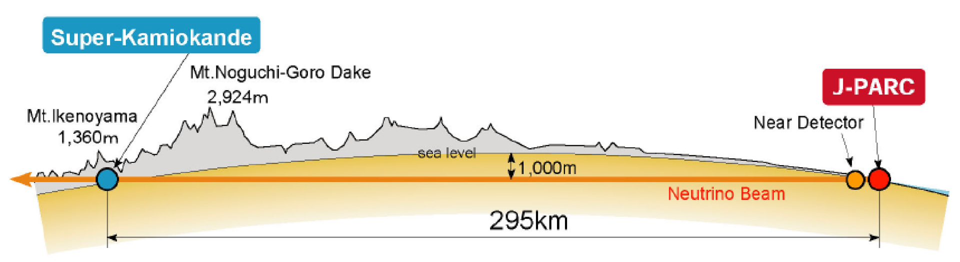

Figure 1: A schematic view of the T2K experiment.

The analysis includes 5 different types of events observed at SK: (1) CC1R_μ (single muon), (2) CC1R_e (single electron) and (3) CC1R_e1π^+ (single electron single pion, where pion is detected as a Michel electron) samples in FHC (neutrino) mode and (4) CC1R_μ and (5) CC1R_e samples in RHC (anti-neutrino) mode.

2 Motivations of the new parameterization

The new parameterization regards $\sin\delta_{CP}$ and $\cos\delta_{CP}$ as two independent parameters:

- The oscillation probabilities are more sensitive to $\sin\delta_{CP}$ and $\cos\delta_{CP}$ instead of δ_{CP} [1]:

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = A_{\mu e}\cos\delta_{CP} + (-)B_{\mu e}\sin\delta_{CP} + C_{\mu e}(C'_{\mu e}). \quad (1)$$

- Around the neutrino energy 0.6 GeV, which is the oscillation maximum for the T2K experiment, the contribution from $\cos\delta_{CP}$ term is much smaller than $\sin\delta_{CP}$ term. (Figure 2 left)
- The $\sin\delta_{CP}$ term contributes to the CP violation and determines the "strength" (extension along the long axis of the ellipses, Figure 2 right) of the violation.
- The $\cos\delta_{CP}$ term contributes to the spectral distortion (width along the short axis of the ellipses, Figure 2 right).

