T violation at a future neutrino factory

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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

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

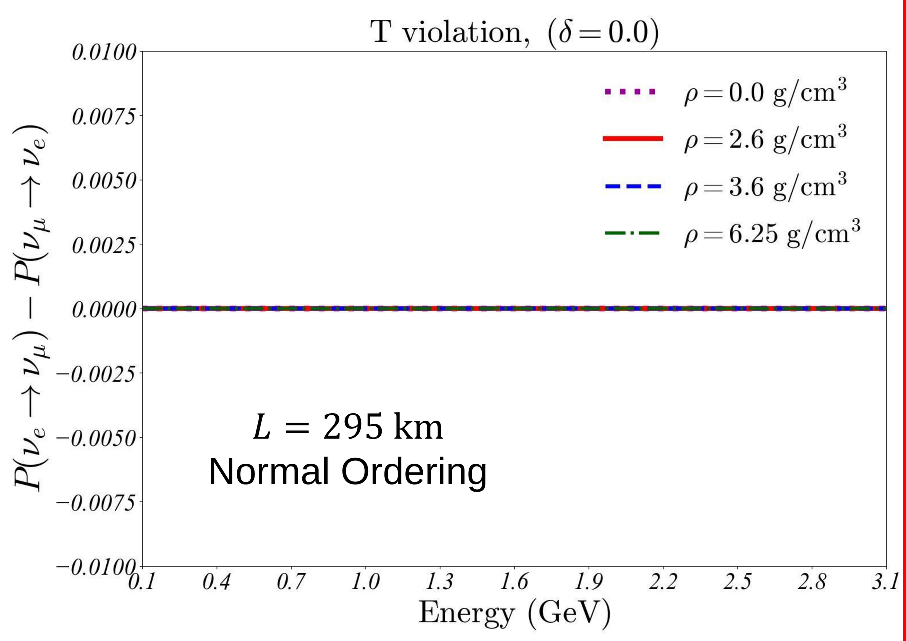
T violation : $P(\nu_\alpha \to \nu_\beta) - P(\nu_\beta \to \nu_\alpha) \propto J$

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

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

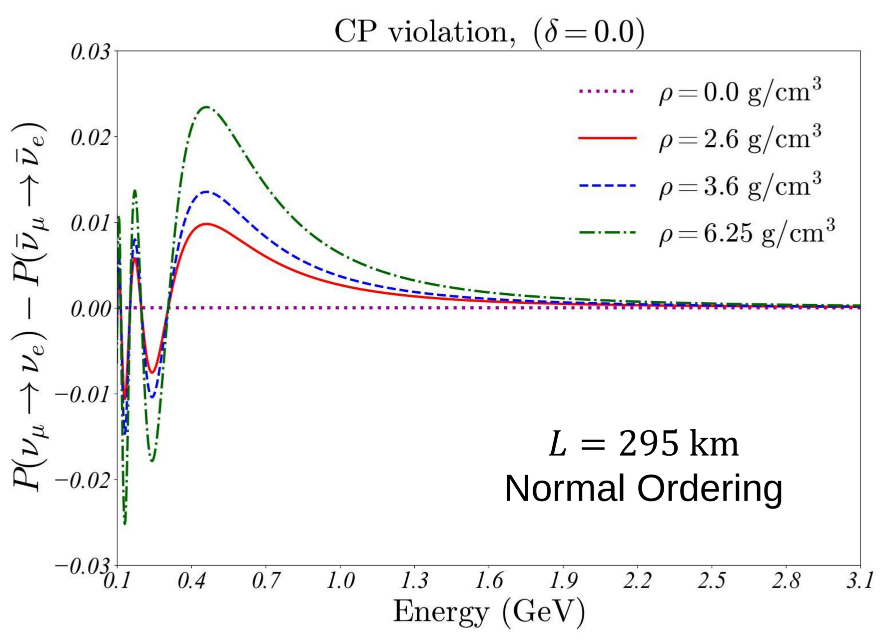


・Formally T-odd when we assume that the matter density is symmetric under the exchange of the neutrino source and the detector.

・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

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

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

・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 $P(\nu_e \to \nu_\mu)$

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

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

(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.

