Matter vs Vacuum Oscillations at Long Baseline Accelerator Neutrino Experiments [Bharti, Rahaman, Uma Sankar, arXiv: 2001.08676]

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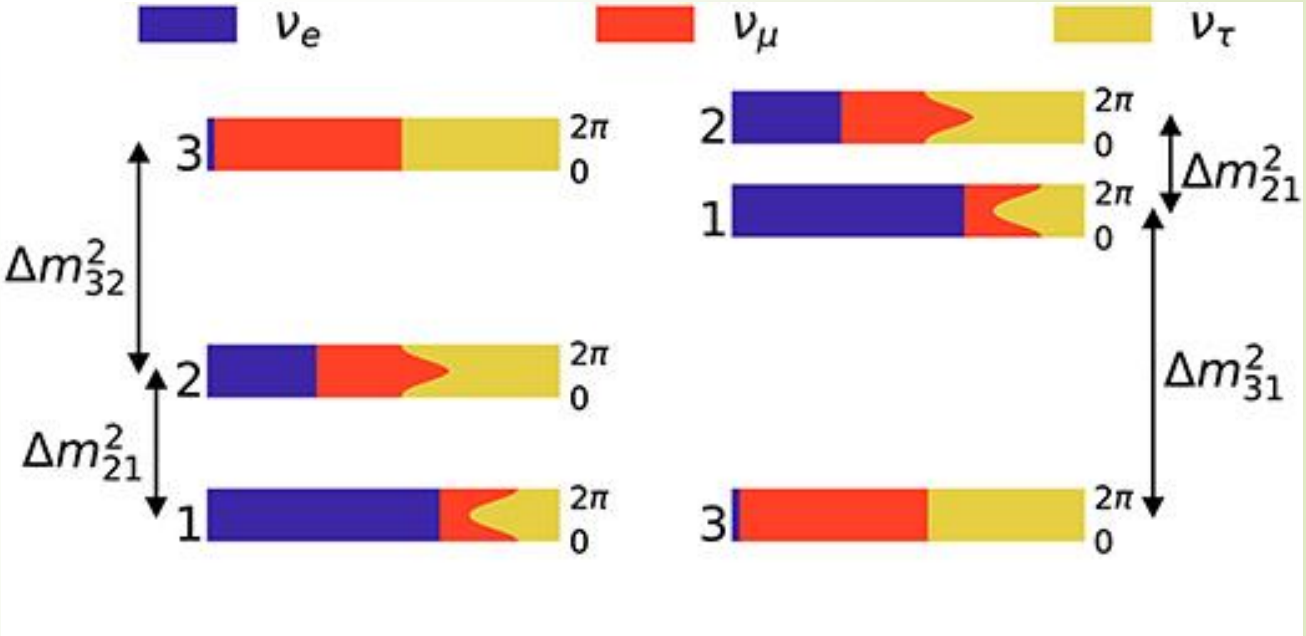
Motivation

- Neutrino oscillations provide a signal for physics beyond Standard Model.
- Two types of oscillation:

1. Oscillations driven by smaller mass squared difference:$\Delta_{21} = m_2^2 - m_1^2$----- Solar neutrino oscillation
2. Oscillations driven by larger mass squared difference: $\Delta_{31} = m_3^2 - m_1^2$----- first noted in pioneering water Cerenkov detector IMB [Casper et al., Phys. Rev. Let. 66, 2561 (1991); Becker-Senzdy et al.,Phys. Rev. D 46, 3720 (1992)] and Kamiokande [Hirata et al., Phys. Lett. B 280, 146 (1992); Fukuda et al., Phys. Lett. B 335, 237 (1994)].

- Atmospheric neutrino experiment Super Kamiokande [Fukuda et al, arXiv: hep-ex/9807003] and long-baseline accelerator neutrino experiments MINOS, NOvA and T2K [Michael et al., arXiv: hep-ex/0607088; Abe et al., arXiv: 1308.0465; Adamson et al., arXiv: 1701.05891] observed spectral distortions in the ν_μ and $\bar{\nu}_\mu$ survival probabilities.
- Initial analysis of these distortions were done with vacuum oscillation hypothesis to obtain $|\Delta_{31}|$ and $\sin 2\theta_{23}$.
- These experiments could not determine the sign of Δ_{31}:

