Muon beams for neutrino CP violation: A bridge between energy and neutrino frontiers

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1. Introduction

We propose using collimated muon beams to connect the neutrino and energy frontiers, by exploiting collimated muon beams for neutrino oscillation, which generate symmetric neutrino and antineutrino sources: $\mu^+ \to e^+\bar{\nu}_\mu\nu_e$ and $\mu^- \to e^-\nu_\mu\bar{\nu}_e$. Interfacing with long baseline neutrino detectors such as DUNE and T2K, this experiment can be applied to measure tau neutrino properties, and also to probe neutrino CP phase, by measuring muon electron (anti-)neutrino mixing or tau (anti-)neutrino appearance, and differences between neutrino and antineutrino rates. This proposal benefits from collimated and manipulable muon beams, leading to a large acceptance of neutrino sources in the far detector, and symmetric beams that make it useful for observing CP violation. Importantly, $\bar{\nu}_{e,\mu} \to \bar{\nu}_\tau$ and $\nu_{e,\mu} \to \nu_\tau$, and, $\bar{\nu}_e \to \bar{\nu}_\mu$ and $\nu_e \to \nu_\mu$ oscillation signals can be collected simultaneously, and μ^- and μ^+ routes can be exchanged to reduce bias or possible systematic uncertainties. We estimate that 10^4 tau neutrinos can be collected per year and expect to reach 5 σ of sensitivity for $\delta_{CP} \sim |\pi/2|$ with only 1-2 years of data acquisition. The proposed experiment can serve as a brighter tau neutrino factory and could be improved with a more intensive muon beam targeting for future muon collider.

2. Methods to prob CP phase

Conventionally, neutrinos are obtained from muon decays which is initially produced from pion decay made available from proton on-target experiment for neutrino oscillation experiments like T2K and DUNE. Here we propose a novel approach to obtain reach flux of muons with low emittance and higher energy peak. The below figure explains this approach.

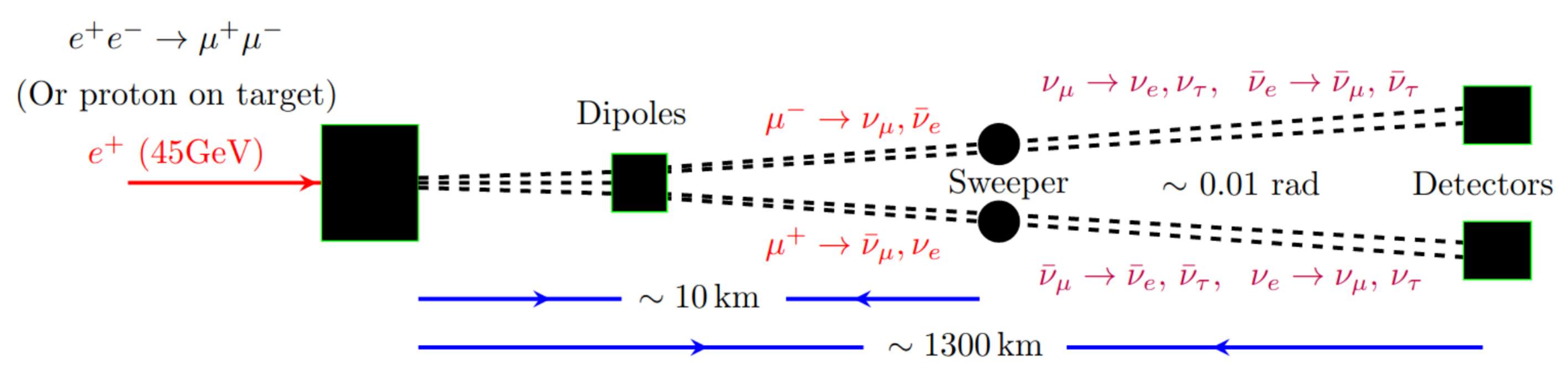

Fig. 1. A proposed neutrino oscillation experiment to probe neutrino CP-violating phase by measuring muon electron and their antineutrino oscillation and the differences of resulted $\nu_{e,\mu} \to \nu_\tau, \nu_e \to \nu_\mu$. Positrons are accelerated up to 45 GeV energies and hit on fixed electron-rich target.

