INO India-based Neutrino Observatory

Matter vs Vacuum Oscillations in Atmospheric Neutrinos [arXiv : 1907.08966]

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ABSTRACT : At present, both vacuum oscillations as well as matter modified oscillations can explain the data of atmospheric neutrino experiments and the long baseline accelerator neutrino experiments equally well. Given the important role the matter effects play in the determination of CP violation in neutrino oscillations, it is imperative to establish the signal for matter effects unambiguously. In this work, we study the ability of ICAL at INO to make a distinction between vacuum oscillations and matter modified oscillations. We find that it is possible to obtain a 3 σ discrimination in ten years irrespective of whether the atmospheric mass square difference is positive or negative.

Motivation

- Neutrino oscillations, driven by the larger mass-squared difference Δ_{31} are observed by the atmospheric neutrino experiment Super-Kamiokande [1] and the long-baseline accelerator neutrino experiments MINOS [2], T2K [3] and NOvA [4].
- The main oscillation signature in all these experiments is the deficit of ν_μ / $\bar{\nu}_\mu$ event rate compared to the expected value.
- This deficit in all these experiments was analyzed initially under the hypothesis of **vacuum oscillations**.
- Due to the propagation of the neutrinos through earth matter, it is expected that the oscillation probabilities would be modified by matter effects.
- In the case of long-baseline accelerator experiments, the survival probabilities $P_{\mu\mu}$ and $P_{\bar{\mu}\bar{\mu}}$ are essentially the same for vacuum and for matter modified oscillations. Hence the values of $|\Delta_{31}|$and $\sin 2\theta_{23}$ obtained will be the same for both the hypotheses.
- In the case of atmospheric neutrinos, $P_{\mu\mu}$ and $P_{\bar{\mu}\bar{\mu}}$ are expected to undergo significant changes due to matter effects. However, at present Super-Kamiokande is able to make only a small distinction between them [5].
- In the long-baseline accelerator experiment, the ν_e / $\bar{\nu}_e$ appearance data is sensitive to matter effects. But they are also sensitive to the unknown CP violating phase δ_{CP} . Hence the present long-baseline accelerator neutrino experiments can not make a distinction between vacuum and matter modified oscillations, even with the inclusion of the appearance data [6].
- Given the matter effect - δ_{CP} degeneracy, it is imperative to establish the signal for matter effects independently before measuring $\delta_{CP.}$
- The charge identification capability of ICAL at INO gives it a good ability to distinguish between vacuum oscillations and matter modified ones.

Matter vs Vacuum Oscillation

- While propagating through earth matter, electron neutrinos are expected to undergo forward elastic scattering with electrons via CC interaction. This induces a potential for the electron neutrinos. Consequently the oscillation probabilities change.
- The matter modified oscillation probabilities are calculated numerically using nuCraft [7].
- Matter effect reduces $P_{\mu\mu}$ and keeps $P_{\bar{\mu}\bar{\mu}}$ unaltered for NH (Δ_{31} positive). Situation is reversed for IH (Δ_{31} negative).(as illustrated in the figure below).
- So matter vs. vacuum oscillation discrimination will come from μ^- data for NH and μ^+ data for IH.