1. Normal hierarchy (NH): $\Delta_{31} > 0$
2. Inverted hierarchy (IH): $\Delta_{31} < 0$



- Due to propagation through earth matter, neutrino oscillation probabilities are expected to be modified by matter effects.
- These matter effects are sensitive to the sign of Δ_{31}.
- Up to baseline of 1000 km, the matter effect leads to negligible change in the survival probabilities of ν_μ and $\bar{\nu}_\mu$. [Gandhi et al., arXiv: 0707.1723]
- The ν_μ and $\bar{\nu}_\mu$ disappearance data in long baseline experiments lead to same values of $|\Delta_{31}|$ and $\sin 2\theta_{23}$ for three possible cases:

1. Vacuum oscillations
2. Matter effect with NH
3. Matter effect with IH

- In the case of atmospheric neutrino, the survival probabilities are expected to undergo significant changes due to matter effect.
- But at present, Super Kamiokande is capable of making only small distinctions between vacuum oscillation and matter effect. [Abe et al., arXiv: 1710.09126]

- Two current long-baseline accelerator neutrino experiments NOvA [Ayres et al., 2007] and T2K [Abe et al., arXiv: 1106.1238] are currently looking for the evidence of matter modified neutrino oscillations.
- They measure two survival probabilities $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ and two oscillation probabilities $P(\nu_\mu \rightarrow \nu_e)$ and $P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)$.
- Sensitivity to matter effects come from oscillation probabilities. [M. Narayan and S. Uma Sankar, arXiv: hep-ph/9904302]
- But this oscillation probabilities are also sensitive to unknown CP violating phase δ_{CP}.

$$P(\nu_\mu \to \nu_e)$$

$$= \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2 \hat{\Delta}(1-\hat{A})}{\left(1-\hat{A}\right)^2}$$

$$+ \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\hat{\Delta}+\delta_{CP}) \frac{\sin \hat{\Delta} \hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1-\hat{A})}{1-\hat{A}}$$

[Cervera et al., arXiv: hep-ph/0002108]

$\hat{\Delta} = 1.27\Delta_{31} L(\mathrm{km})/E(\mathrm{GeV})$, $\alpha = \Delta_{21}/\Delta_{31}$ and $\hat{A} = A/\Delta_{31}$.

A is the Wolfenstein matter term.

$A(\mathrm{eV}^2) = 0.76 \times 10^{-4} \rho(\mathrm{g/cc}) E(\mathrm{GeV})$

- Oscillation probability depends on sign of Δ_{31}, value of δ_{CP} and octant of θ_{23}.
- It is possible to cancel the change induced by matter effect by choosing a wrong value of δ_{CP} or wrong octant of θ_{23}.
- Given a set of data, three solutions are possible [Prakash, Raut, Uma Sankar, arXiv: 1201.6485]:

1. Matter modified oscillation with NH and δ_{CP}^{1}
2. Vacuum oscillation with δ_{CP}^{2}
3. Matter modified oscillation with IH and δ_{CP}^{3}

- For T2K matter effect leads to small changes in the appearance probabilities.
- Therefore the value of δ_{CP} obtained from T2K data is independent of whether matter effect is included or not.
- For NOvA, the changes introduced in appearance probabilities is comparable to the change induced when δ_{CP} value is changed by 90^o. [Bharti, Prakash, Rahaman, Uma Sankar, arXiv: 1805.10182]
- Therefore, the measured value of δ_{CP} depends significantly on the oscillation hypothesis used to analyse the NOvA data.

- Matter effects play a crucial role in the solution of solar neutrino problem. [Mikheev, Smirnov, Sov. J. Nucl. Phys. 42, 913 (1985)]
- Matter effect in the case of oscillation driven by Δ_{21} has been established in more than 5 σ confidence level (C.L.). [Fogli et al., arXiv: hep-ph/0506083]
- As of now, there is no evidence of matter effects in the case of oscillation driven by Δ_{31}.
- Establishing CP violation in neutrino sector is one of the most important goals of the current and future long-baseline neutrino oscillation experiments.
- To achieve this goal, it is important to establish matter effects in the case of oscillation driven by Δ_{31} independently as has been done in the case of oscillation driven by Δ_{21}.

