A Review of the Tension between the T2K and NOνA Appearance Data and Hints to New Physics

Rahaman, Razzaque, Sankar, Universe 8 (2022) 2, 109, arXiv: 2201.03250

Ushak Rahaman

IFIC Instituto de Física Corpuscular (Univ. de Valéncia CSIC)

30th April, 2021

1. Evolution of the tension between NOνA and T2K data
2. Resolution of the tension with BSM physics
3. Conclusions

1. Evolution of the tension between NOνA and T2K data
    - Brief introduction to neutrino oscillation
    - NOνA and T2K
    - Parameter degeneracy
    - 2018 data
    - 2019 data
    - 2020 data
2. Resolution of the tension with BSM physics
3. Conclusions

Neutrino flavour and mixing

- Three neutrino flavours: ν_e, ν_μ and ν_τ.
- They are produced and detected in interactions
- They are called flavour or interaction eigenstates.
- Flavour states mix with each other to form three mass eigenstates ν_1, ν_2 and ν_3 with masses m_1, m_2 and m_3 respectively:

$$\begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} = U^\dagger \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} \tag{1.1}$$

- U is a unitary 3×3 matrix.

Neutrino flavour and mixing

$$U = \begin{bmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - s_{13}c_{12}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{13}c_{23}s_{12}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}, \qquad (1.2)$$

- $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$.
- The neutrino oscillation probabilities depend on three mixing angles: θ_{12}, θ_{13}, and θ_{23}; two independent mass squared differences: $\Delta_{21} = m_2^2 - m_1^2$ and $\Delta_{31} = m_3^2 - m_1^2$; and a CP violating phase: δ_{CP}.

Measurement of neutrino mixing parameters

- Long baseline reactor neutrino experiment KamLAND measured $\Delta_{21} = (7.9 \pm 0.5) \times 10^{-5}\,\mathrm{eV}^2$, and $\tan^2\theta_{12} = 0.0.4^{+0.10}_{-0.07}$.
- Sign of Δ_{21} was measured to be positive by the synergy of solar neutrino experiments SNO, Super-Kamiokande, and Gallium experiments.
- Short baseline reactor neutrino experiment Daya Bay measured $|\Delta_{31}| = (2.47 \pm 0.07) \times 10^{-3}\,\mathrm{eV}^2$, and $\sin^2 2\theta_{13} = 0.00856 \pm 0.0029$
- Long baseline accelerator neutrino experiment MINOS measured $|\Delta_{31}| = (2.3 - 2.5) \times 10^{-3}\,\mathrm{eV}^2$, and $\sin^2\theta_{23} = (0.35 - 0.65)$
- Both short baseline reactor experiment and long baseline accelerator experiments measured the magnitude of Δ_{31}, but not the sign.
- Both atmospheric neutrino data, and accelerator neutrino data prefer $\sin^2 2\theta_{23} \simeq 1$.

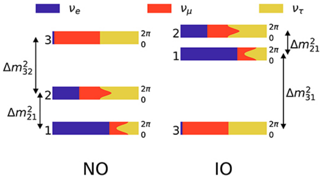
Values of neutrino oscillation parameters as of June, 2012

Parameters	bfp$\pm 1\,\sigma$
$\theta_{12}/^o$	$33.36^{+0.81}_{-0.78}$
$\theta_{23}/^o$	$40.0^{+2.1}_{-1.5} \oplus \left[50.4^{+1.3}_{-1.3}\right]$
$\theta_{13}/^o$	$8.66^{+0.44}_{-0.46}$
$\delta_{CP}/^o$	300^{+66}_{-138}
$\frac{\Delta_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.18}_{-0.19}$
$\frac{\Delta_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$2.473^{+0.070}_{-0.067}$
$\frac{\Delta_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$\left[-2.427^{+0.042}_{-0.065}\right]$

Table 1: Global best-fit values of neutrino oscillation parameters in June, 2012 [Gonzalez-Garcia et al., arXiv: 1209.3023].

Unknown parameters

- The unknown parameters are: sign of Δ_{31}, octant of θ_{23} and CP violating phase δ_{CP}.
- Depending on the sign of Δ_{31}, there can be two possible mass ordering:
  1. Normal hierarchy (NH): $\Delta_{31} > 0$ ($m_3 >> m_2 \geq m_1$)
  2. Inverted hierarchy (IH): $\Delta_{31} < 0$ ($m_2 \geq m_1 >> m_3$)
- For $\sin^2 2\theta_{23} < 1$, there can be two octants of θ_{23}:
  1. Higher octant (HO): $\sin^2 \theta_{23} > 0.5$
  2. Lower octant (LO): $\sin^2 \theta_{23} < 0.5$
- Long baseline accelerator neutrino experiments T2K and NOνA are expected to determine these unknowns.



