

# Matter vs Vacuum Oscillation in Atmospheric Neutrinos

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WORK DONE WITH

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**INO** India-based  
Neutrino  
Observatory



# Motivation

- ▶ Neutrino oscillations, driven by the larger mass-squared difference  $\Delta_{31}$  have been observed by the atmospheric neutrino experiment Super-Kamiokande and long-baseline accelerator neutrino experiments MINOS, T2K and NO $\nu$ A.
- ▶ The main oscillation signature in all these experiments is the deficit of  $\nu_{\mu} / \bar{\nu}_{\mu}$  event rate compared to the expected value. This deficit in all these experiments was analyzed initially under the hypothesis of **vacuum oscillations**.
- ▶ 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 [arXiv:0707.1723]. Hence the values of  $|\Delta_{31}|$  and  $\sin 2\theta_{23}$  obtained will be very close for both the hypotheses.

# Motivation

- For long-baseline accelerator experiments, the  $\nu_e / \bar{\nu}_e$  appearance data is sensitive to matter effects. But they are also sensitive to the unknown CP violating phase  $\delta_{\text{CP}}$ . 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 [arXiv:hep-ph/0002108[hep-ph]].

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 \hat{\Delta}(1 - \hat{A})}{(1 - \hat{A})^2} + \\
 & \alpha \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\hat{\Delta} + \delta_{\text{CP}}) \frac{\sin \hat{\Delta} \hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1 - \hat{A})}{1 - \hat{A}} \\
 \hat{\Delta} = & 1.27 \Delta_{31} L/E, \quad \hat{A} = A/\Delta_{31}
 \end{aligned}$$

# Motivation

- ▶ Matter effects are well established in the oscillations driven by the smaller mass square difference  $\Delta_{21}$ . CHOOZ bound on  $\theta_{13}$  and SNO analysis gives  $5\sigma$  evidence of matter effects in solar neutrinos. [arxiv: hep-ph/0506083]
- ▶ But the atmospheric neutrino oscillation in earth matter and solar neutrino oscillation in Sun, are driven by  $\Delta_{31}$  and  $\Delta_{21}$  respectively.
- ▶ The energy range of the neutrinos are of different magnitude. For solar neutrinos the maximum energy is 18 MeV. Whereas the minimum energy of atmospheric neutrinos is few hundreds of MeV and maximum flux is at energy of GeV order.
- ▶ Also the neutrinos experience different kind of matter density.
- ▶ Given these the survival and oscillation probabilities take completely different form for atmospheric and solar neutrinos.

# Motivation

- ▶ 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 ( $\sim 1.6\sigma$ ) between them [arXiv:1710.09126 [hep-ex]].
- ▶ Given the matter effect -  $\delta_{CP}$  degeneracy, the determined value of  $\delta_{CP}$  depends on the oscillation hypothesis to fit the data (vacuum vs. matter modified).
- ▶ Therefore it is imperative to establish the signal for matter effects independently before measuring  $\delta_{CP}$ .
- ▶ The charge identification capability of ICAL [arXiv:1505.07380] at INO gives it a good ability to distinguish between vacuum oscillations and matter modified ones.

# Matter vs Vacuum Oscillation

- ▶ The matter modified oscillation probabilities have been calculated numerically using nuCraft [arXiv:1409.1387 [astro-ph.IM]].
- ▶ So matter vs. vacuum oscillation discrimination will come from  $\nu_\mu$  disappearance data for NH and  $\bar{\nu}_\mu$  disappearance data for IH.

