# Alternate methods to distinguish CP violation from Matter Effects in Neutrino Oscillation Experiments

Pokhee Saharia [1] Prof. Federico Sanchez [2] Dr. Satyajit Jena [1]

[1]Indian Institute of Science Education and Research, Mohali [2]University of Geneva

## CP Violation in Neutrino Oscillations

- Neutrinos are elementary particles within the framework of the Standard Model of particle physics - occur in three flavors. A neutrino beam propagating through space can change flavor from one point to another, in other words, they *oscillate*. The existence of neutrino oscillations are the only proof of BSM physics that is directly accessible experimentally in our labs
- Charge-Parity is a fundamental symmetry in Physics, and the breaking of it is referred to as CP violation. It answers the question - how differently do particles and their antiparticles behave? Therefore, CP violation in neutrino oscillations - how differently do neutrinos and antineutrinos oscillate? The measurement of CP violation in the leptonic sector could lead to answers about the matter-antimatter asymmetry in the universe after the Big-Bang

### Matter Effects in CP violation

Matter is CP asymmetric, hence it affects neutrino and antineutrinos differently when they propagate. This leads to a "matter-induced" component of CP violation in neutrino oscillations, in addition to the genuine component - hindrance in measuring a genuine signal for CP violation. However, these two components come from different origins, and it is possible to exploit this factor to identify possible energy regions where the components can be separated [1].

## The T2K Experiment

- Long baseline neutrino experiment in Japan to probe the $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ channels, and their respective disappearance channels
- JPARC (Tokai) provides an intense beam of accelerated protons which collides on a graphite target (carbon). It produces a bunch of charged mesons - guided with magnetised horns before they decay into neutrinos
- Neutrinos detected 295km away into the water Cherenkov detector Super-Kamiokande (SK) to study the oscillations. Set of Near Detectors (ND280) are placed near the production site to provide strong contraints on the systematic uncertainties (flux + X-section)

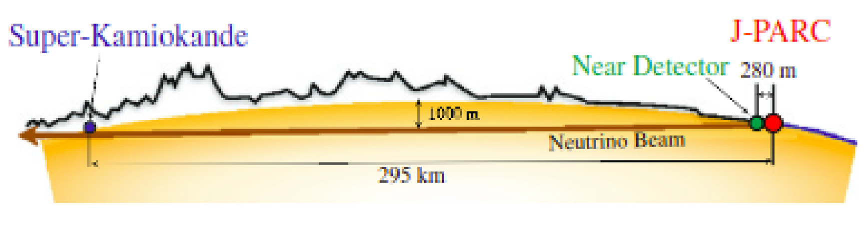


**Fig. 1:** Schematic layout of the T2K experiment

## Research objectives

- Study the percentage of corrections imposed by the matter effects on the total oscillation probability
- Identify a region of interest in the observable phase space of the T2K Near Detector where the corrections have a maximal effect

## Analysis of Transition Probabilities

- Decompose the transition probability as a linear combination of trigonometric functions of the CP violating phase $\delta$

$$P_{\nu_\mu\to\nu_e}(E_\nu,\delta) = A0 + A1\sin(\delta) + A2\cos(\delta) + A3\sin(2\delta) + A4\cos(2\delta) + ....$$
$$P_{\bar{\nu}_\mu\to\bar{\nu}_e}(E_{\bar{\nu}},\delta) = \bar{A}0 + \bar{A}1\sin(\delta) + \bar{A}2\cos(\delta) + \bar{A}3\sin(2\delta) + \bar{A}4\cos(2\delta) + .... \quad (1)$$

- Compute the fourier transforms of the individual terms to discern their signatures as a function of the neutrino energy

$$A0 = \int_0^{2\pi} P_{\nu_\mu\to\nu_e} d\delta \quad (2)$$

.. and so on.

