Japanese neutrino factory
$\sim$ CP/T violation in neutrino factories $\sim$

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I study the sensitivity to the CP/T-violation search as an asymmetry in presence of ambiguities of the theoretical parameters. This talk is based on the work [1].

I. INTRODUCTION

In near future completely unknown parameters for the lepton sector will be:

$$\begin{array}{ll} U_{e3}(\theta_{13}) & : \text{Last Mixing}, \\ \text{Sign of } \delta m^2 & \simeq \text{Matter Effect}, \\ \sin\delta & : \text{CP Violation}, \end{array}$$

There are many analyses about how we can observe them with a neutrino factory with muon storage ring.[2, 3] I agree the analyses about U_{e3} and the sign of δm^2, but I cannot understand them about CP violation.

First of all what is CP violation? In general, Lagrangian takes the form

$$L = c\, O + \text{ h.c} = c\, O + c^*\ O^*, \tag{1}$$

where c is a coupling and O represents an operator. Its CP transformation is given by

$$L = c^*\ O + c\, O^*. \tag{2}$$

Therefore if c is complex CP is not conserved. Thus CP violation is characterized by the imaginary part of the couplings. An experiment and its analysis for CP violation should be sensitive to the imaginary part of the couplings.

The imaginary part appears in an experiment as a difference between a particle and an antiparticle. Then the next question arises whether the naive parameter fitting,

$$\chi_1^2(\delta_0) \equiv \sum_{\text{bin}_j} \frac{[N_j(\delta) - N_j(\delta_0)]^2}{N_j(\delta)} + \frac{[\overline{N}_j(\delta) - \overline{N}_j(\delta_0)]^2}{\overline{N}_j(\delta)}, \tag{3}$$

which is often used for the analysis of neutrino factories, is really sensitive to the imaginary part. [4] Moreover there is another big problem that the matter effect gives another source for the difference. Unless we can estimate this effect precisely enough, the genuine CP violation effect, which arises from the imaginary part of the coupling in a Lagrangian, will be hidden by this effect. Therefore at the same time we have another question whether we can estimate the matter effect precisely enough?

II. MEASUREMENT OF CP VIOLATION, AMBIGUITIES OF THEORETICAL PARAMETERS AND FAKE CP VIOLATION DUE TO MATTER EFFECT

From the point of view stated in the introduction, the statistics with which we talk about CP violation should satisfy the following properties. i) Leading contribution comes from the CP violation term. ii) If $J = 0$, $\chi^2 = 0$. The second requirement means that we have to subtract the matter effect.

I propose the suitable statistics for an analysis of CP violation, which satisfies the properties stated above,

$$\tilde{\chi}_3^2(\delta_0) = \sum_{j=1}^{n} \frac{\left[\widetilde{\overline{N}}(\delta_0)N(\delta) - \widetilde{N}(\delta_0)\overline{N}(\delta)\right]^2}{\widetilde{\overline{N}}(\delta_0)^2 N(\delta) + \widetilde{N}(\delta_0)^2\overline{N}(\delta)}, \tag{4}$$

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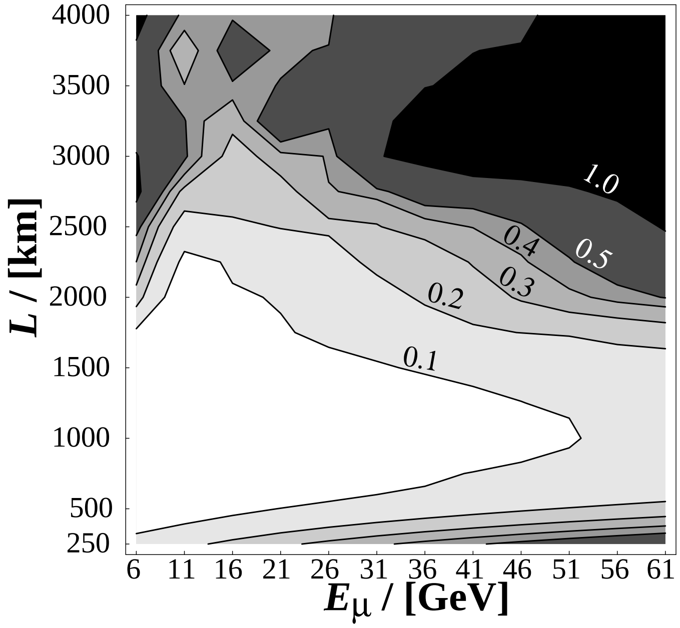

FIG. 1: Required muon number $\times$ detector size in the unit $10^{21} \times 100$kt. Parameters for "observed event number" $N_j(\delta = \pi/2)$ are $\sin\theta_{13} = 0.1, \sin\theta_{23} = 1/\sqrt{2}, \sin\theta_{12} = 0.5, \delta m^2_{31} = 3 \times 10^{-3}\mathrm{eV}^2, \delta m^2_{21} = 1 \times 10^{-4}\mathrm{eV}^2$ and matter effect is approximated by constant density $a(L)$, which is calculated with PREM. The "theoretical event number" $\tilde{N}(\delta_0)_j$ are calculated assuming 10 % ambiguities in each parameter.

where $\delta_0 \equiv \{0, \pi\}$. Note that since we do not know all the other parameters, we have to calculate the theoretically expected event numbers with whole allowed regions of theoretical parameters. We have to take into account the ambiguities of theoretical parameters. In other words, we have ambiguities to estimate the event number not only experimentally but also theoretically. Note also that we have to compare "event number" with that in both case $\delta = 0, \pi$.[1] If eq.(4) is large enough we can claim that we observe the CP violation.