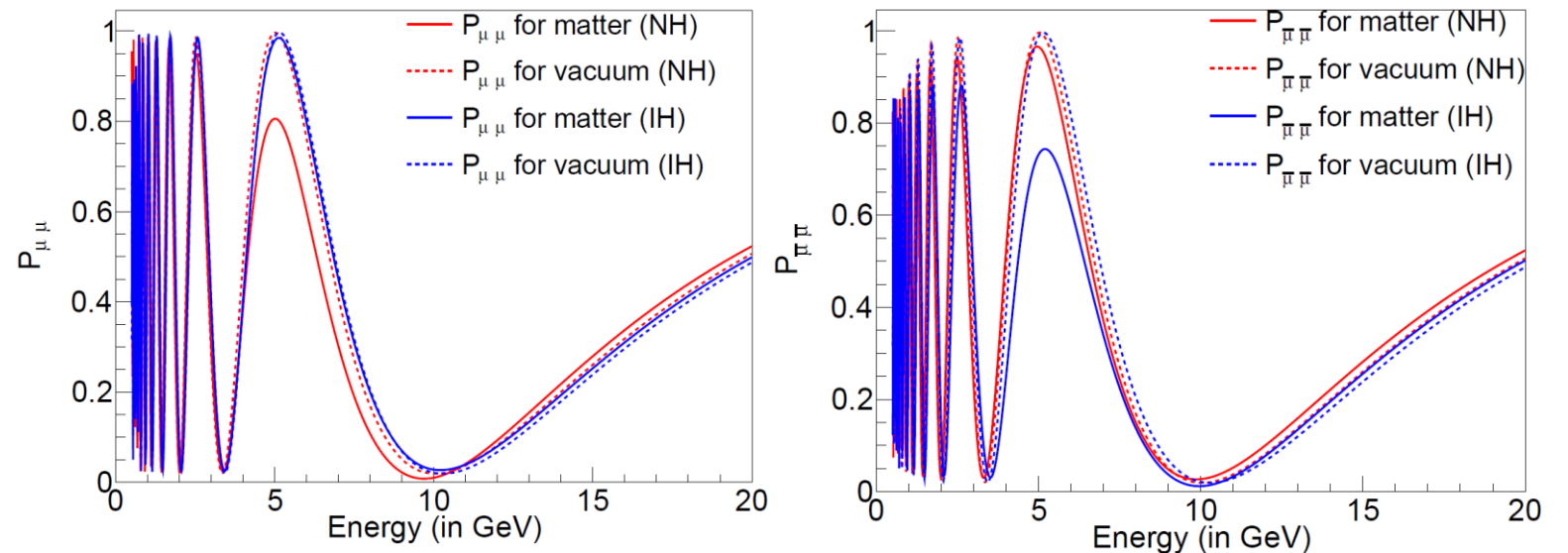


Figure : 1 Oscillation Probabilities for 5000 km

# Methodology

- ▶ NUANCE [arXiv: hep-ph/0208030] event generator is used to simulate 500 years of unoscillated atmospheric neutrino events in the detector using Kamioka flux. 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 [arXiv: 1510.02792], from the hits in the detector forms tracks of the muons and reconstructs their momenta, directions and charge.
- ▶ This reconstructed energy and direction of tracks have been used to bin the events.
- ▶ Oscillated  $\nu_e / \bar{\nu}_e$  events will contribute to  $\nu_\mu / \bar{\nu}_\mu$  events. To take this contribution into account, we took all  $\nu_e / \bar{\nu}_e$  events and redefined  $e^- / e^+$  as  $\mu^- / \mu^+$  respectively.
- ▶ These redefined  $\mu^-$  and  $\mu^+$  events are reconstructed using ICAL code.

# Oscillation Parameters

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
$\Delta_{31}$	$2.525 * 10^{-3} \text{ eV}^2$	$-2.505 * 10^{-3} \text{ eV}^2$
$\Delta_{21}$	$7.39 * 10^{-5} \text{ eV}^2$	$7.39 * 10^{-5} \text{ eV}^2$
$\delta_{CP}$	$0^\circ$	$0^\circ$

- ▶ The parameter values shown in adjacent table have been used for matter oscillation.
- ▶ Varying  $\sin^2\theta_{12}$  and  $\Delta_{21}$  in their  $3\sigma$  range has negligible effect on the probabilities so they were kept fixed for vacuum oscillation.
- ▶ When  $\sin^2\theta_{13}$  and  $\Delta_{31}$  are varied in their  $2\sigma$  ranges,  $\chi^2_{minimum}$  came at the best fit value. So marginalization was not done for them.
- ▶  $\sin^2\theta_{23}$  has been varied over a range from 0.4 to 0.64.
- ▶ Matter and vacuum oscillation discrimination is insensitive to  $\delta_{CP}$ .



# Binning Scheme

- ▶ 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  $\cos\theta_{\text{track}}$  is considered.
- ▶ For horizontal events track reconstruction is not possible. So we have considered  $\cos\theta_{\text{track}}$  in the range 0.1 to 1.0.
- ▶ As track direction reconstruction is very accurate for ICAL , the  $\cos\theta_{\text{track}}$  bin is taken to be 0.01.