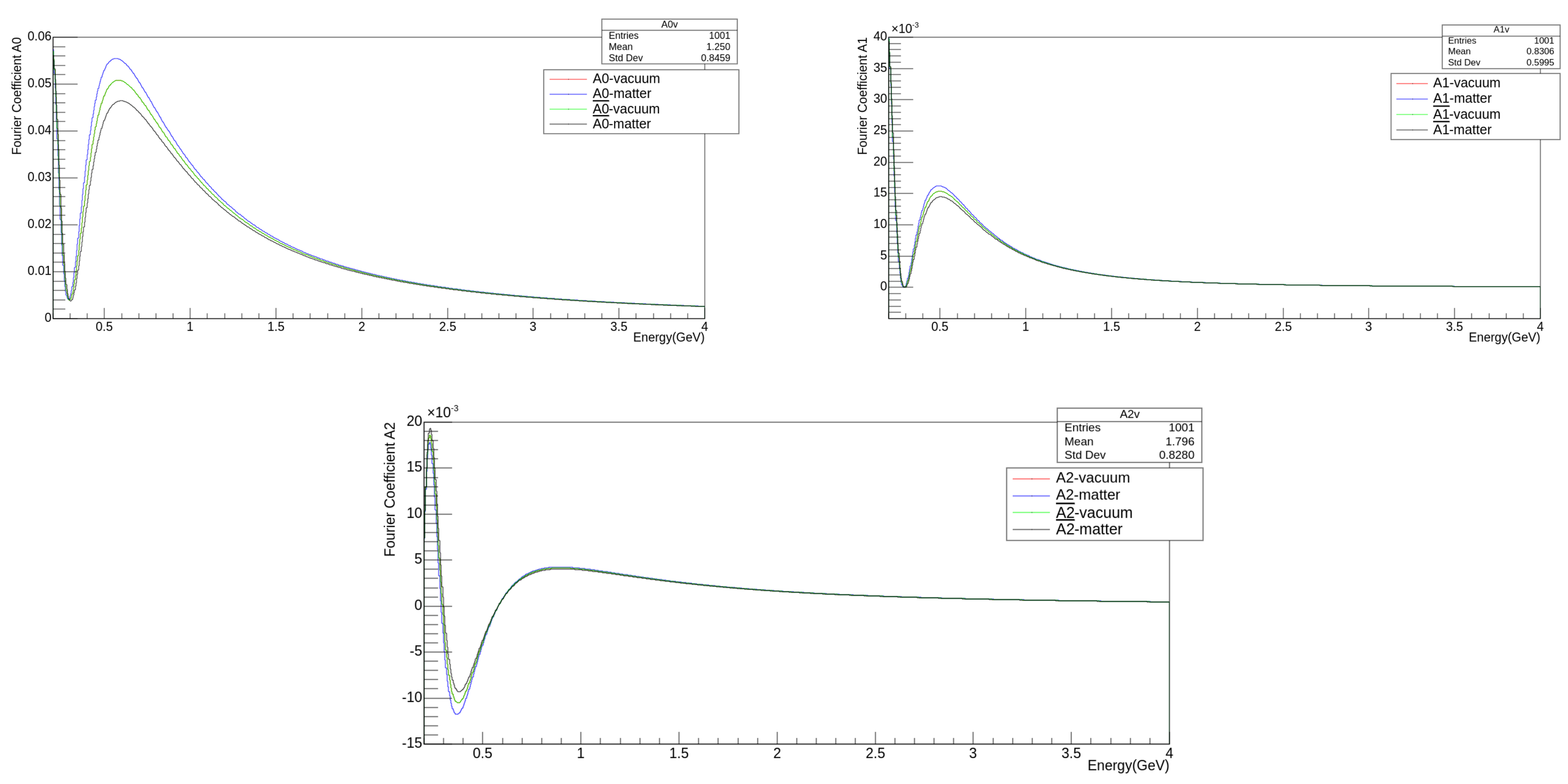

**Fig. 2:** Different signatures of the fourier coefficients

- Compute the matter corrections $\Delta\overset{(-)}{A0} = \overset{(-)}{A0}_{matter} - \overset{(-)}{A0}_{vacuum}$ (and so on) as a function of the incoming neutrino energy

