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Matter effects in long-baseline neutrino experiments

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The search for CP violation in the lepton sector is one of the central goals of modern neutrino physics, motivated by the need to explain the matter–antimatter asymmetry of the Universe. In long-baseline accelerator experiments, the interpretation of neutrino and antineutrino appearance signals is complicated by matter effects: coherent forward scattering in the Earth can mimic or modify genuine CP violation. We study these effects in the T2K and NOvA experiments within the standard three-flavour oscillation picture, comparing the vacuum case with realistic matter potentials. Using CP-odd ellipses as a visualisation tool, we scan the unknown CP phase over its full range and plot the corresponding neutrino and antineutrino probabilities. The ellipses are constructed for different values of the atmospheric mixing angle, including maximal mixing and both octants, and for several matter densities. The parametric degeneracy between the CP phase and the octant of the atmospheric mixing angle remains a fundamental challenge. T2K provides a cleaner measurement of CP violation because its matter effect is small, whereas NOvA is more sensitive to the mass hierarchy because its matter effect is large. This complementarity makes a joint analysis essential for separating intrinsic CP violation from matter-induced asymmetries. The next generation of long-baseline experiments, especially DUNE, will address these challenges directly. With a 1300-kilometre baseline, higher neutrino energies and a large liquid-argon detector, DUNE will experience strong matter effects and will be able to determine the mass hierarchy and search for CP violation with high sensitivity. Extending the CP-odd ellipse approach to DUNE will help optimise the separation of genuine CP violation from matter effects and clarify the role of the octant degeneracy. Together with Hyper-Kamiokande, DUNE is expected to provide a decisive test of CP violation in the lepton sector.

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