# $\chi^2$ Calculation

- ▶ The matter oscillated events are used as data and two sets are formed  $N_{ij}^{data,\mu^-}$ ,  $N_{ij}^{data,\mu^+}$ .
- ▶ Vacuum oscillation as a hypothesis was tested against the data, described above.
- ▶ Using vacuum hypothesis two other samples have been created  $N_{ij}^{vac,\mu^-}$ ,  $N_{ij}^{vac,\mu^+}$ .
- ▶ We calculate the test event samples  $N_{ij}^{test,\mu^-}$  and  $N_{ij}^{test,\mu^+}$  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,  $\pi_{ij}^k$  ( $k = 1, 2, 3$ ), each with its pull parameter  $\xi_k$ . The first systematic error is dependent on flux normalization, which is independent of track momentum and track direction. The second one is the systematic error dependent on track momentum and the third one is dependent on track direction.

# $\chi^2$ Calculation

- ▶ We take  $\pi_{ij}^{norm} = 0.2$ , 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 [arXiv:hep-ph/040485].

$$\pi_{ij}^{tilt} = \pi_i^{tilt} = 0.05 * \ln\left(\frac{E_\nu}{2}\right)$$

- ▶ 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 [arXiv:hep-ph/040485].

$$\pi_{ij}^{nudir} = \pi_j^{nudir} = 0.05 * |\cos \theta_\nu|$$

- ▶ We used the Poissonian definition of  $\chi^2$  and also added the prior  $\xi_k^2$  for the pull parameters. The 500 years data and test event samples were divide by 50 to get the event samples for 10 year exposure time.

# Marginalization

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

# Result

- ▶ From **figure 2** we see that ICAL is capable of distinguishing between vacuum and matter modified oscillation with  $\chi^2 = 11.8$  (9.5) for NH (IH) for 10 years of exposure time.
- ▶ Without charge identification the value of  $\chi^2$  reduces to half.

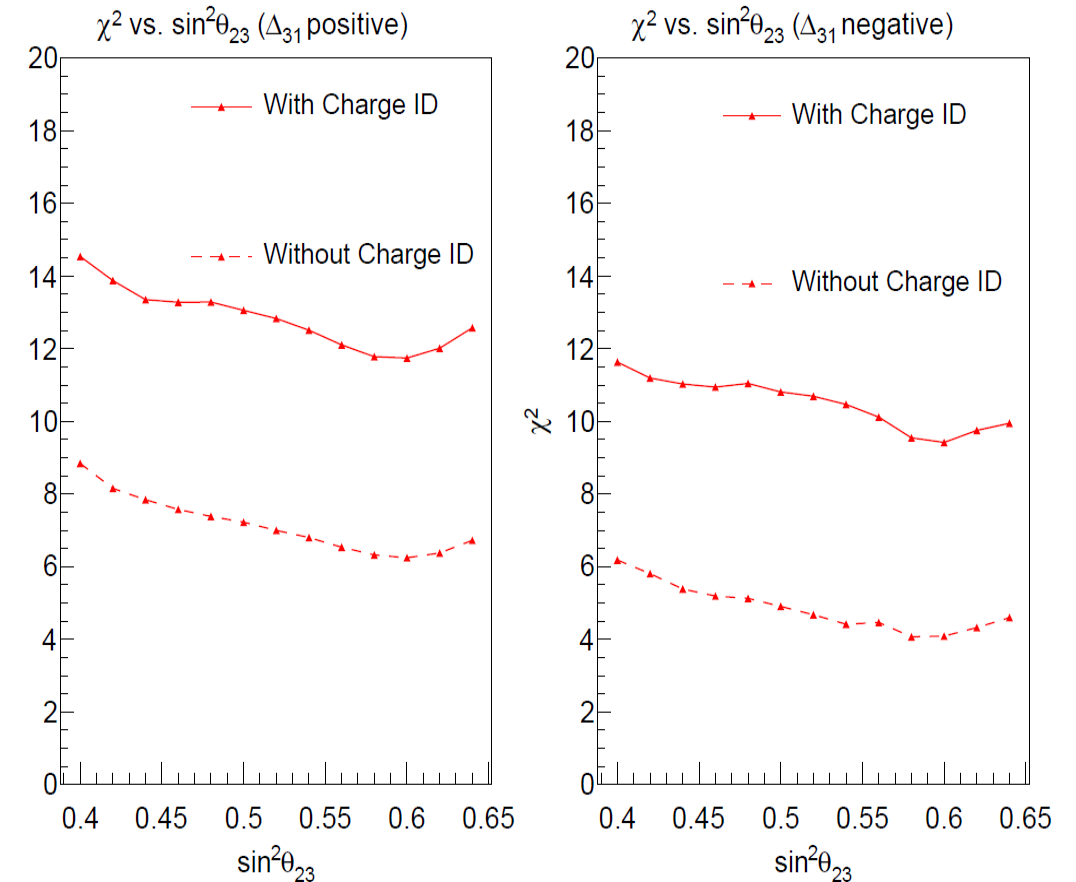


Figure : 2 Sensitivity of ICAL to matter vs. vacuum oscillations assuming with and without charge identification.