Analysis procedure

- We calculated theoretical event rates using GLoBES [Huber et al., arXiv: hep-ph/0407333], for the appearance and disappearance channels in neutrino and anti-neutrino modes for T2K and NOvA.
- We have tuned the efficiencies in the software to match the simulated event rates given my the collaborations when the input values of the oscillation parameters are at their best-fit values.
- These event rates are calculated using matter term parameterized as $q * A$, where A is the standard Wolfenstein matter term and q is a multiplicative factor.
- Δ_{21} and $\sin^2 \theta_{12}$ have been fixed in their best-fit values taken from [http://www.nu-fit.org/?q=node/45].
- The values of $\sin^2\theta_{13}$, $\sin^2\theta_{23}$ and $|\Delta_{31}|$ have been varied in their $3\ \sigma$ range taken from [http://www.nu-fit.org/?q=node/45] for both the hierarchies.

- δ_{CP} has been varied in its complete range $[0{,}360^{o}]$.
- The non-standard matter effect term q has been varied from 0 to 2.
- Theoretical event rates have been calculated for both hierarchies separately.

- These theoretical event rates have been compared with the experimental event rates by computing χ^2 between theory and experiment:

$$\chi^2 = \sum_i 2\left[\left(\mathrm{N}_i^{\mathrm{th}} - \mathrm{N}_i^{\mathrm{exp}}\right) + \mathrm{N}_i^{\mathrm{exp}} \times \ln\left(\frac{\mathrm{N}_i^{\mathrm{exp}}}{\mathrm{N}_i^{\mathrm{th}}}\right)\right] + \sum_j \left[2 \times \mathrm{N}_j^{\mathrm{th}}\right] + \chi^2(\mathrm{sys})$$

- $\chi^2(\mathrm{sys})$ arises due to systematic uncertainty.
- For each of the two experiments we used 10% systematic uncertainties using pull method.
- We varied the pull parameter in its 3 σ range and then marginalized the χ^2 over it to calculate χ^2_m as a function of oscillation parameters, hierarchies and q.

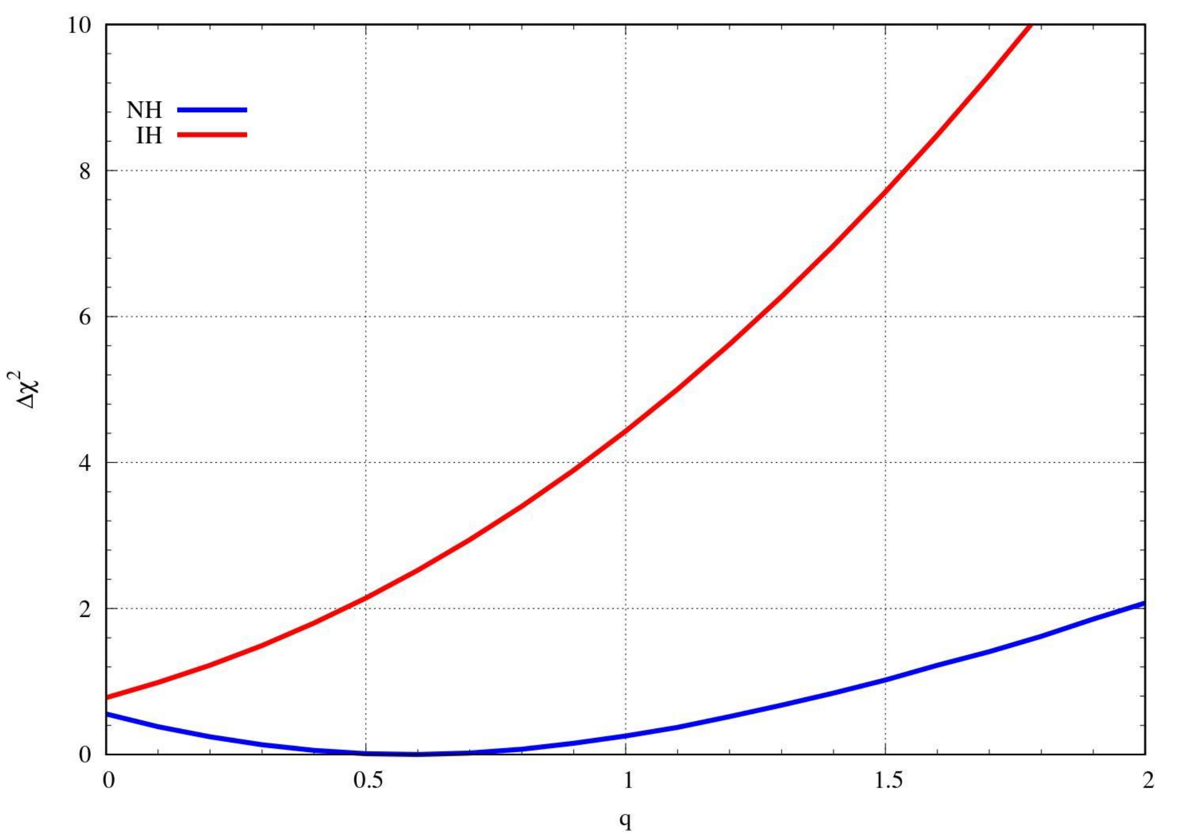
- Total χ^2 has been calculated by adding all the χ_m^2s from different channels and modes for both the hierarchies.
- $\chi^2(\mathrm{tot})$ is a function of all the oscillation parameters, hierarchies and q.
- We determined the minimum of $\chi^2(\mathrm{tot})$ to subtract it from all the $\chi^2(\mathrm{tot})$ to determine $\Delta\chi^2$ as a function of oscillation parameters, hierarchies and q.
- Then we marginalized $\Delta\chi^2$ over all the parameters except hierarchy and q.

