T violation at a future neutrino factory

Ryuichiro Kitano (YITP), Joe Sato (Yokohama National Univ.), Sho Sugama (Yokohama National Univ.)
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Introduction

Motivation

- Testing T violation in lepton sector has not been achieved.
- CP and T violation measurements as a non-trivial check of the CPT theorem in QFT.

Framework of standard 3 flavor ν oscillation in matter

Assumption: constant electron density

$$i\frac{d}{dt}\begin{pmatrix}\nu_e(\bar{\nu}_e)\\ \nu_\mu(\bar{\nu}_\mu)\\ \nu_\tau(\bar{\nu}_\tau)\end{pmatrix} = \left[U_{PMNS}^{(*)}\mathrm{diag}(0,\Delta E_{21},\Delta E_{31})U_{PMNS}^{\dagger(T)} + \mathrm{diag}(\pm A,0,0)\right]\begin{pmatrix}\nu_e(\bar{\nu}_e)\\ \nu_\mu(\bar{\nu}_\mu)\\ \nu_\tau(\bar{\nu}_\tau)\end{pmatrix}$$

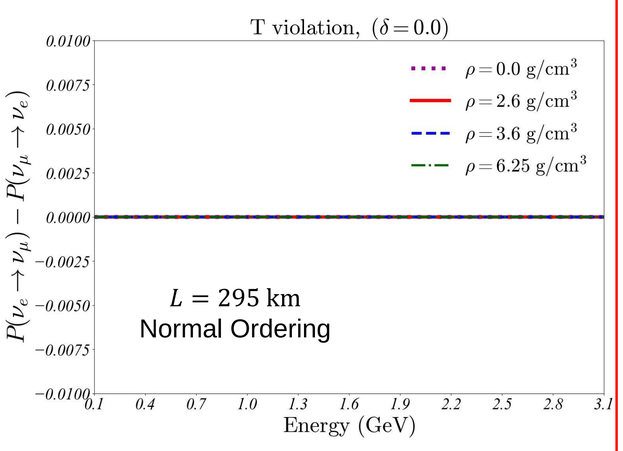
T violation : $P(\nu_\alpha \to \nu_\beta) - P(\nu_\beta \to \nu_\alpha) \propto J$

$J = \frac{c_{13}}{8}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin\delta$: Jarlskog factor

CP violation : $P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

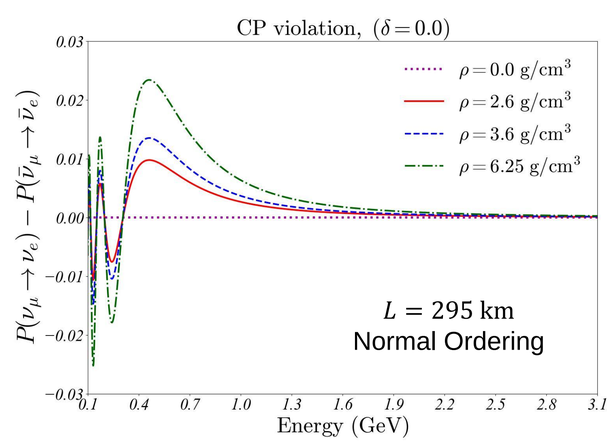
Non-negligible matter effects and δ_{CP} contribution

T violation



- Formally T-odd when we assume that the matter density is symmetric under the exchange of the neutrino source and the detector.
- No matter effect for $\delta = 0$.
- Matter effects is not important.

CP violation



- Fake CP violation due to the matter effect.
- Matter effects may mimic CP violation.

How to measure the T violation

- Utilize μ^+ beam from muon collider experiment at the J-PARC site (μTRISTAN).
- Assume to point the beam toward the Hyper-Kamiokande (HK).
- Only ν_e and $\bar{\nu}_\mu$ beam can be used. Therefore, we consider combining it with the T2HK experiment.

$P(\nu_e \to \nu_\mu)$ from μTRISTAN — $P(\nu_\mu \to \nu_e)$ from T2HK

combine

Can observe T violation $P(\nu_e \to \nu_\mu) - P(\nu_\mu \to \nu_e) \propto \sin\delta$

Robust test of CP phase independent of matter effects!