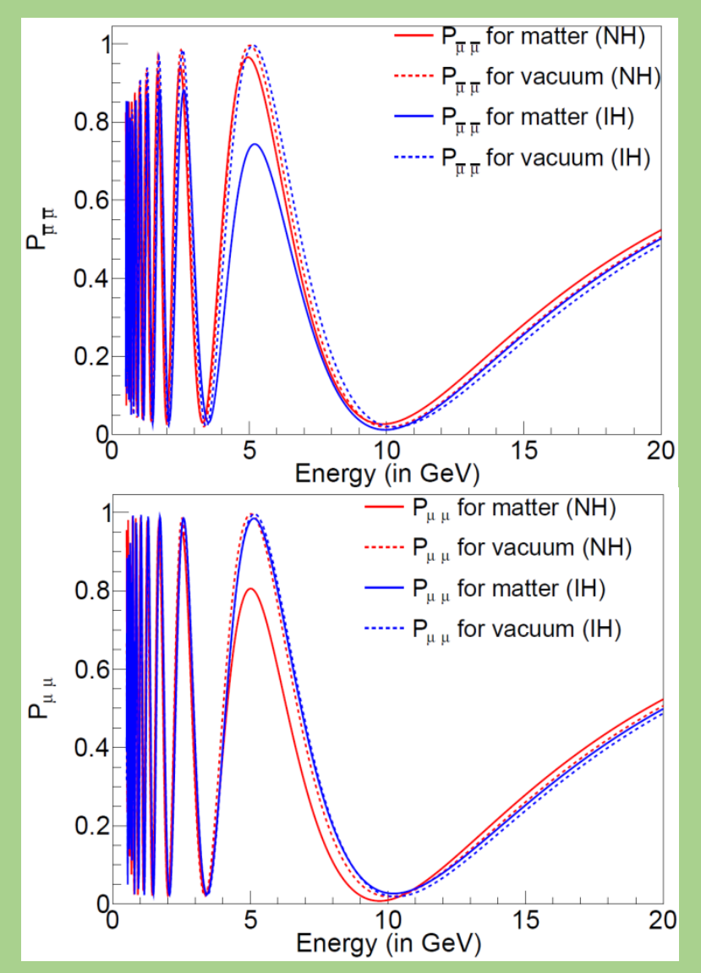

Figure : 1 Oscillation Probabilities for 5000 km

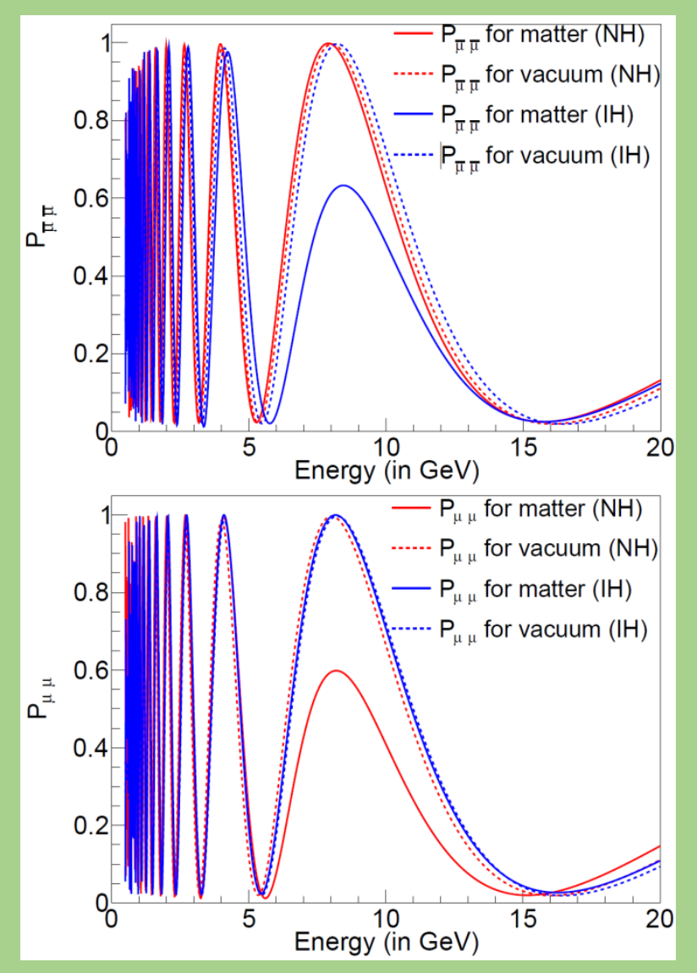

Figure : 2 Oscillation Probabilities for 8000 km

Methodology

- NUANCE [8] event generator is used to simulate the atmospheric neutrino events in the detector. NUANCE provides the particle ID and momenta of all interacting particles.
- The final state particle information is then passed to GEANT4 simulator of ICAL. The simulator mimics the ICAL response.
- The reconstruction code [9], from the hits in the detector forms tracks of muons and reconstructs their momenta and directions.
- This reconstructed energy and direction of tracks have been used to bin the events.
- For this work 500 years of un-oscillated neutrino data was produced using Kamioka flux. NUANCE takes the ICAL geometry as input also.
- ν_μ / $\bar{\nu}_\mu$ events are passed through the GEANT4 reconstruction code.
- The momentum and direction of the reconstructed tracks are stored. The charge of the particle is stored.
- Oscillated ν_e / $\bar{\nu}_e$ events will contribute to ν_μ / $\bar{\nu}_\mu$ events. To take this contribution into account, we took all ν_e / $\bar{\nu}_e$ events and redefined e^- / e^+ as μ^- /μ^+ respectively.
- These redefined μ^- and μ^+ events are reconstructed using ICAL code.