- Later we have calculated the expected data from the future runs of T2K, NOvA and future experiment DUNE.
- These future expected event rates have been calculated using the best-fit values of mass squared differences, mixing angles and δ_{CP} for $q = 1$.
- These simulations have been done considering both NH and IH as true hierarchies.
- These simulated evnts have been considered as experimental events and the χ^2 values have been calculated between theory and experiment as described earlier.
- In the case of simulation, χ^2 is equivalent to $\Delta\chi^2$.

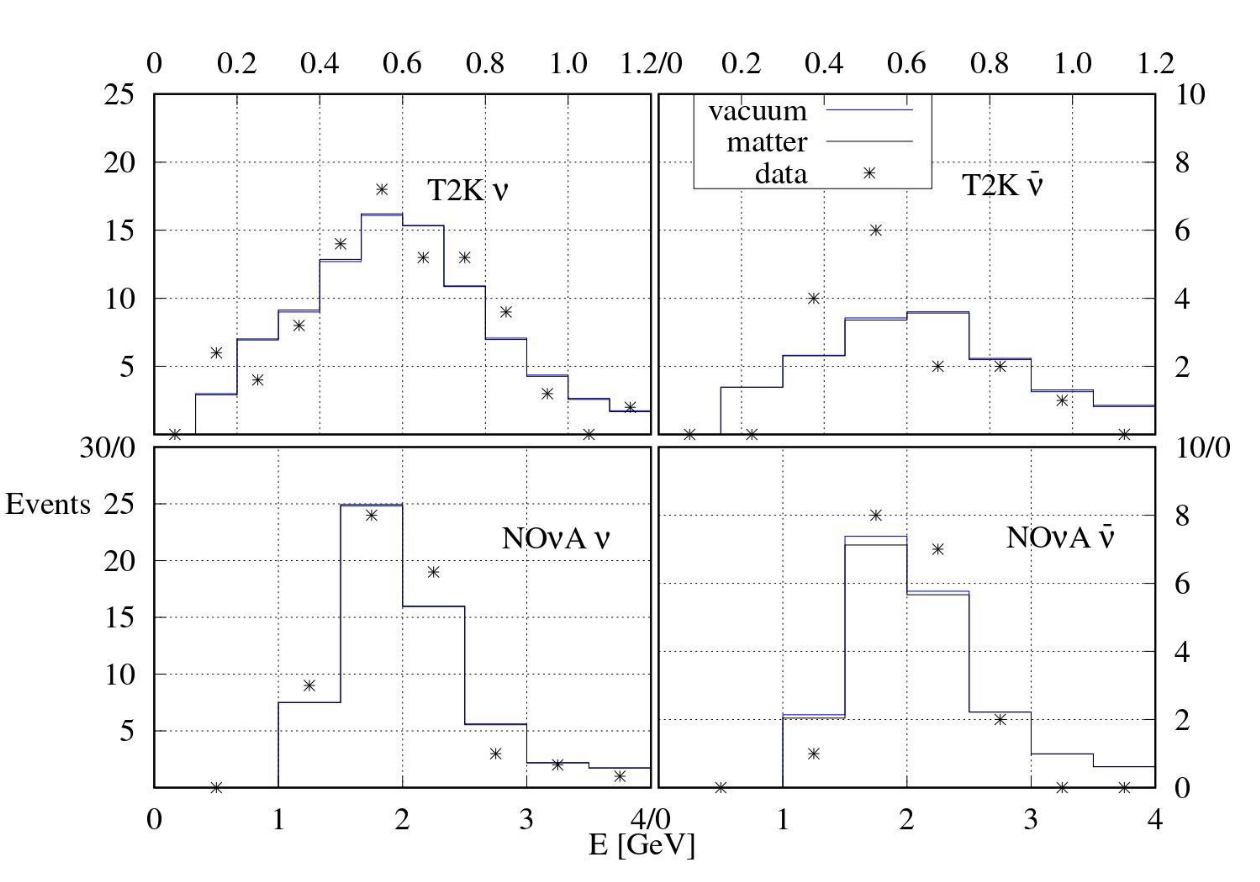
Results

- NOvA has taken data corresponding to 8.85×10^{20} POT in neutrino mode and 12.33×10^{20} POT in anti-neutrino mode. [Acero et al., arXiv: 1906.04907]