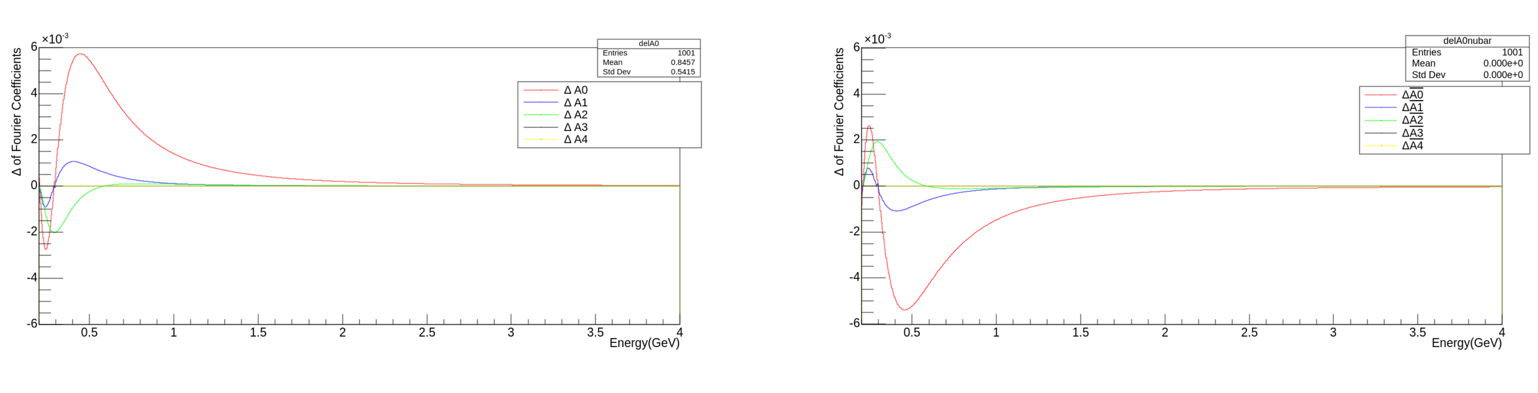

**Fig. 3:** Matter Corrections for neutrino and antineutrino oscillations

## Cross-Section Contributions

Following from Figures [2]-[3], matter effects for T2K represent $\sim$10% of the total oscillation probability, and the maximum effects of these terms manifest only in the lower neutrino energy regions.

### Neutrino-nucleus interactions

- Most common neutrino interaction in detectors - Charged Current Quasi Elastic (CCQE). The momentum and scattering angle of the outgoing lepton forms the set of detector observables.

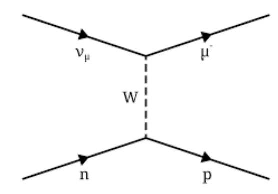

**Fig. 4:** Neutrino-nucleus CCQE interaction

- Neutrino-nucleus cross sections in detectors are the most important source of systematic errors - essential to see the fractional contribution of the matter effects for each of the fourier coefficients to the total cross section