The method is to fire accelerated positrons on electron-rich fixed targets and produce with larger flux of muon beams that outmatches the conventional approach for muon production. The incident energy of positrons are around 45 GeV, and they produced muon pairs after collision with electrons inside target material. The intersection angel between outgoing muon pairs are approximately 0.005 rad with a large boost of $\gamma \sim 200$. As shown in the above figure, muons beams fly about 10 Km and radiate neutrinos before being swept away. Neutrinos then further fly through 1300 Km distance to reach DUNE or T2K-like detectors. Generally the number of muon pairs produced per positron bunch on target can be expressed as

$$n(\mu^+\mu^-) = n^+\rho_{e^-}\ell\, \sigma(\mu^+\mu^-),$$

where n^+ is the number of e^+ in each positron bunch, ρ_{e^-} is the electron density in the target material, ℓ is the thickness of the target, and $\sigma(\mu^+\mu^-)$ is the cross section of the muon pair production. The number of muon pairs per positron bunch on target can be estimated maximally as $n(\mu^+\mu^-) \approx n^+ \times 10^{-5}$. Assuming positron bunch density as 10^{12}/bunch and bunch crossing frequency as 10^5/sec, we get muon production rate $dN_\mu/dt \sim 10^{12}$/sec or 10^{19}/year. The energy spectrum of neutrinos detected on far detector side is show in the blow figure. It is clear that, at the opening angle of 0.005 radian, corresponding neutrino energy lies between 5 to 10 GeV, and peaks at 7 GeV, which is significantly greater than the tau neutrino threshold.