# Result

- Recently Super-Kamiokande looked for non standard matter effect [arXiv:1710.09126 [hep-ex]]. They parameterized the matter term as ( $\alpha^*$  standard matter term) and varied  $\alpha$  in the range 0, 2. The vacuum oscillation corresponds to the case  $\alpha = 0$  and standard matter oscillation corresponds to  $\alpha = 1$ .

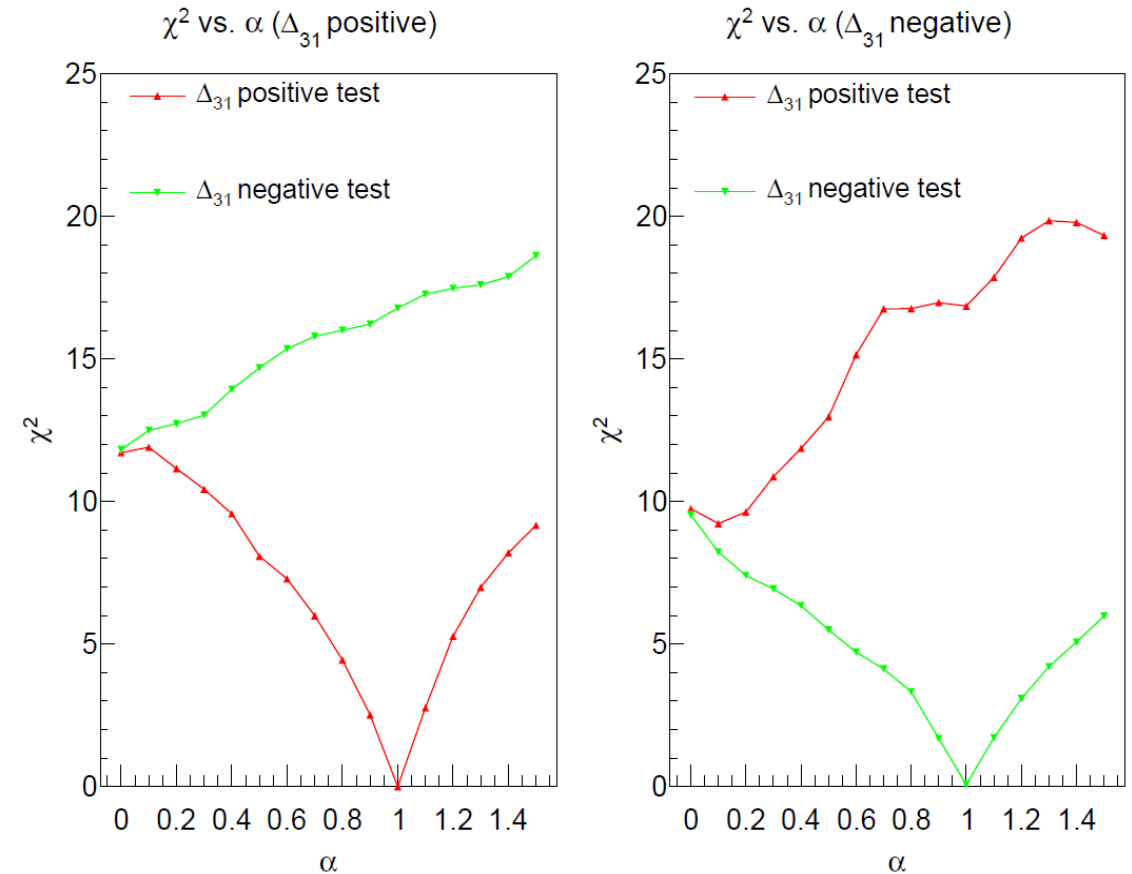


Figure : 3 Sensitivity of ICAL to fractional matter effects.

# Conclusion

- ▶ ICAL at INO is capable of establishing the earth matter effect in atmospheric neutrinos with  $\chi^2 = 11.8$  (9.5) for NH (IH) for 10 years of exposure time irrespective of the unknown CP violating phase.
- ▶ The sensitivity reduces to half once the charge identification ability of ICAL is neglected.

THANK YOU