In fig.1 I plot the required muon number $\times$ detector size in the unit $10^{21} \times 100$kt as a function of muon energy and baseline length for a parameter set listed in the figure caption. As we can see from the figure, we need more muons in longer length. This is due to the fake CP violation by the matter effect, which is given in the high energy limit by

$$\left\{\frac{2}{3}\sin^2\theta_{23}\sin^2 2\theta_{13}\cos 2\theta_{13} + \frac{1}{3}(2\cos 2\theta_{13} - 1)J_{/\delta}\cos\delta\right\}\left(\frac{a(L)L}{4E}\right)\left(\frac{\delta m^2_{31}L}{4E}\right)^3 \tag{5}$$

Comparing the genuine CP violation, which is given in the high energy limit by

$$J_{/\delta}\sin\delta\left(\frac{\delta m^2_{31}L}{4E}\right)^3 \tag{6}$$

$$J_{/\delta} \equiv \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\frac{\delta m^2_{21}}{\delta m^2_{31}}$$

we find that in longer baseline we have more fake CP violation effect.

Similar calculation with other parameter shows [1] that $L \sim 1000$km and $E_\mu \sim$10 GeV seems optimum.

Furthermore by observing the correlation of the sensitivity between $\sin\theta_{13}$ and δ we find that χ^2_3 has a good property as a statistics for CP violation.[1]

III. MEASUREMENT OF T VIOLATION

Similar calculation can be done for the T violation mode. In this case even if there are ambiguities in parameters, we have same sensitivity as that for the case without any ambiguities in parameters besides CP

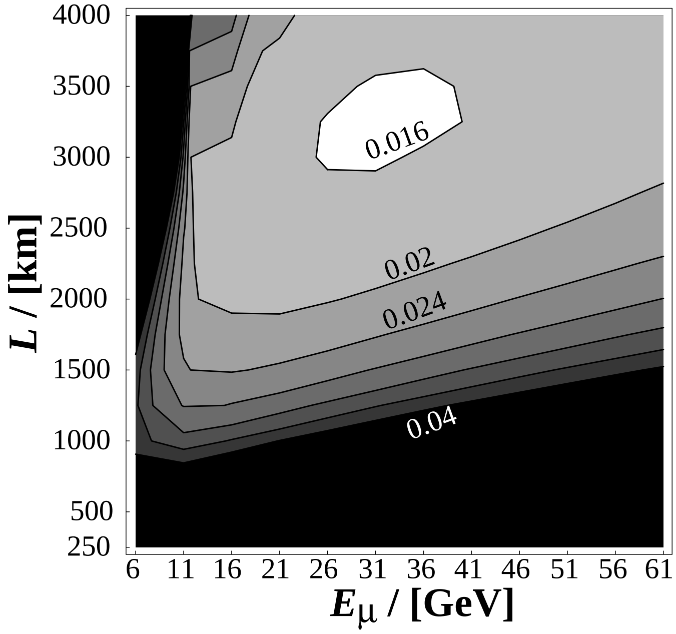

FIG. 2: Similar plot with fig.1 for T violation channel.

violation phase. See fig.2 This is due to the fact

$$\tilde{\chi}_3^2 \propto J_m^2 \propto J^2 \tag{7}$$
$$J_m \equiv \frac{\delta m_{21}^2 \delta m_{32}^2 \delta m_{13}^2}{\delta \tilde{m}_{21}^2 \delta \tilde{m}_{32}^2 \delta \tilde{m}_{13}^2} J \qquad : J \text{ in matter}$$

Namely there is no fake T violation effect. There is no effect of ambiguities of theoretical calculation!!

IV. SUMMARY AND DISCUSSION

We have investigated the feasibility of observation of CP violation as the difference between ν and $\bar{\nu}$. We have seen that we need to very carefully subtract the matter effect. We have found that $L \sim 1000$km and $E_\mu \sim 10$GeV seems optimum unless we find a better statistics than χ_3^2.

On the other hand T violation mode shows very clean signal for genuine CP violation since there is almost no matter effect.

[1] M. Koike, T. Ota and J. Sato, hep-ph/0011387.
[2] S. Geer, Phys. Rev. **D57** (1998) 6989, erratum *ibid.* **D59** (1999) 039903.
[3] e.g. Neutrino Factory and Muon Collider Collaboration (D. Ayres *et al.*), physics /9911009; C. Albright *et al.* hep-ex/0008064.
[4] J. Sato, hep-ph/0008056.