Unknown parameters

- These experiments can measure four probabilities:
  1. Two disappearance probabilities $P_{\mu\mu}$ and $P_{\bar{\mu}\bar{\mu}}$: improve precision on $|\Delta_{31}|$ and $\sin 2\theta_{23}$.
  2. Two appearance probabilities $P_{\mu e}$ and $P_{\bar{\mu}\bar{e}}$: give information on CP violation, mass hierarchy and octant of θ_{23}.

NOνA

- The source for NOνA experiment is the NuMI beam from the Fermilab [Ayres et al., NOνA Technical Design report].
- The detector is 14 kT Totally Active Scintillator Detector (TASD) located 810 km away from Fermilab at 0.8° off-axis.
- It was scheduled to have neutrino and anti-neutrino run of 3 years each with a beam power of 700 kW, corresponding to 6×10^{20} POT/year.
- Started taking data in 2014.
- 2017: Neutrino data in both disappearance and appearance mode with 6.05×10^{20} POT. [Adamson et al., arXiv: 1701.0589, 1703.0332]
- 2018: Neutrino data in both disappearance and appearance mode with 8.85×10^{20} POT. [Acero et al., arXiv: 1806.00096]

NOνA

- 2019: (anti-) Neutrino data in both disappearance and appearance mode with $8.85\,(12.33) \times 10^{20}$ POT. [arXiv: 1906.04907]
- 2020: (anti-) Neutrino data in both disappearance and appearance mode with $1.36\,(1.25) \times 10^{21}$ POT. [A. Himmel, Talk given at Neutrino 2020 on 2nd July, 2020]

T2K

- The source for T2K experiment is the J-PARC accelerator in Tokai, Japan.
- The detector is the 22.5 kT fiducial mass Super Kamiokande water Cerenkov located 295 km away from source at 2.5° off-axis.
- Flux peaks at 0.7 GeV which is also the first oscillation maxima.
- Started taking data in 2009.
- 2013: Neutrino data in both disappearance and appearance mode with 6.6×10^{20} POT. [Abe et al., arXiv: 1311.4750, 1403.1532]
- 2015: Anti-neutrino data in both disappearance and appearance mode with 4×10^{20} POT. [Slazgeber et al., arXiv: 1508.0615]
- 2017: (anti-) Neutrino data in both disappearance and appearance mode with $7.252\,(7.531) \times 10^{20}$ POT. [Haegel et al. arXiv: 1709.0418]

T2K

- 2019: (anti-) Neutrino data in appearance mode with $1.49\,(1.64) \times 10^{21}$ POT. (anti-) Neutrino data in disappearance mode with $14.7\,(7.6) \times 10^{20}$ POT. [arXiv: 1910.03887, 1807.07891]
- 2020: (anti-) Neutrino data in both disappearance and appearance mode with $1.97\,(1.63) \times 10^{21}$ POT. [P. Dunne, Talk given at Neutrino 2020 on 2nd July, 2020]

1. Evolution of the tension between NOνA and T2K data
   - Brief introduction to neutrino oscillation
   - NOνA and T2K
   - Parameter degeneracy
   - 2018 data
   - 2019 data
   - 2020 data
2. Resolution of the tension with BSM physics
3. Conclusions

Oscillation probability

$$\begin{aligned} P_{\mu e} &\simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 \hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2} \\ &+ \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\hat{\Delta}+\delta_{CP}) \frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1-\hat{A})}{1-\hat{A}}, \quad (1.3) \end{aligned}$$

$\alpha = \frac{\Delta_{21}}{\Delta_{31}}$, $\hat{\Delta} = \frac{\Delta_{31} L}{4E}$ and $\hat{A} = \frac{A}{\Delta_{31}}$. A is the Wolfenstein matter term [L. Wolfenstein, Phys. Rev.D17, 2369 (1978)], given by $A = 2\sqrt{2} G_F N_e E$, where E is the neutrino beam energy and L is the length of the baseline. Anti-neutrino oscillation probability $P_{\bar{\mu}\bar{e}}$ can be obtained by changing the sign of A and δ_{CP} in eq. 1.3.