$$N = \int (P_l, \theta_l|E_\nu).\phi.\Delta A0(E_\nu)dE \quad (3)$$

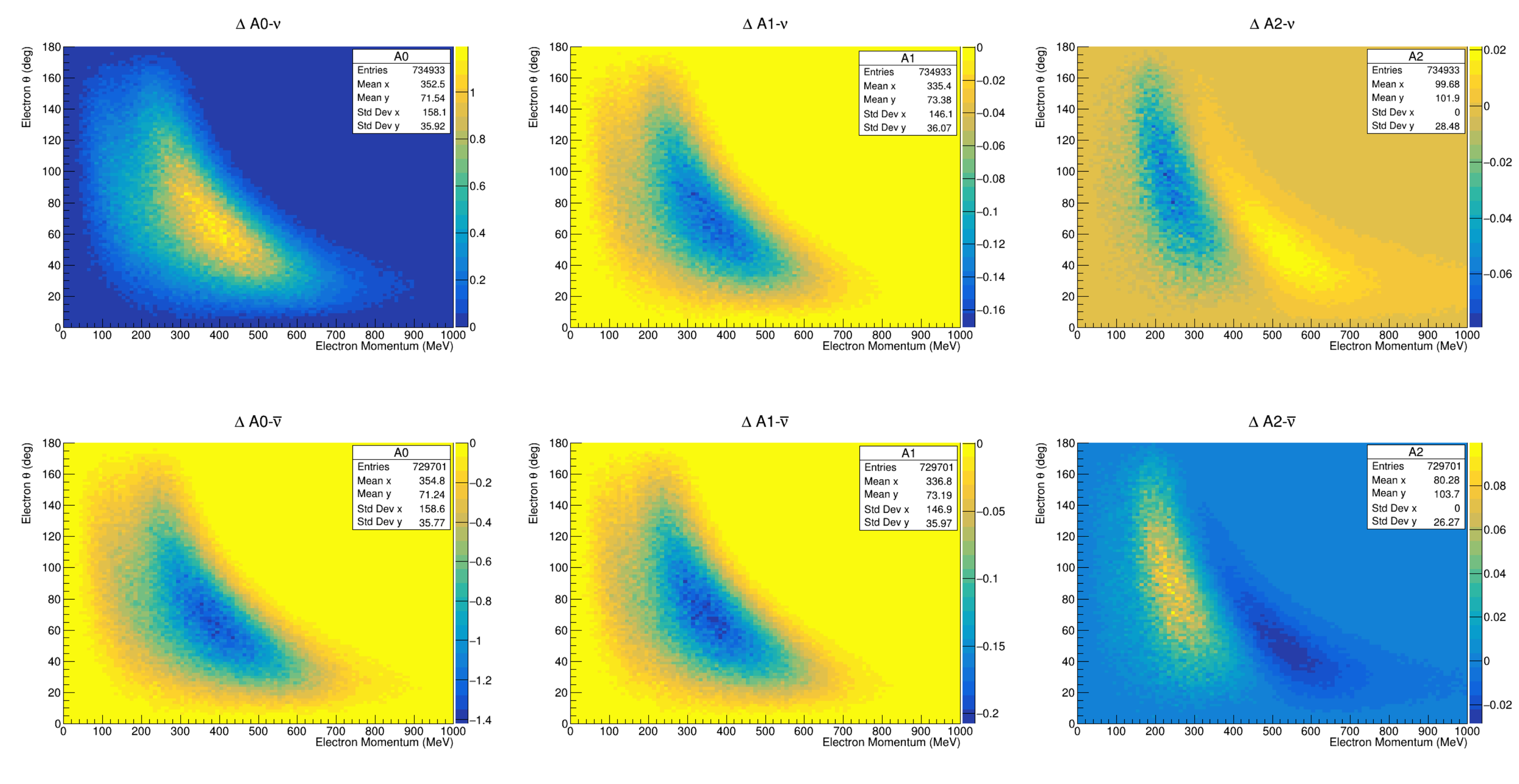

**Fig. 5:** Comparison of the parameter weights on the cross-section for neutrinos and antineutrinos

### Neutrino-electron interactions

- Neutrino-electron interactions probe an energy region much lower than neutrino-nucleus interactions, due to the difference in masses of the two targets

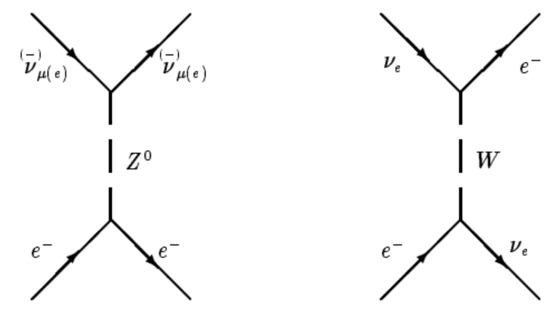

**Fig. 6:** Elastic neutrino-electron scattering

- A similar weightage analysis of the parameters on the phase space of the electron - energy region of a very narrow band where the matter effects manifest

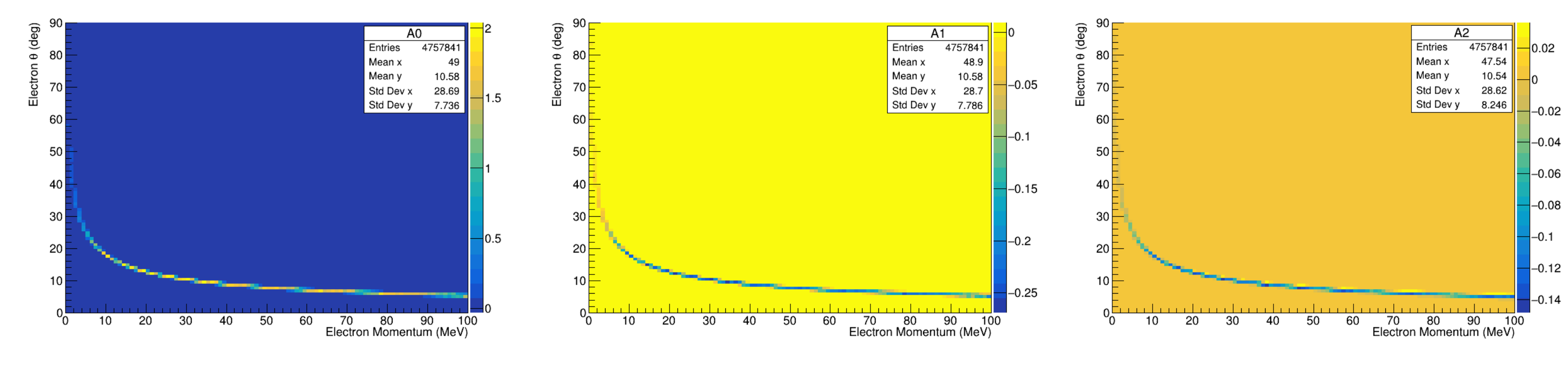

**Fig. 7:** Parameter weights on the neutrino-electron scattering cross section

## Summary and further discussions

- Studied the oscillation probability in T2K to identify the signal region of the energy spectrum where the delta CP effect is the strongest – through a **fourrier decomposition of the total probability**
- This is **correlated with matter effects (MSW)**. For T2K ( 300km), the matter effects are at most 10% of the CP asymmetry - well suited to measure delta CP regardless of the mass hierarchy
- Identified the **region in the reconstructed variable (in neutrino-nucleus interactions) where each $A_i$ component has an effect** - very low energy regions, not probed well with said interactions
- **Similar analysis with MC events of neutrino-electron scattering** - a very narrow spectrum, as opposed to an expected dispersion, because of a limited range in energy
- Presents a precedent for **similar analyses on neutrino-electron scattering interactions for flux prediction in future experiments** (DUNE, HyperK) with better statistics

## References

[1] Alejandro Segarra. "Breaking of Discrete Symmetries and Global Lepton Number in Neutrino Physics". PhD thesis. IFIC, 2019.