- T2K has taken data corresponding to 14.9×10^{20} POT in neutrino mode and 16.4×10^{20} POT in anti-neutrino mode. [Abe et al., arXiv: 1910.03887]
- These data have been fit to standard 3 flavor oscillation hypothesis with variable matter term.

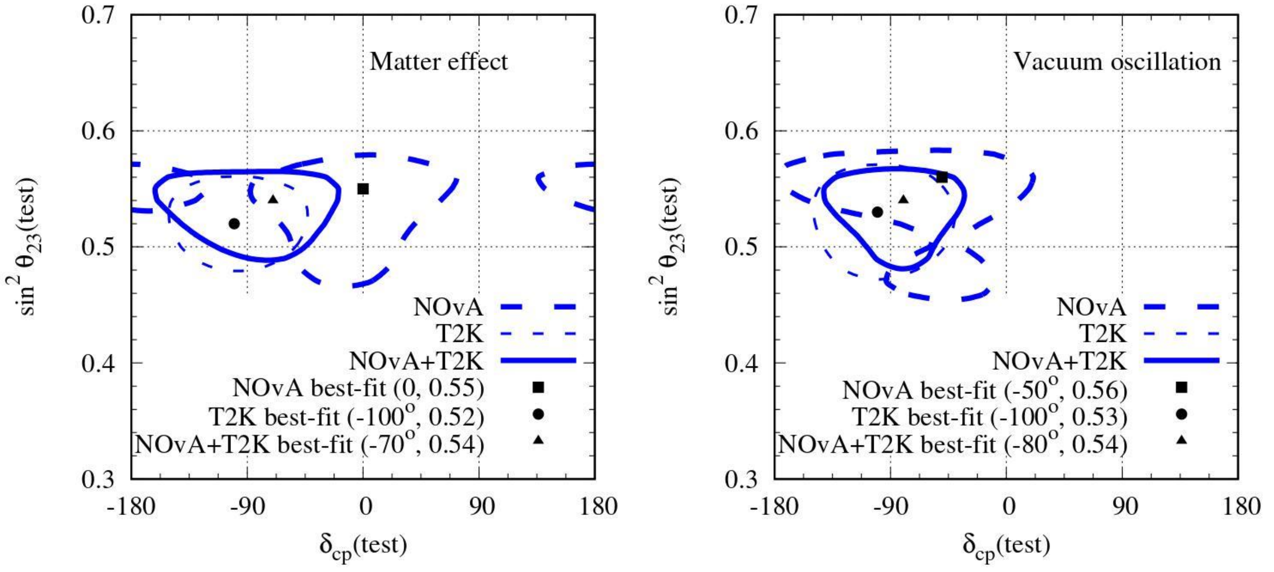
- The minimum $\chi^2 = 173.2$ occurs for $\Delta_{31} > 0$ and $q = 0.7$.
- Standard matter oscillation ($q = 1$) with NH has essentially the same χ^2.
- Standard matter oscillation with IH has been disfavoured with $\Delta\chi^2 = 4.5$.
- Vacuum oscillation ($q = 0$) provides as good fit to the data as matter modified oscillation with NH ($\chi^2 = 173.8$).