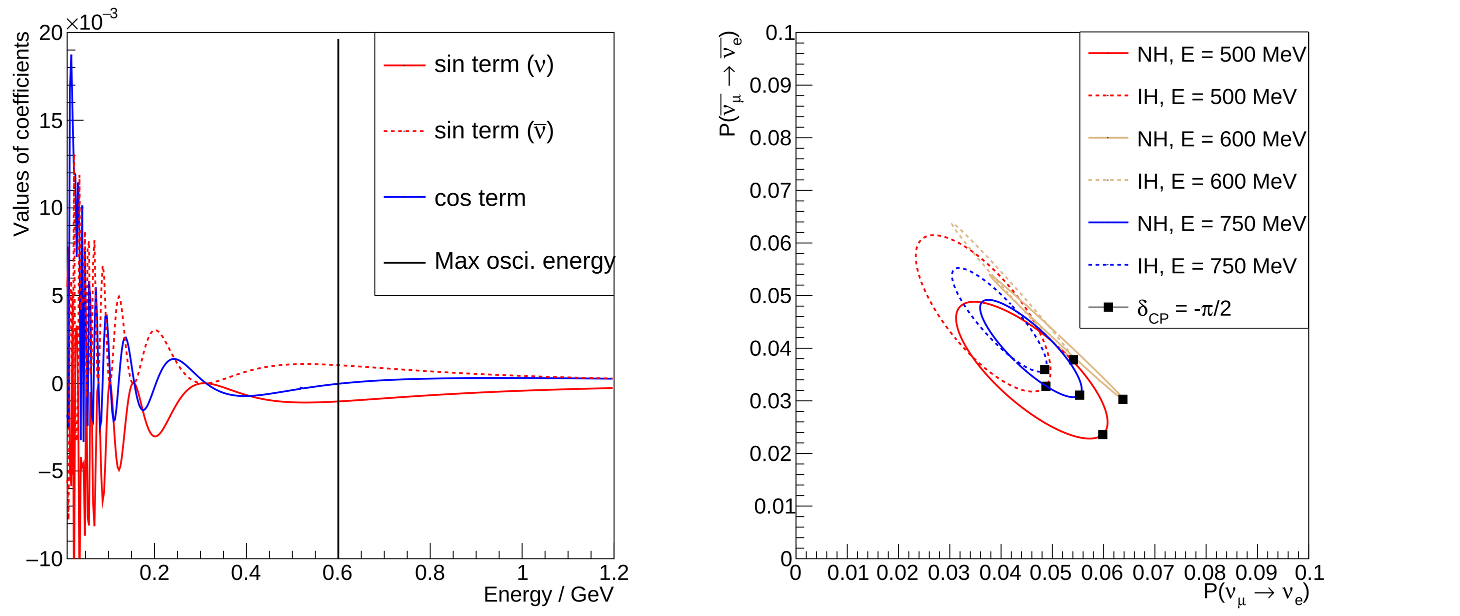

Figure 2: Left: Coefficients of $\sin\delta_{CP}$ and $\cos\delta_{CP}$ in Eqn. (1) as a function of neutrino energy. Right: Effects of $\sin\delta_{CP}$ and $\cos\delta_{CP}$ terms in $P(\overline{\nu}_\mu \to \overline{\nu}_e) - P(\nu_\mu \to \nu_e)$ bi-probability space [3].

3 Modifications to the oscillation probabilities

Write $\sin\delta_{CP}$ and $\cos\delta_{CP}$ as X_S and X_C for convenience.

- First introduce two polar coordinates ρ and δ (not δ_{CP}), which are related to X_S and X_C through Cartesian polar transformations:

$$\rho(X_S, X_C) = \sqrt{X_S^2 + X_C^2},\ \delta(X_S, X_C) = \begin{cases} \arctan\frac{X_S}{X_C}, & \text{if } X_C \geq 0 \\ \arctan\frac{X_S}{X_C} + \pi, & \text{if } X_C < 0 \text{ and } X_S > 0 \\ \arctan\frac{X_S}{X_C} - \pi, & \text{if } X_C < 0 \text{ and } X_S \leq 0 \end{cases} \quad (2)$$

- Then the oscillation probabilities $P_{\alpha\beta}(\delta_{CP}, \vec{\theta})$ are modified as a linear combination form:

$$P'_{\alpha\beta}(X_S, X_C, \vec{\theta}) = \frac{1+\rho(X_S, X_C)}{2} P_{\alpha\beta}(\delta(X_S, X_C), \vec{\theta}) + \frac{1-\rho(X_S, X_C)}{2} P_{\alpha\beta}(\delta(X_S, X_C) + \pi, \vec{\theta}). \quad (3)$$

4 Analysis Strategy

The analysis performs a simultaneous fit of the near detector (ND280) and SK data using a Bayesian MCMC technique. We use the Bayesian posterior density:

$$-\log P(\vec{\Theta}|D) = \sum_i \left[N_i^p(\vec{\Theta}) - N_i^d + N_i^d \log\left(N_i^d / N_i^p(\vec{\Theta})\right)\right] + \frac{1}{2}\sum_j \Delta\vec{\Theta}_j^T V_j^{-1} \Delta\vec{\Theta}_j + \lambda\left(\sqrt{X_S^2 + X_C^2} - 1\right)^2. \quad (4)$$

- **First term**: The data in each ND280 and SK sample are binned and compared.
- **Second term**: The parameters with Gaussian priors are summed over.
- **Last term**: A physical constraint is added on X_S and X_C, where λ determines the strength of the constraint. During the fit, two constraint cases are considered:
  - Weak ($\lambda = 0.2$), where non-standard PMNS phenomenon is expected to be shown.
  - Strong ($\lambda = 2$), where standard PMNS model is approximated.