Statistical analysis

$$\chi^2_{\mathrm{TV}} \equiv \sum_j \frac{\left[P_j^{\mathrm{TV}}(\delta_0,\ \rho_0) - P_j^{\mathrm{TV}}(\delta^{\mathrm{test}},\ \rho^{\mathrm{test}})\right]^2}{\Delta {P_j}^2}$$

$$P_j^{\mathrm{TV}}(\delta,\rho) \equiv P_j(\nu_e \to \nu_\mu) - P_j(\nu_\mu \to \nu_e)\Big|_{\mathrm{T2HK}}$$

- Measure $\nu_e \to \nu_\mu$ at the HK.
- The charges of the muons must be identified (generated by the CC process $\nu_\mu n \to \mu^- p$ and $\bar{\nu}_\mu p \to \mu^+ n$).
- At the HK, in principle, ν_μ and $\bar{\nu}_\mu$ are distinguished by neutron tagging method.

Oscillation probability $P(\nu_e \to \nu_\mu)$

$$P(\nu_e \to \nu_\mu) = \frac{1}{\kappa}\frac{\left(\kappa N_{\mathrm{far}}^{\nu_e\to\nu_\mu} + (1-\kappa)N_{\mathrm{far}}^{\bar{\nu}_\mu\to\bar{\nu}_\mu}\right) - (1-\kappa)N_{\mathrm{far}}^{\bar{\nu}_\mu\to\bar{\nu}_\mu}\Big|_{\mathrm{T2HK}}}{\kappa N_{\mathrm{near}}^{\nu_e\to\nu_e}}$$

$\kappa \equiv \frac{1+C_{\mathrm{id}}}{2}$, C_{id}: charge identification efficiency

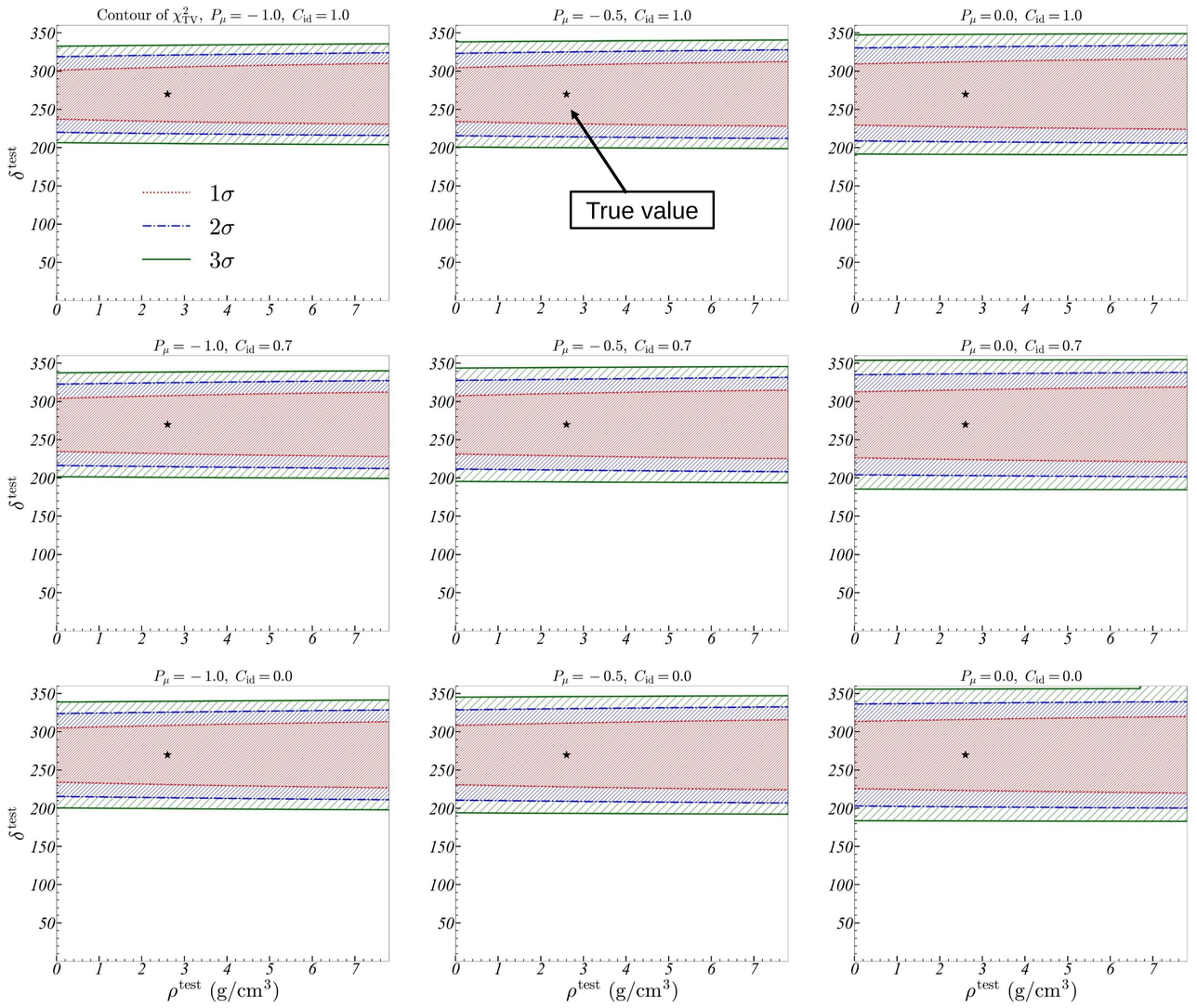
(probability to correctly identify ν_μ for an actual ν_μ event)