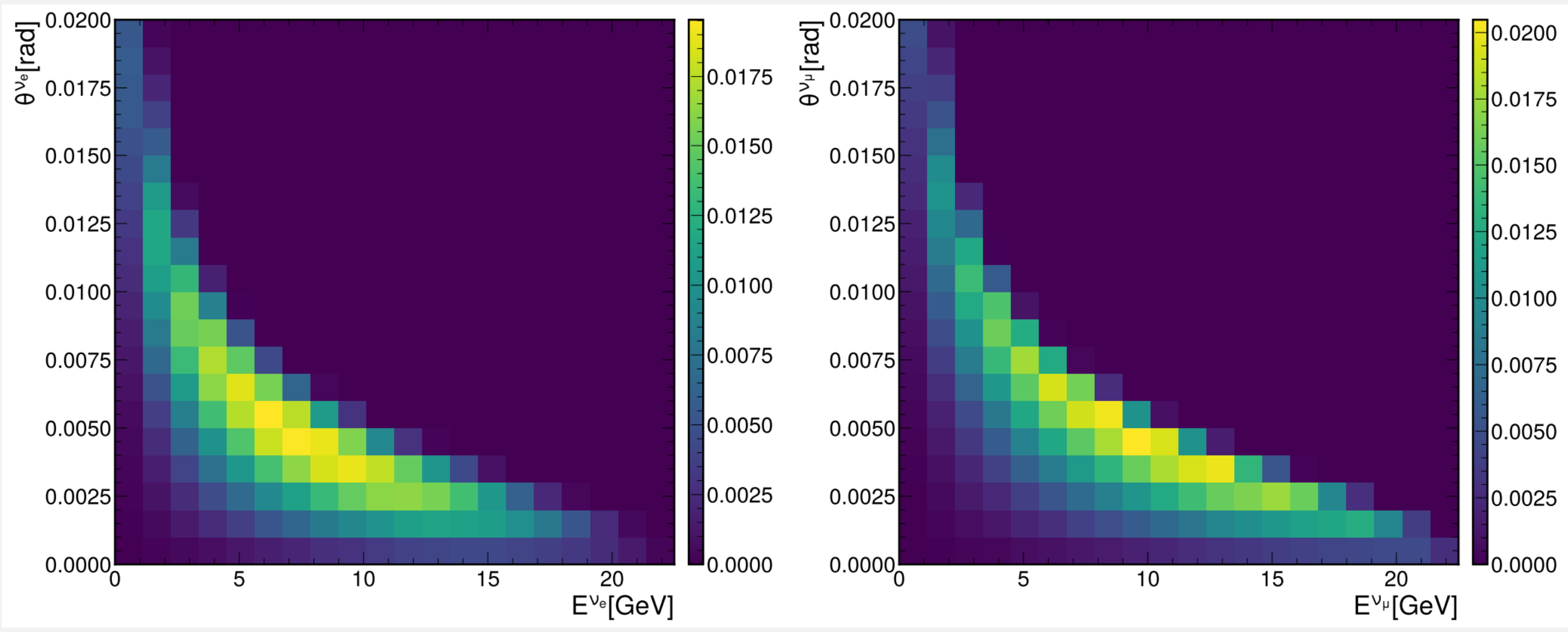

Fig. 2. 2D distribution of energy and angle with respect ot muon flying direction, for muon and electron neutrinos from 22.5 GeV $\mu^+ \to e^+\bar{\nu}_\mu\nu_e$ on the left and for μ^- on the right.

3. CP violation in neutrino oscillation

In a gauge theories of neutrino masses, the lepton mixing matrix typically contains a number of CP violating phases that may affect neutrino oscillations. It has been recognized that the Dirac phase present in the simplest three-neutrino model could in principle be observed in neutrCP violating ino oscillation experiments. These are the most promising way to probe directly the Dirac CP phase present in the neutrino mixing matrix. The simple measure of CP violation would be the difference of oscillation probabilities between neutrinos and anti-neutrinos. We consider four types of oscillation modes:

- $P(\nu_\mu \to \nu_\tau) \simeq \sin^2 2\theta_{23}\cos^4\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E_\nu}\right) \pm \frac{1.27\Delta m^2_{21}\,L}{E_\nu}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E_\nu}\right) * 8J_{CP},$
- $P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E_\nu}\right) \mp \frac{1.27\Delta m^2_{21}\,L}{E_\nu}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E_\nu}\right) * 8J_{CP},$
- $P(\nu_e \to \nu_\tau) \simeq \sin^2 2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E_\nu}\right) \mp \frac{1.27\Delta m^2_{21}\,L}{E_\nu}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E_\nu}\right) * 8J_{CP},$
- $P(\nu_e \to \nu_\mu) \simeq \sin^2 2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E_\nu}\right) \pm \frac{1.27\Delta m^2_{21}\,L}{E_\nu}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E_\nu}\right) * 8J_{CP},$

where the “Jarlskog Invariant” J_{CP} reads as

$$\begin{aligned} J_{CP} &= sin\theta_{13}\cos^2\theta_{13}sin\theta_{12}cos\theta_{12}sin\theta_{23}cos\theta_{23}sin\delta_{CP} \\ &= 0.03359 \pm 0.0006(\pm 0.0019)sin\delta_{CP}. \end{aligned}$$

This factor has the same form for the oscillations of all the neutrino flavors and finally is a function of CP violating phase. Using the current measured values of the mixing angles and squared mass differences and taking the distance of neutrino propagation as L=1300 Km, we have the numeric values for the neutrino oscillations at $E_\nu = 7$ (5) GeV (see Figure 3.):

- $P(\nu_\mu \to \nu_\tau)$ =0.2916 $\pm$0.0026 sin δ_{CP} (0.5093 $\pm$ 0.0048 sin δ_{CP}),
- $P(\nu_\mu \to \nu_e)$ =0.0151 $\mp$0.0026 sin δ_{CP} (0.0264 $\mp$ 0.0048 sin δ_{CP}),
- $P(\nu_e \to \nu_\tau)$ =0.0119 $\mp$0.0026 sin δ_{CP} (0.0209 $\mp$ 0.0048 sin δ_{CP}),
- $P(\nu_e \to \nu_\mu)$ =0.0151 $\pm$0.0026 sin δ_{CP} (0.0264 $\pm$ 0.0048 sin δ_{CP}).

The ‘+’ sign is for neutrino oscillation, while ‘-’ sign is for anti-neutrino oscillation.