$\rightarrow$ Through comparing the fit results from these two models, we want to see whether the current T2K data has any preference on each model.

5 Fit results and conclusions

Constraint	X_S	X_C
Weak ($\lambda = 0.2$)	$-1.69^{+0.32}_{-1.07}$	$-1.89^{+3.86}_{-1.12}$
Strong ($\lambda = 2$)	$-1.30^{+0.43}_{-0.49}$	$-0.55^{+1.10}_{-0.62}$
Official T2K run 1-9 fit (best-fit $\delta_{CP} = -1.74$)	-0.99	-0.17

- The 68% credible intervals of the best-fit values from the strong constraint model cover the results from T2K official fit [2]. $\rightarrow$ The strong constraint model is indeed an approximation to the standard PMNS model.
- In the weak constraint model the best-fit values deviate far from the unitarity circle $X_S^2 + X_C^2 = 1$, but the 90% credible interval still has intersections with that circle, which means some physical δ_{CP} values are still included with 90% credible level. (Figure 3 left)

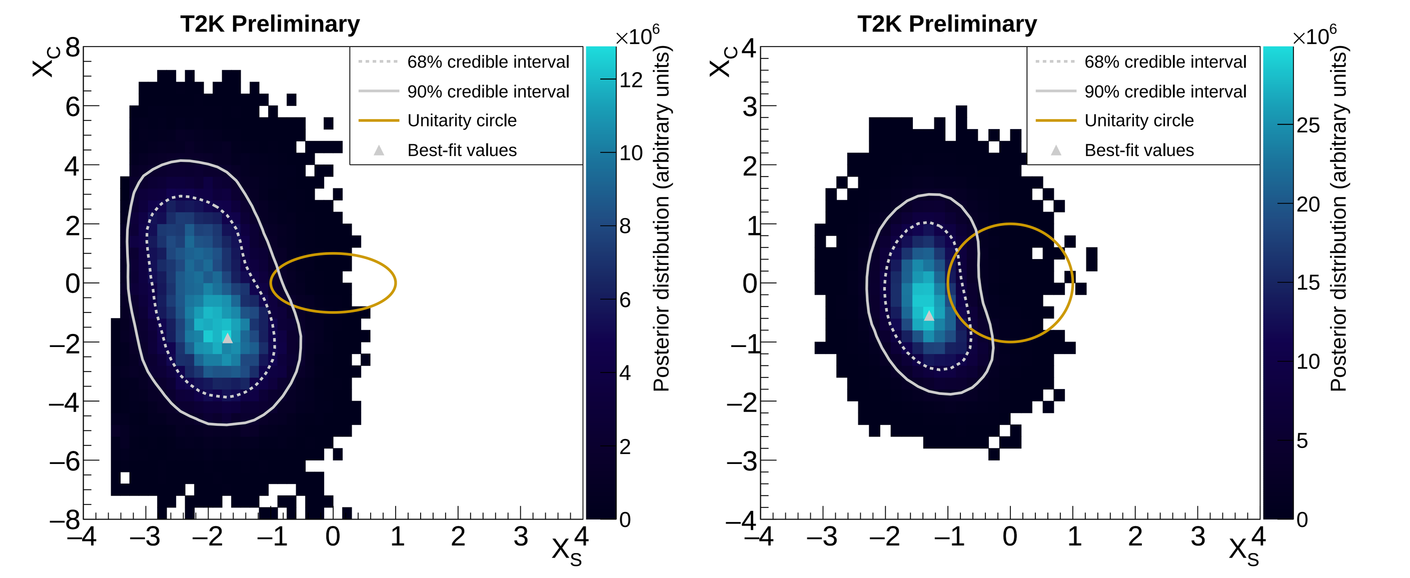

Figure 3: The fit results in X_S - X_C parameter space, with weak (left) and strong (right) constraint.