- Treatment of $C_{\mathrm{id}} = 0.0$: adding the background events ($\kappa = 1$ and $1-\kappa = 1$) without performing charge identification analysis.

Parameter determination

χ^2 analysis for T violation

- Set true values as $\delta_0 = 270^\circ$ and $\rho_0 = 2.6$ g/cm^3.
- Take the bin size to be 50 MeV, and the muon polarization factor $P_\mu = -1.0,\ -0.5,\ 0.0$. Smear the neutrino spectrum with $\Delta E = 50$ MeV.
- The efficiency of the charge identification, $C_{\mathrm{id}} = 1.0, 0.7, 0.0$.



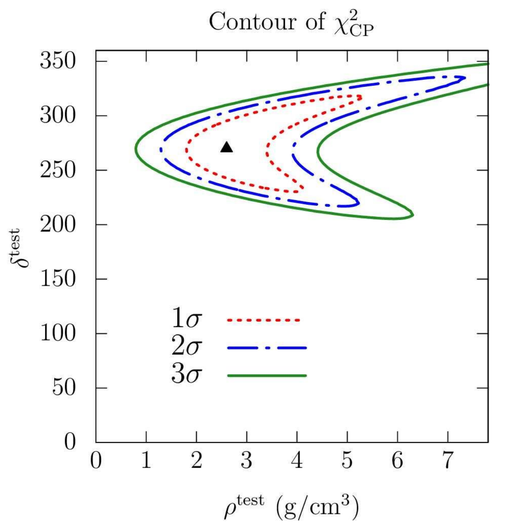
- CP (or T) conserving point, $\delta = 0,\ 180^\circ$ can be excluded at the level of 3σ even for the unpolarized muon beam.
- For the best case, $C_{\mathrm{id}} = 1.0$ and $P_\mu = -1.0$, the CP angle δ is determined with an accuracy of about $\pm 30^\circ$.
- χ^2_{TV} only depends on the parameters, δ.
- 1σ confidence level is determined from $\chi^2 = 1$, i.e. for a single degree of freedom.

χ^2 analysis for CP violation

$\chi^2_{\mathrm{CP}}(\delta^{\mathrm{test}},\ \rho^{\mathrm{test}})$ is similarly analyzed

$$P_j^{\mathrm{CP}} = P_j(\nu_\mu \to \nu_e)\Big|_{\mathrm{T2HK}} - P_j(\bar{\nu}_\mu \to \bar{\nu}_e)\Big|_{\mathrm{T2HK}}$$

- Non-trivial dependence of the allowed region on ρ^{test} appears.
- Information of ρ is critically important.
- The measurement of T violation will be an important additional information for the measurement of the CP angle δ.
- Additional measurement of T violation helps to discriminate the matter effect.



Possible CPT test?

$$P_j^{\mathrm{CPT}} = P_j(\nu_e \to \nu_\mu) - P_j(\bar{\nu}_\mu \to \bar{\nu}_e)\Big|_{\mathrm{T2HK}} = P_j^{\mathrm{TV}} + P_j^{\mathrm{CP}}$$

Under our assumptions, this quantity would not measure anything as it should be trivially vanishing up to matter effects. The analysis of this kind will be a quite important fundamental test of symmetry in physical laws of the Universe.

Summary

- Testing T violation in the lepton sector remains as an important task in particle physics.
- We studied the possibility of measuring T violation, $P(\nu_e \to \nu_\mu) - P(\nu_\mu \to \nu_e)$ considering the baseline from J-PARC to Hyper-Kamiokande.
- By combining $P(\nu_e \to \nu_\mu)$ from μTRISTAN with $P(\nu_\mu \to \nu_e)$ from T2HK, the T violation can be defined.
- For the case of maximum CP violation, $\delta = 270^\circ$, CP invariant theories ($\delta = 0$ or 180°) can be excluded at more than 3σ level.
- T violation can be a good measure which is not sensitive to the detailed density profile of the Earth.
- Finally, A more complete analysis will be necessary to establish the feasibility.