- Observed appearance event numbers in both neutrino and anti-neutrino modes have been plotted along with their predicted rates at best-fit points.
- There is hardly any difference between the predictions of vacuum and matter modified oscillations.

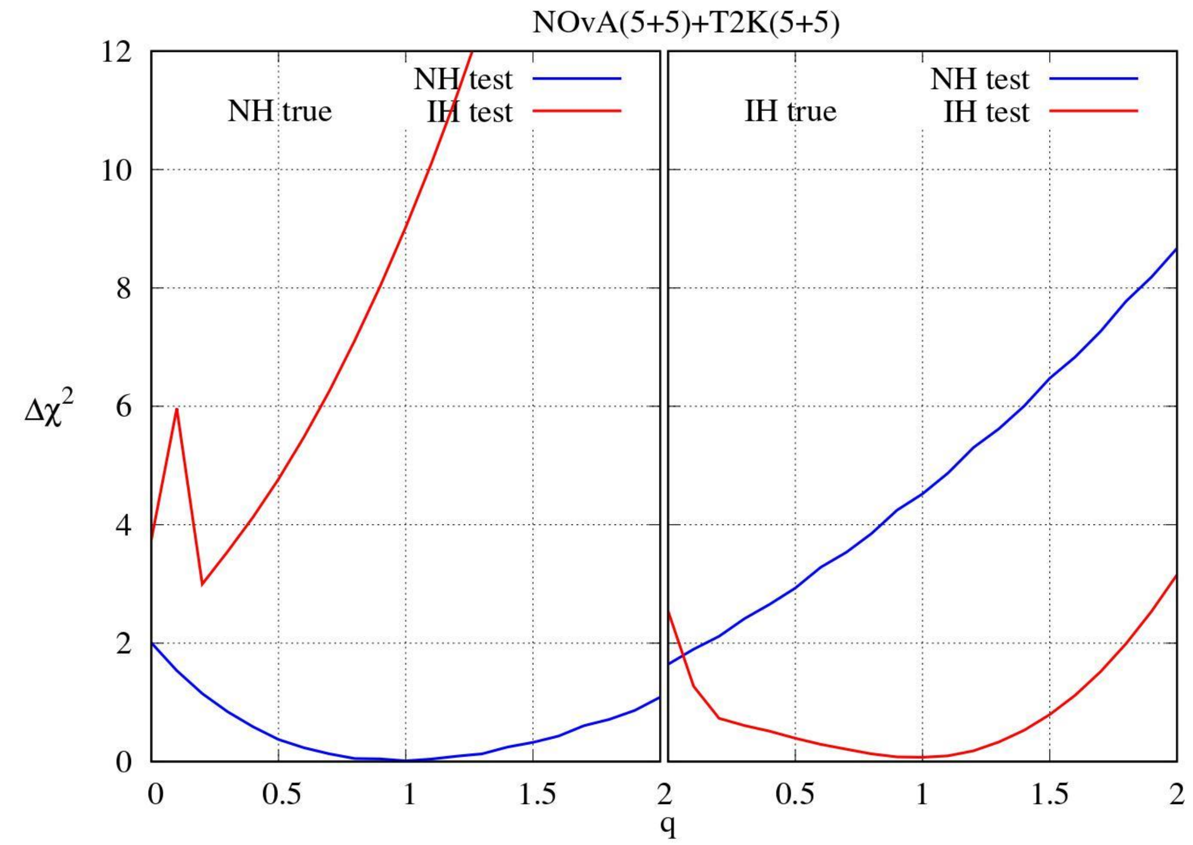


- Best-fit points and $1\ \sigma$ contours of T2K data, NOvA data and T2K+NOvA data for the two cases of vacuum and matter modified neutrino oscillations with NH.
- Best fit points of T2K hardly changes with oscillation hypothesis.
- Best fit value of δ_{CP} for NOvA largely depends on oscillation hypothesis.
- There is less discrepancy between the two experiments in case of vacuum oscillation hypothesis.