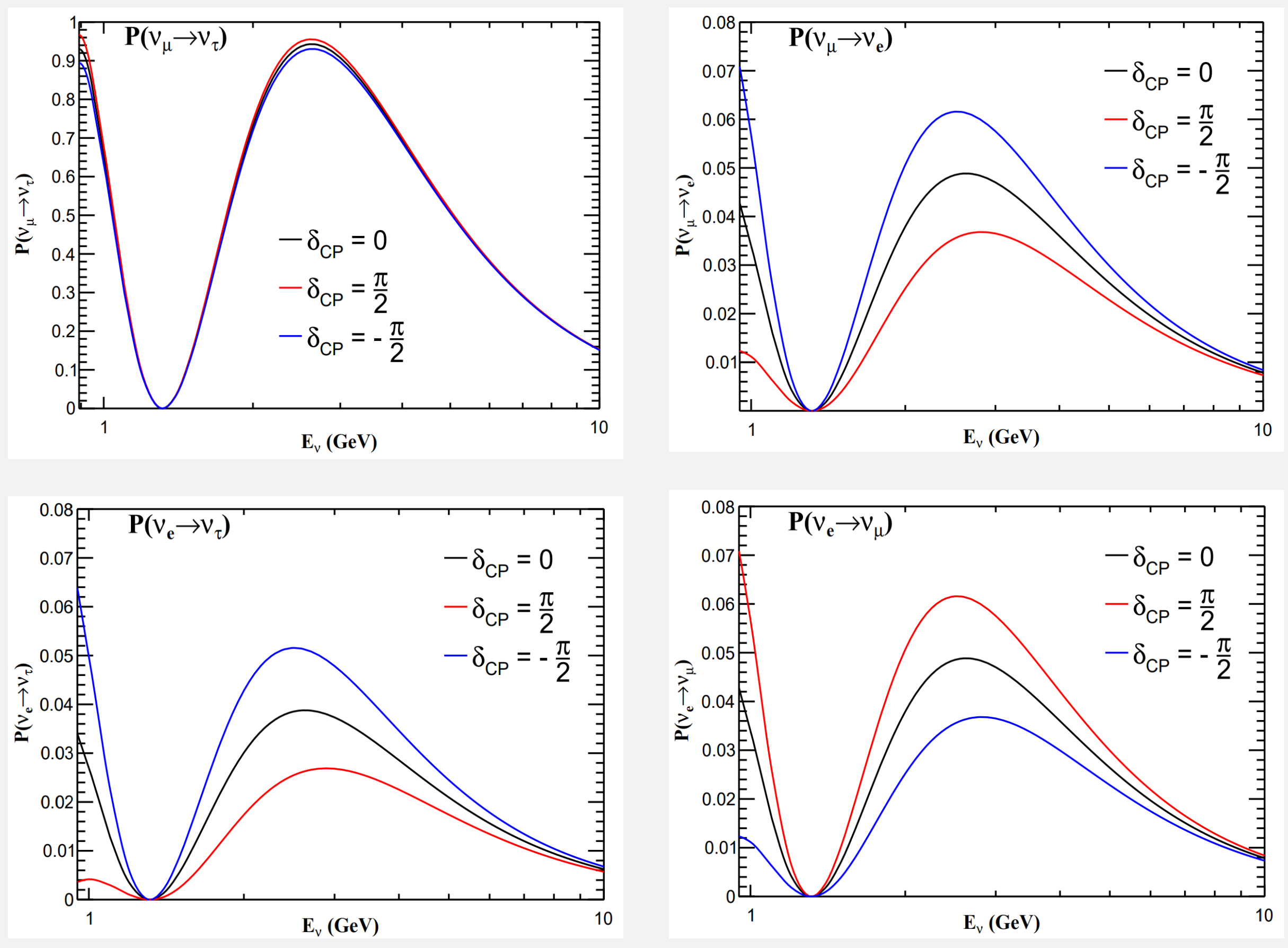

Fig. 3. The oscillation probability of $\nu_\mu \to \nu_\tau, \nu_\mu \to \nu_e, \nu_e \to \nu_\tau$ and $\nu_e \to \nu_\mu$ at three δ_{CP} angles as function of ν_μ energy, for a long baseline of L = 1300 Km. For simplicity, we follow the generic assumption that most cases the atmospheric mass difference dominates, while ignoring contributions from subleading terms.