- Bi-probability plot and bi-rate plot can be used to further compare two models. In bi-rate plot the axis is the number of events instead of oscillation probability.

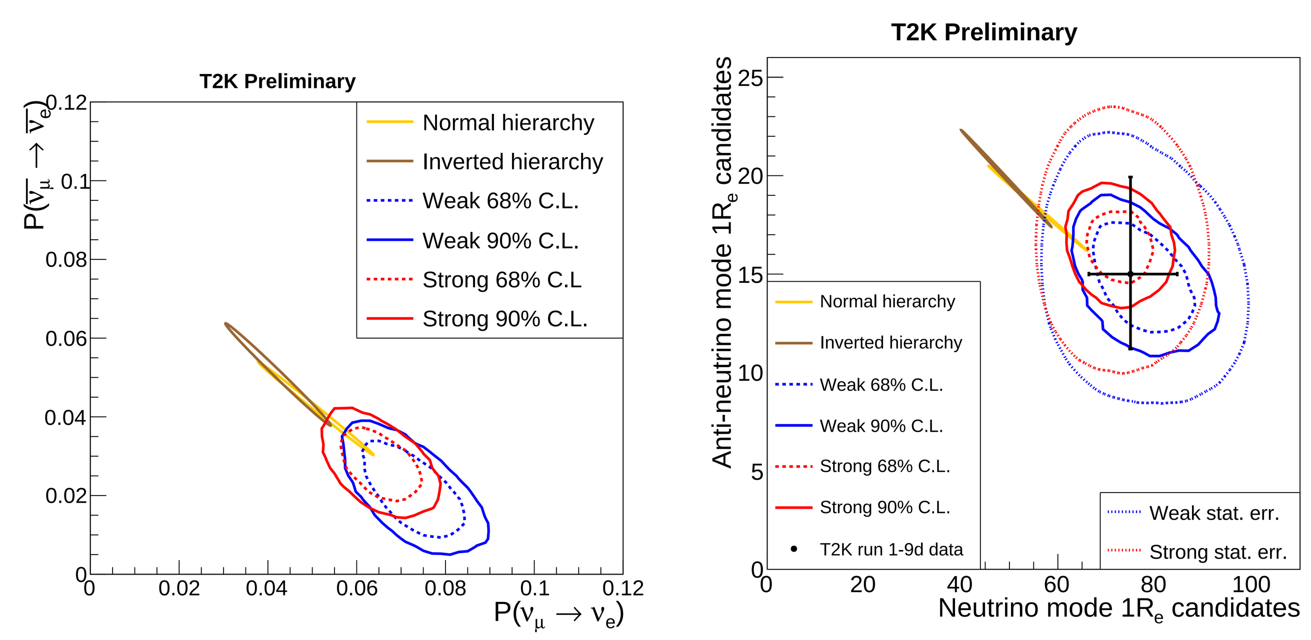

Figure 4: The fit results in bi-probability plot (left) and bi-rate plot (right).

The contours from weak and strong constraint models significantly overlap in both 68% and 90% credible levels. $\rightarrow$ A good agreement between the two fits from each model, showing consistency between current T2K data and the standard PMNS model.

References

[1] H. Yokomakura, K.Kimura and A. Takamura, *Phys. Lett. B* **544**, 286-294 (2002).

[2] K. Abe *et al.* (T2K Collaboration), arXiv:1910.03887.

[3] K. Abe *et al.* (T2K Collaboration), arXiv:1911.07283.

Acknowledgements

I would like to thank Phill Litchfield, who brought this reparameterization framework into my attention. I am also very grateful to people in T2K MaCh3 group for their help concerning the technical aspects of the MaCh3 software.