- Oscillation probability depends on sign of Δ_{31}, octant of θ_{23}, and δ_{CP}.
- $P_{\mu e}$ is enhanced if δ_{CP} is in the lower half plane (LHP, $-180^\circ < \delta_{CP} < 0$), compared to $\delta_{CP} = 0$.
- $P_{\mu e}$ can be suppressed by the same amount if δ_{CP} is in the upper half plane (UHP, $0^\circ < \delta_{CP} < 180^\circ$).
- If Δ_{31} is positive (negative), $P_{\mu e}$ can be enhanced (suppressed) by 22% for NOνA and 8% for T2K.
- If θ_{23} is in HO (LO), $P_{\mu e}$ can be enhanced (suppressed), compared to $\theta_{23} = \pi/4$.
- Since each of the unknowns can take 2 different values, there are 8 combinations of the unknowns.
- If θ_{13} is not known precisely, it'll lead to eight-fold degeneracy in $P_{\mu e}$.
- Since θ_{13} isprecisely known, the degeneracy is less severe.
- These degeneracies are- hierarchy-δ_{CP} degeneracy, octant-hierarchy degeneracy, and octant-δ_{CP} degeneracy.

1. Evolution of the tension between NOνA and T2K data
   - Brief introduction to neutrino oscillation
   - NOνA and T2K
   - Parameter degeneracy
   - 2018 data
   - 2019 data
   - 2020 data
2. Resolution of the tension with BSM physics
3. Conclusions

Analysis of 2018 data from NOνA and T2K

- NOνA published their results with $8.85\,(6.9) \times 10^{20}$ POT in neutrino (anti-neutrino) mode. [M. Sanchez, Talk given at Neutrino 2018 conference]
- T2K published their results with $14.7\,(7.6) \times 10^{20}$ POT in neutrino (anti-neutrino) mode. [Abe et al., arXiv: 1807.07891]
- The best-fit point for NOνA (T2K) was $\sin^2\theta_{23} = 0.58\,(0.526)$ and $\delta_{CP} = 30.6^\circ\,(-107.1^\circ)$ at NH.
- At IH, the best-fit point for NOνA (T2K) was $\sin^2\theta_{23} = 0.58\,(0.530)$ and $\delta_{CP} = -95.4^\circ\,(-81.9^\circ)$.
- At NH NOνA disfavoured δ_{CP} values close to -90°.
- T2K ruled out NOνA best-fit point on $\sin^2\theta_{23} - \delta_{CP}$ plane at 95% C.L.
- NOνA ruled out T2K best-fit point on $\sin^2\theta_{23} - \delta_{CP}$ plane at 90% C.L.
- The IH best-fit point of NOνA (T2K) is allowed at $1\,\sigma$ $(2\,\sigma)$.

There was a mild tension between NOνA and T2K. [Nizam, Bharti, Prakash, Rahaman, Sankar, arXiv: 1811.01210]

① Evolution of the tension between NOνA and T2K data
- Brief introduction to neutrino oscillation
- NOνA and T2K
- Parameter degeneracy
- 2018 data
- 2019 data
- 2020 data

② Resolution of the tension with BSM physics

③ Conclusions

Analysis of 2019 data from NOνA and T2K

- In the 2019 data, the best-fit point of NOνA was at NH, $\delta_{CP}/\pi = 0^{+1.3}_{-0.4}$ and $\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$. [arXiv: 1906.04907]
- For T2K, the best-fit point for NH (IH) was $\delta_{CP}/\pi = -1.89^{+0.70}_{-0.58}$ $(-1.38^{+0.48}_{-0.54})$, $\sin^2\theta_{23} = 0.53^{+0.03}_{-0.04}$. [arXiv: 1910.03887, 1807.07891]
- There was a visible difference between the δ_{CP} values from both the experiments.
- Both experiments disfavoured each other's best-fit point at $1\,\sigma$ C.L.

① Evolution of the tension between NOνA and T2K data

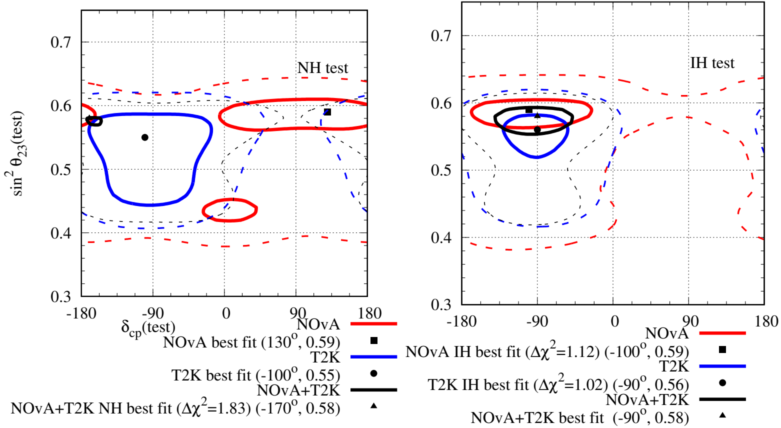
- Brief introduction to neutrino oscillation
- NOνA and T2K
- Parameter degeneracy
- 2018 data
- 2019 data
- **2020 data**