Parameters used for Vacuum and Matter oscillation

- Varying $\sin^2\theta_{12}$ and Δ_{21} in their 3σ range has negligible effect on the probabilities so they were kept fixed.
- $\sin^2\theta_{13}$ and Δ_{31} have been varied in their 2σ range.
- $\sin^2\theta_{23}$ has been varied over a range from 0.4 to 0.64.
- Matter and vacuum oscillation discrimination is insensitive to δ_{CP} .
- The parameter values shown in Table 1 have been used for matter oscillation.

Parameter	NH	IH
$\sin^2\theta_{12}$	0.310	0.310
$\sin^2\theta_{13}$	0.02240	0.02263
$\sin^2\theta_{23}$	0.582	0.582
Δ_{31}	$2.525 * 10^{-3}$ eV^2	$-2.505 * 10^{-3}$ eV^2
Δ_{21}	$7.39 * 10^{-5}$ eV^2	$7.39 * 10^{-5}$ eV^2
δ_{CP}	0°	0°

Table : 1 Parameters used for matter oscillation

Binning Scheme

- The matter oscillated events are used as data and two sets are formed N_{ij}^{data,μ^-}, N_{ij}^{data,μ^+}.
- 17 track momentum and 90 track direction bins are used.
- The momentum bins are (1,2), (2.0,2.2), (2.2,2.4), (2.4,2.6), (2.6,2.8), (2.8,3.0), (3.0,3.5), (3.5,4.0), (4.0,4.5), (4.5,5.0), (5.0,6.0), (6.0,7.5), (7.5,9.0), (9.0,11.0), (11.0,14.0), (14.0,20.0), (20.0,100.0).
- Oscillation signature is only visible for upgoing events so only positive values of $\cos\theta_{track}$ is considered.
- Horizontal events have poor track reconstruction. So we considered $\cos\theta_{track}$ in the range 0.1 to 1.0.
- As track direction reconstruction is very accurate, the $\cos\theta_{track}$ bin is taken to be 0.01.

χ^2 Calculation

- Vacuum oscillation as a hypothesis was tested against the data, described above.
- Using vacuum hypothesis two other samples have been created N_{ij}^{vac,μ^-}, N_{ij}^{vac,μ^+}.
- We calculate the test event samples N_{ij}^{test,μ^-} and N_{ij}^{test,μ^+} as follows $N_{ij}^{test,\mu^-/\mu^+} = N_{ij}^{vac,\mu^-/\mu^+}[1 + \pi_{ij}^k \xi_k]$
- Here we have considered three systematic errors π_{ij}^k (k = 1, 2, 3) each with its pull parameter ξ_k. The first systematic error is of flux normalization, which is independent of track momentum and track direction. The second one is the systematic error in track momentum and the third one is the error in track direction.
- We take π_{ij}^{norm}= 0.2, independent of track momentum or direction.
- We constructed a transfer matrix to convert event spectrum in neutrino energy to event spectrum in track momentum. Using this transfer matrix we have calculated the second systematic error, $\pi_{ij}^{trkmm} = \pi_i^{trkmm}$, using the tilt error in atmospheric neutrino calculation.
- A similar procedure is used to calculate the third systematic error, $\pi_{ij}^{trkdir} = \pi_j^{trkdir}$, from the direction dependent systematic error of atmospheric neutrino.
- We used the Poissionian definition of χ^2 and also added the prior ξ_k^2 for the pull parameters.

Marginalization

- Marginalization over $\sin^2\theta_{13}$, Δ_{31} , $\sin^2\theta_{12}$ and Δ_{21} has no effect on χ^2 minimization.
- Marginalization for $\sin^2\theta_{23}$ has been done in the range 0.4 to 0.64 in steps of 0.02.
- ξ_k has been varied in steps of 0.1 between -3 to 3.
- Marginalization over δ_{CP} has been carried out, using four test values, 0°, 90°, 180°, 270°. These has negligible effect on χ^2 minimum.
- Present global best fit value of δ_{CP} is closed to 270°. We repeated our calculation with this as input value for matter oscillations. The results are unchanged.