4. Sensitivity estimation

- We consider first the tau neutrino and anti-neutrino appearance from muon and electron neutrino oscillations:

$$\begin{aligned} \mu^+ \to e^+\,\bar{\nu}_{\mu1}\,\nu_{e1} &\implies \bar{\nu}_{\mu1} \to \bar{\nu}_{\tau1},\ \nu_{e1} \to \nu_{\tau1}, \\ \mu^- \to e^-\,\nu_{\mu2}\,\bar{\nu}_{e2} &\implies \nu_{\mu2} \to \nu_{\tau2},\ \bar{\nu}_{e2} \to \bar{\nu}_{\tau2}, \end{aligned}$$

where ‘1’ and ‘2’ represents the two far detectors as shown in Fig.1 . According to the given numbers and the oscillation probability in section 2 & 3, we can estimate tau neutrino CC events per year as :
$N^{cc}_\tau \sim [(3 \times 10^4) \pm (2.6 \times 10^2)]/year,$
where (2.6×10^2) corresponds to the CP violation term. If we count on tau-related events in the far detector inclusively, our signals double. The sensitivity can be estimated then as:

$$\frac{\bar{\nu}_{\tau2} + \nu_{\tau2} - \bar{\nu}_{\tau1} - \nu_{\tau1}}{\sqrt{\bar{\nu}_{\tau2} + \nu_{\tau2} + \bar{\nu}_{\tau1} + \nu_{\tau1}}}$$

which is around 4.2 σ level in one year and can excess 5 σ within within 2 years of running.

- If the detector can distinguish tau neutrino from anti-neutrino such as the CERN SHiP experiment,

$$\frac{\bar{\nu}_{\tau2} - \nu_{\tau1}}{\sqrt{\bar{\nu}_{\tau2} + \nu_{\tau1}}}$$

then with only $P(\nu_e \to \nu_\tau)$, we could have higher CP sensitivity around 11 σ in one year alone!

- We can also exploit electron to muon oscillation which has also clear sensitivity on neutrino CP phase, if the far detector can distinguish muon neutrino from antineutrino, possibly can be achieved with moderate magnets. The sensitivity can be estimated then to be 9.5 σ in one year.

5. Summary and outlook

We propose here a new idea to exploit collimated muon beams which generate symmetric neutrino and anti-neutrino sources:$\mu^+ \to e^+\bar{\nu}_\mu\nu_e$ and $\mu^- \to e^-\nu_\mu\bar{\nu}_e$. Interfacing with long base line neutrino detectors, this experiment can be useful to probe neutrino CP phase as well as the properties of tau neutrinos, by measuring muon anti-neutrino disappearance or tau anti-neutrino appearance, and differences between neutrino and antineutrino rates. There are several significant benefits leading to large neutrino flux and high sensitivity on CP phase, including 1) collimated and manipulable muon beams, which lead to a larger acceptance of neutrino sources in the far detector side; 2) symmetric muon and anti-muon beams, and thus symmetric neutrino and anti-neutrino sources, which make this proposal an ideal method to measure CP violation. 3) Importantly, there are approximately 10^4 tau neutrinos and anti-neutrinos can be collected per year, so this makes our experiment as brighter tau neutrino factory. Moreover, 5 σ deviations of sensitivity can be easily reached for CP phase as $|\pi/2|$ within one year of data taking.

As future prospects, the existence of sterile neutrinos is still controversial, based on earlier and recent measured results of LSND, MiniBooNE experiments. Given that the rich flux of both the muon and electron neutrinos produced after muon decay, our proposal may serve as a potential tool to probe sterile neutrino related parameters, such as Δm^2_{41} and additional CP violating phases!

6. Reference

Alim Ruzi, Tianyi Yang, Dawei Fu, Sitian Qian, Leyun Gao, and Qiang Li. arXiv: 23 01.02493