② Resolution of the tension with BSM physics

③ Conclusions

Analysis of 2020 data from NOνA and T2K

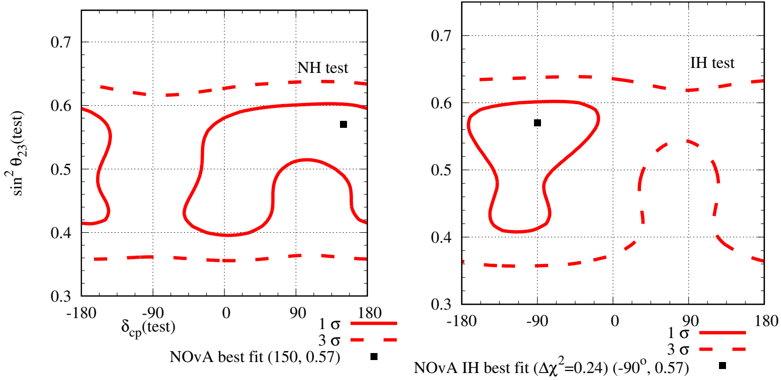
- In the 2020 data, the best-fit point of NOνA was at NH, $\delta_{CP} = 0.82\pi$ and $\sin^2\theta_{23} = 0.57$. [A. Himmel, Talk given at Neutrino 2020 conference]
- For T2K, the best-fit point for NH (IH) was $\delta_{CP} = -1.6$, $\sin^2\theta_{23} = 0.53$. [P. Dunne, tale given at Neutrino 2020 conference]
- The tension is even stronger as there is no overlap at the $1\,\sigma$ region on $\sin^2\theta_{23}$ plane between the two experiments.


NH test
IH test
$\sin^2\theta_{23}$(test)
δ_{cp}(test)
0.3
0.4
0.5
0.6
0.7
-180
-90
0
90
180
NOvA
NOvA best fit (130°, 0.59)
T2K
T2K best fit (-100°, 0.55)
NOvA+T2K
NOvA+T2K NH best fit ($\Delta\chi^2$=1.83) (-170°, 0.58)
NOvA
NOvA IH best fit ($\Delta\chi^2$=1.12) (-100°, 0.59)
T2K
T2K IH best fit ($\Delta\chi^2$=1.02) (-90°, 0.56)
NOvA+T2K
NOvA+T2K best fit (-90°, 0.58)

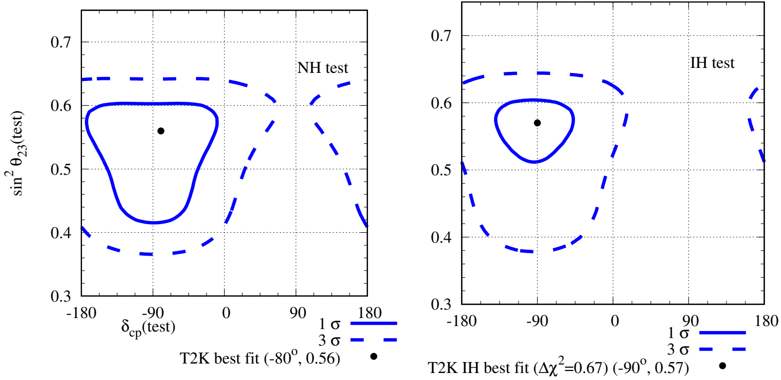
Analysing the tension

- We will take vacuum oscillation (no effect of sign of Δ_{31}), $\theta_{23} = \pi/4$, and $\delta_{CP} = 0$, as our reference point: 000.
- Parameter value for which $P_{\mu e}$ is increased (decreased) will be labelled as $+$ $(-)$.
- NH: $+$, IH: $-$, HO: $+$, LO: $-$, $\delta_{CP} = -90^\circ$: $+$, $\delta_{CP} = +90^\circ$: $-$
- For the POT of 2020 data, the expected number of ν_e, and $\bar{\nu}_e$ appearance events for NOνA are 76.14, and 32.93 respectively.
- NOνA observed 82, and 33 ν_e, and $\bar{\nu}_e$ events respectively. The moderate excess in ν_e appearance channel can be explained by three possible solutions in hierarchy-octant-δ_{CP}: A. $+-+$, B. $++-$, C. $-++$.