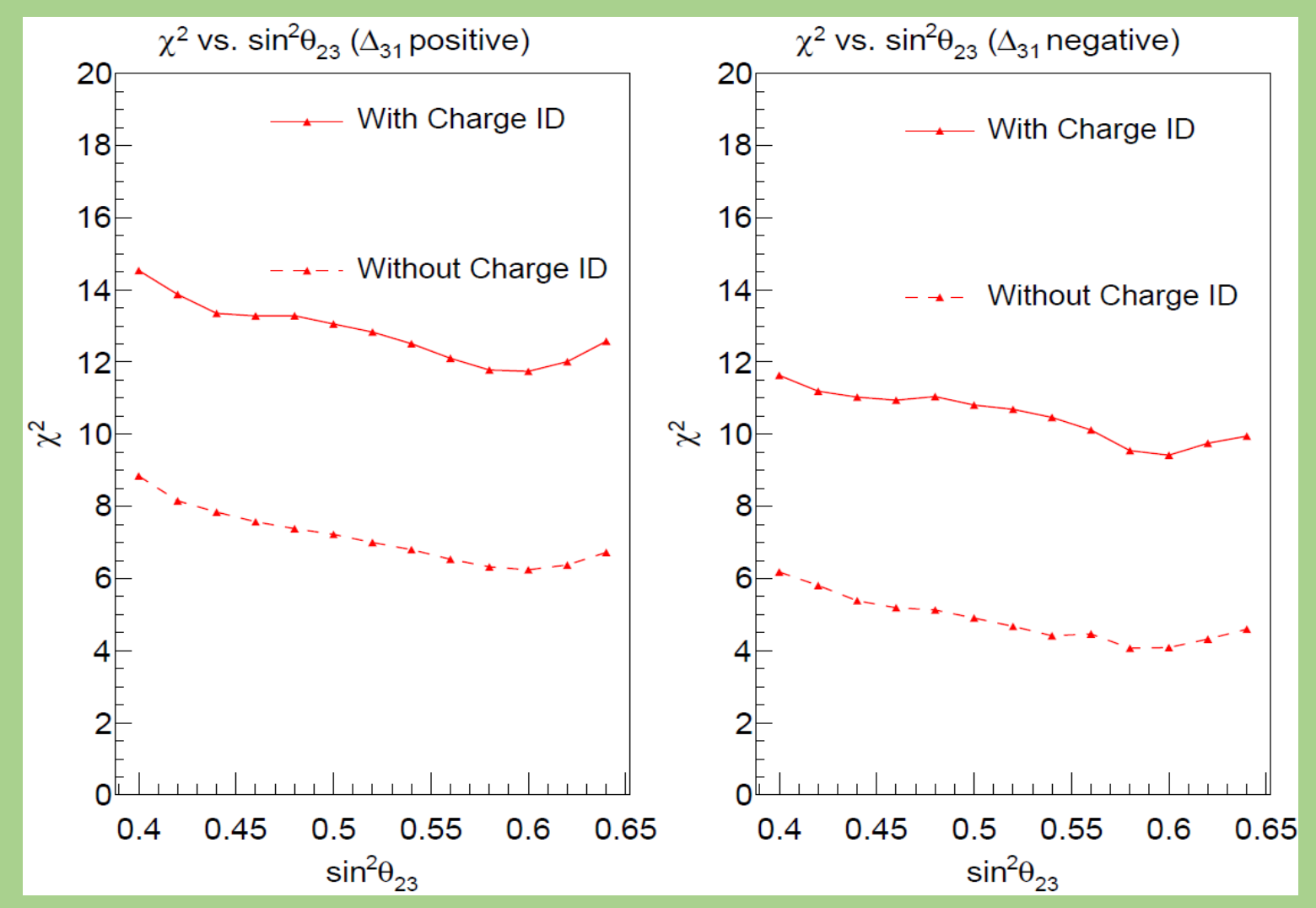

Figure : 3 Sensitivity of ICAL to matter vs. vacuum oscillations assuming with and without charge identification