Expectation from T2K and NOvA

- Using GLoBES we simulated T2K data 37.4×10^{20} POT each in neutrino and anti-neutrino mode corresponding to a 5 year run in each mode.
- NOvA events have been simulated for 30.25×10^{20} POT each for neutrino and anti-neutrino mode again corresponding to 5 years run in each mode.
- Such extended runs can rule out IH at $3\,\sigma$ C.L. if NH is true but rules out NH only at $2\,\sigma$ if IH is true.
- Vacuum oscillation has a very small $\Delta\chi^2 \simeq 2$.

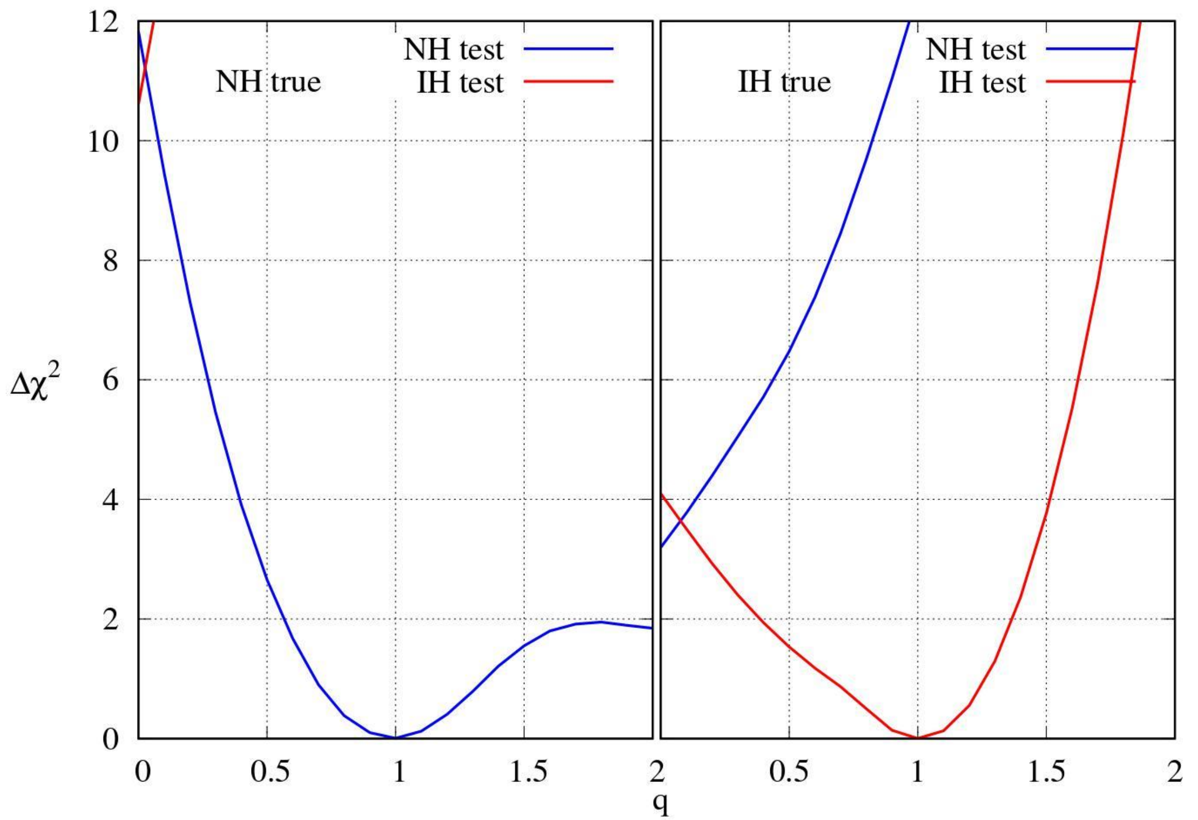


Expectation from DUNE

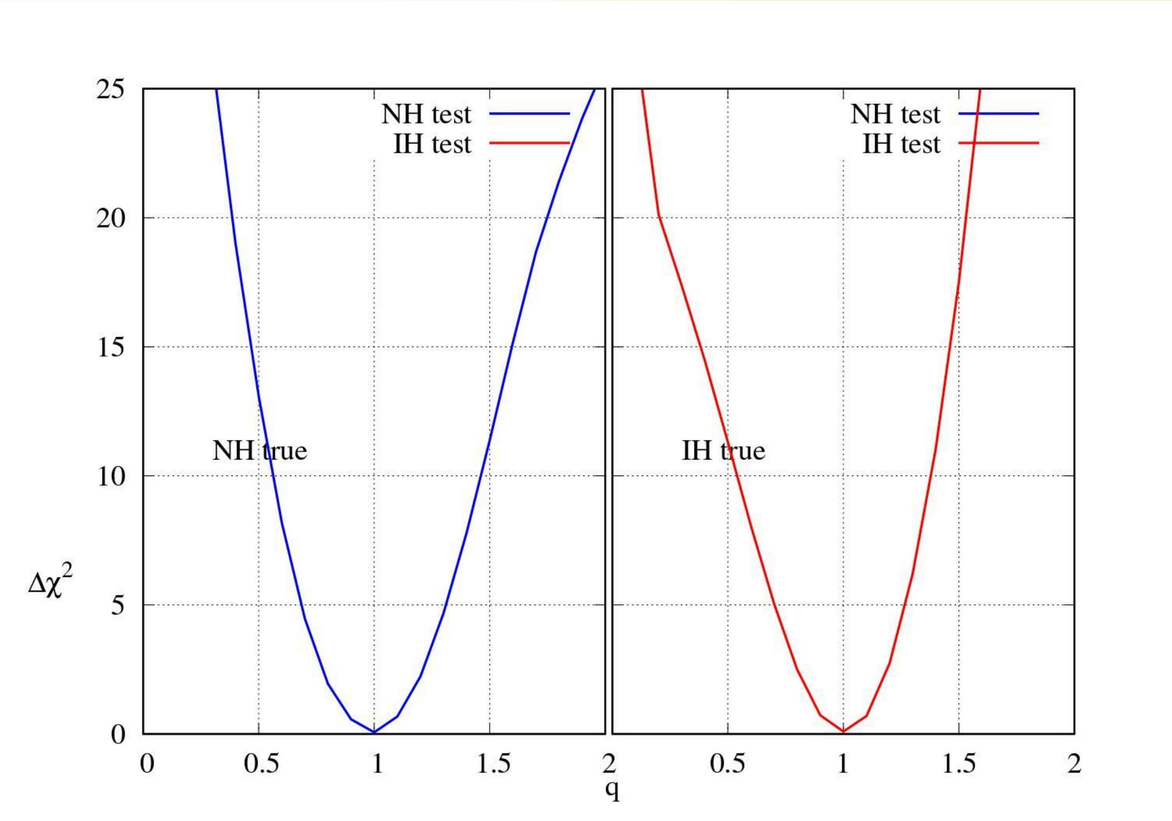
- The future long-baseline accelerator neutrino experiment DUNE is designed to disentangle the changes due to matter effect from the changes due to δ_{CP}.
- Its baseline $L \simeq 1300\ \mathrm{km}$ is much longer than T2K and NOvA.

[Abi et al., arXiv: 1807.10334]

- Its peak energy is correspondingly higher and matter effect larger.
- After 1 year neutrino run (14.7×10^{20} POT), vacuum oscillation can be ruled out at $> 3\ \sigma$ C.L. if NH is the true hierarchy.
- Same can be done only at $2\ \sigma$ C.L. if IH is true.



- $> 5\sigma$ exclusion of vacuum oscillation is possible for both the hierarchies if $(5\,\nu + 5\,\bar{\nu})$ run of DUNE is combined with $(5\,\nu + 5\,\bar{\nu})$ runs of NOvA and $(5\,\nu + 5\,\bar{\nu})$ runs of T2K.
- Values of q outside the range 1 ± 0.4 is ruled out at $3\,\sigma$ or better.



Conclusions

- At the scale of Δ_{31}, vacuum oscillation fits the data as good as matter modified oscillation.
- Extended rums of T2K and NOvA have no discriminating ability against vacuum oscillation.
- A $3\ \sigma$ discrimination against vacuum oscillation can be achieved with one year neutrino run of DUNE only if NH is the true hierarchy.
- $5\ \sigma$ discrimination against vacuum oscillation can be achieved for both the hierarchies only if $(5\ \nu + 5\ \bar{\nu})$ run of DUNE is combined with $(5\ \nu + 5\ \bar{\nu})$ run of T2K and $(5\ \nu + 5\ \bar{\nu})$ run of NOvA.
- Such run can establish the strength of matter effect with good precision.