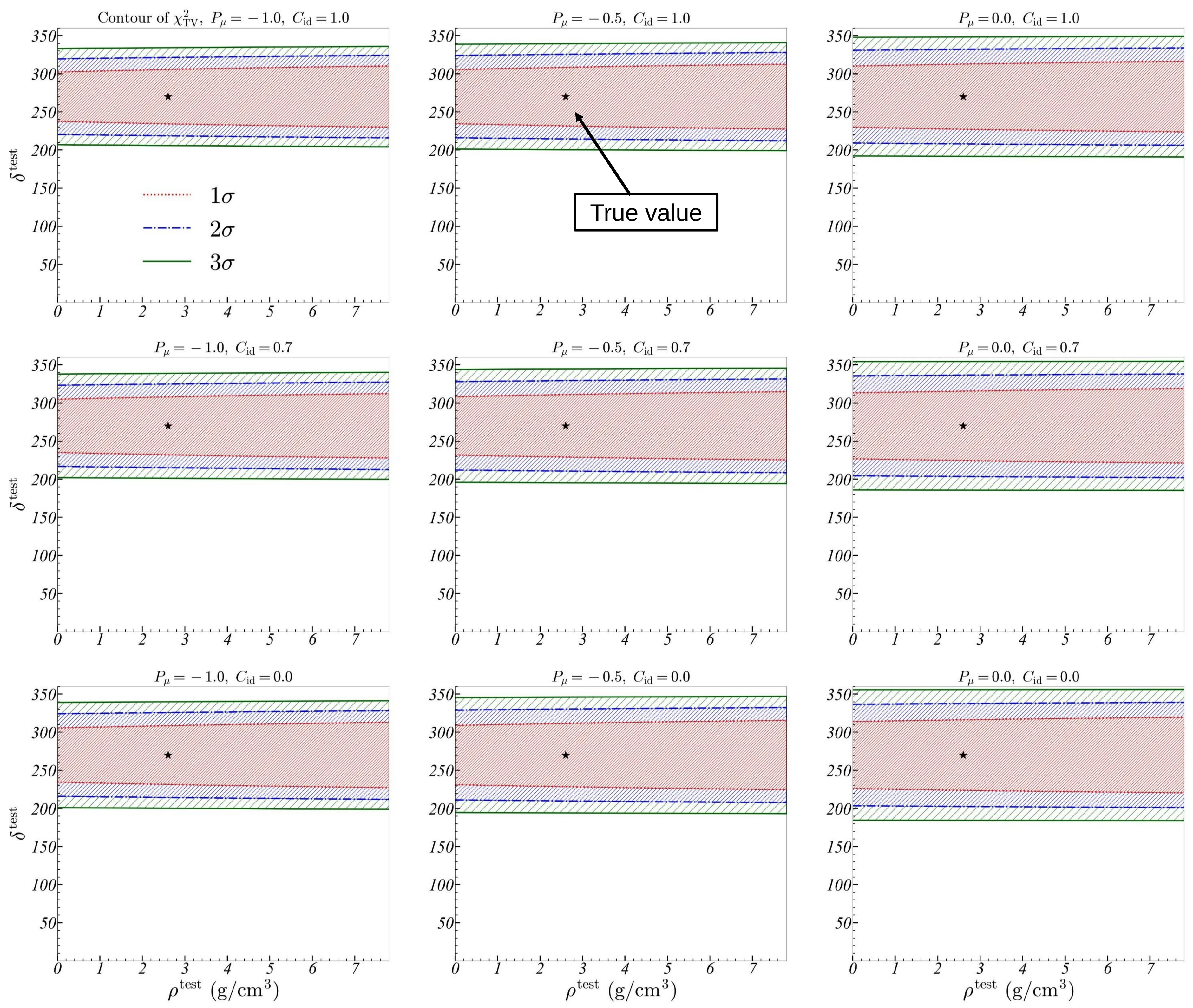
Parameter determination

χ^2 analysis for T violation

・Set true values as $\delta_0 = -\pi/2$ and $\rho_0 = 2.6\ \mathrm{g/cm^3}$.

・Take the bin size to be $50\ \mathrm{MeV}$, and the muon polarization factor $P_\mu = -1.0,\ -0.5,\ 0.0$.

・The efficiency of the charge identification, $C_{\mathrm{id}} = 1.0, 0.7, 0.0$.



・CP (or T) conserving point, $\delta = 0,\ \pi$ 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

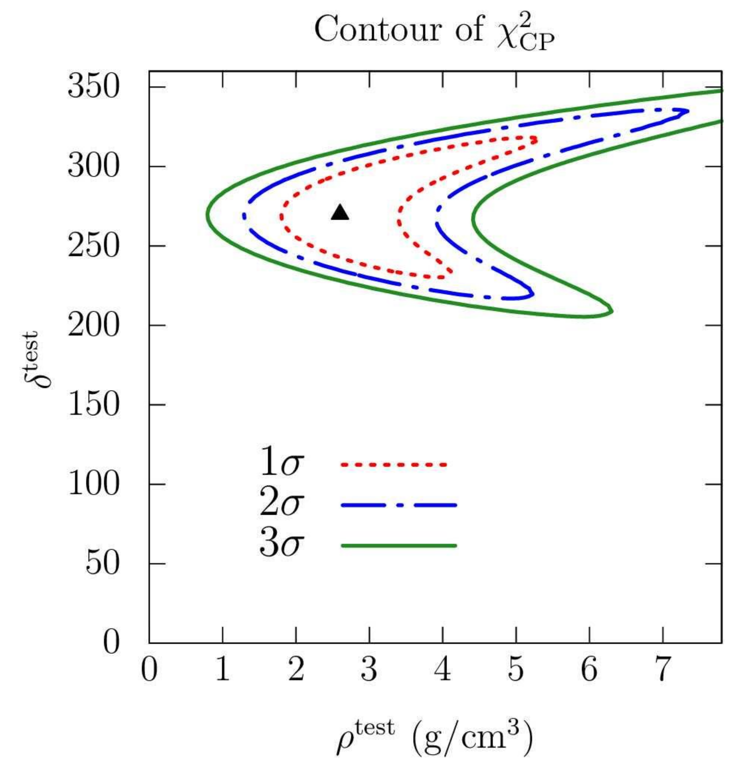
$$P^{\mathrm{CP}}_j = P_j(\nu_\mu \to \nu_e)\Big|_{\mathrm{T2HK}} - P_j(\bar\nu_\mu \to \bar\nu_e)\Big|_{\mathrm{T2HK}}$$

・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?

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

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, $\delta = -\pi/2$, CP invariant theories ($\delta = 0$ or π) 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.