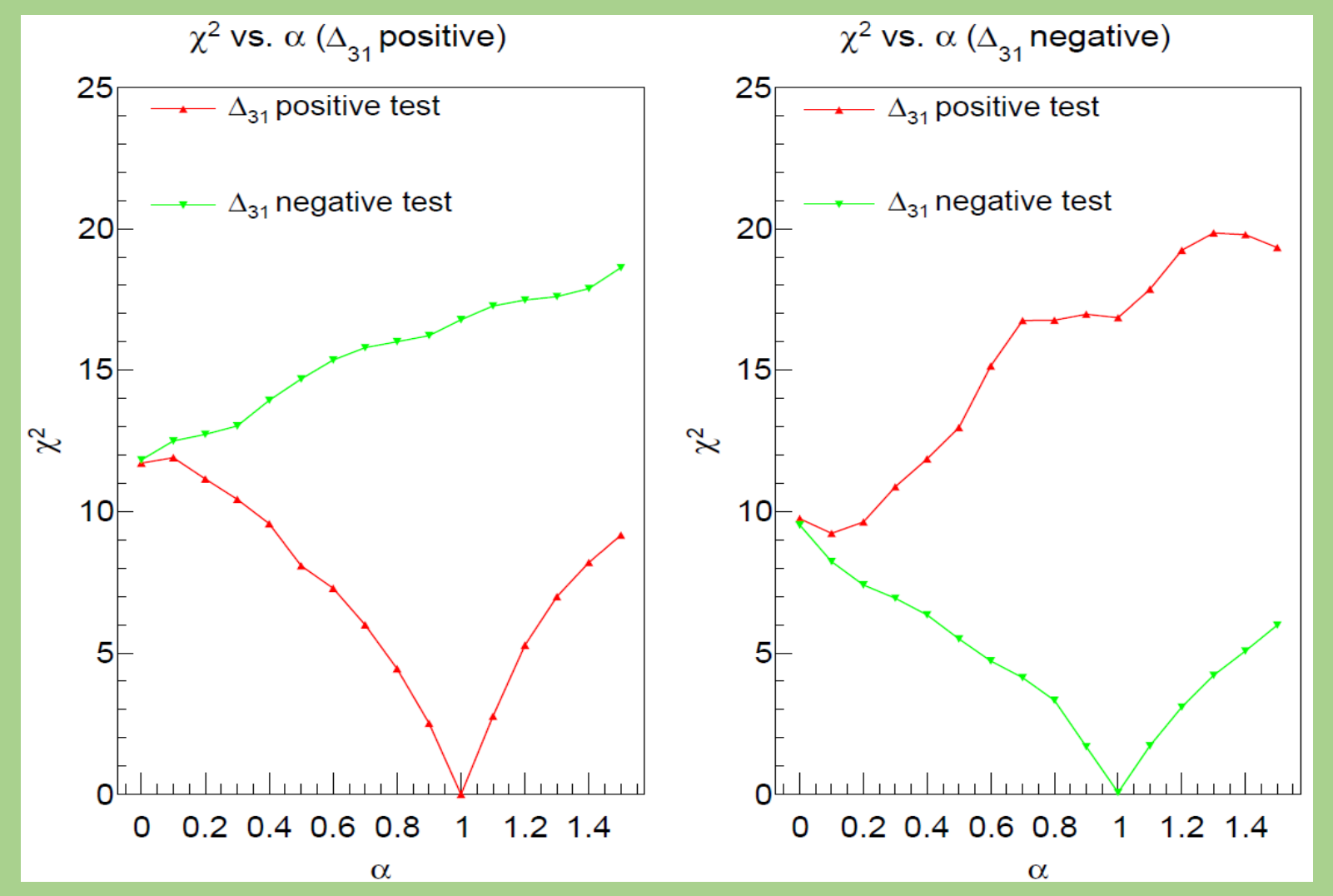

Figure 4 Sensitivity of ICAL to fractional matter effects

Results

- From figure 3 we see that ICAL is capable of distinguishing between vacuum and matter modified oscillation with χ^2 = 11.8 (9.5) for NH (IH).
- As discussed earlier, the charge discrimination capability of ICAL plays an important role in making a distinction between vacuum and matter modified oscillations. To illustrate its importance, we repeated our calculation assuming no charge identification. This reduces χ^2 by half (figure 3).
- Recently Super-Kamiokande looked for non standard matter effect [5]. They parameterized the matter term as (α * standard matter term) and varied α in the range 0, 2. The vacuum oscillation corresponds to the case α = 0 and standard matter oscillation corresponds to α = 1. Super-K disfavors vacuum oscillation with $\Delta\chi^2 = 5$ for positive Δ_{31} (NH) and α =1. Negative Δ_{31} (IH) was disfavored for all values of α with $\Delta\chi^2$ in the range 5 to 6.
- We carried out a similar work for ICAL. From figure 4, we can see that ICAL can rule out the wrong sign of Δ_{31} for any value of α very effectively

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