- The observed $\bar{\nu}_e$ appearance event number is consistent with 000.
- Due to low statistics at $\bar{\nu}_e$ events, other solutions are also allowed at $1\,\sigma$ C.L.
- Exceptions are $+-+$: minimum $\bar{\nu}_e$ event numbers, and $-+-$: maximum $\bar{\nu}_e$ event numbers
- Solution A of ν_e appearance data is excluded when analysed with $\bar{\nu}_e$ data.
- The combined analysis of ν_e and $\bar{\nu}_e$ appearance data have solutions: B. $++-$, C. $-++$.
- Combination of appearance and disappearance data give the same solutions.


NH test
IH test
$\sin^2\theta_{23}$(test)
δ_{cp}(test)
0.3
0.4
0.5
0.6
0.7
-180
-90
0
90
180
1 σ
3 σ
NOvA best fit (150, 0.57)
NOvA IH best fit ($\Delta\chi^2$=0.24) (-90^o, 0.57)

- The expected number of events for T2K at 000 are 78 for ν_e, and 19 for $\bar{\nu}_e$.
- T2K observed 105 for ν_e, and 15 for $\bar{\nu}_e$.
- The large excess can be explained only by the solution: $+++$.
- But disappearance data limit $\sin^2\theta_{23} \leq 0.59$.
- Since only about 20% boost is possible from hierarchy, and octant, δ_{CP} firmly anchors itself around $\delta_{CP} = -90^\circ$ to accommodate the large excess in the observed ν_e appearance event number.
- The small reduction in observed $\bar{\nu}_e$ appearance event is consistent with $+++$ solution.


0.7
0.6
0.5
0.4
0.3
$\sin^2\theta_{23}$(test)
NH test
-180
-90
0
90
180
δ_{cp}(test)
1 σ
3 σ
T2K best fit (-80°, 0.56)
0.7
0.6
0.5
0.4
0.3
IH test
-180
-90
0
90
180
1 σ
3 σ
T2K IH best fit ($\Delta\chi^2$=0.67) (-90°, 0.57)

1. Evolution of the tension between NOνA and T2K data
2. Resolution of the tension with BSM physics
    - Non-unitary mixing of 3 active neutrinos
    - Non-standard NC interaction during propagation of neutrino through matter
3. Conclusions

1. Evolution of the tension between NOνA and T2K data
2. Resolution of the tension with BSM physics
    - Non-unitary mixing of 3 active neutrinos
    - Non-standard NC interaction during propagation of neutrino through matter
3. Conclusions

Motivation

- The short baseline anomalies like LSND anomalies or reactor anomalies can be explained by the existence of one or more sterile neutrino.
- Simplest model consists of $3 + 1$ neutrino mixing.
- 4 mass eigenstates: ν_1, ν_2, ν_3 and ν_4 with masses m_1, m_2, m_3, m_4, where $m_4 >> m_1$, m_2, m_3 and $\Delta_{41} = 0.1 - 10\,\mathrm{eV}^2$.
- If the extra neutrinos are isosinglet neutral heavy leptons (NHL), in the minimum extension of SM, they would not take part in neutrino oscillation.
- The admixture of such leptons in the charged current weak interactions would affect the neutrino oscillations, and the neutrino oscillations would be described by an effective 3×3 non-unitary mixing matrix.

Motivation

- Do the data fron NOνA and T2K exclude non-unitarity?
- If not, can we reach a better agreement between the two experiments with non-unitary mixing?

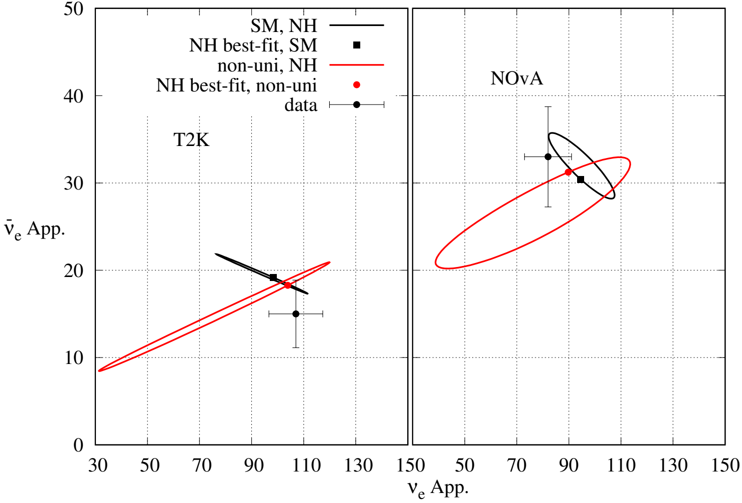
Non-unitary mixing matrix

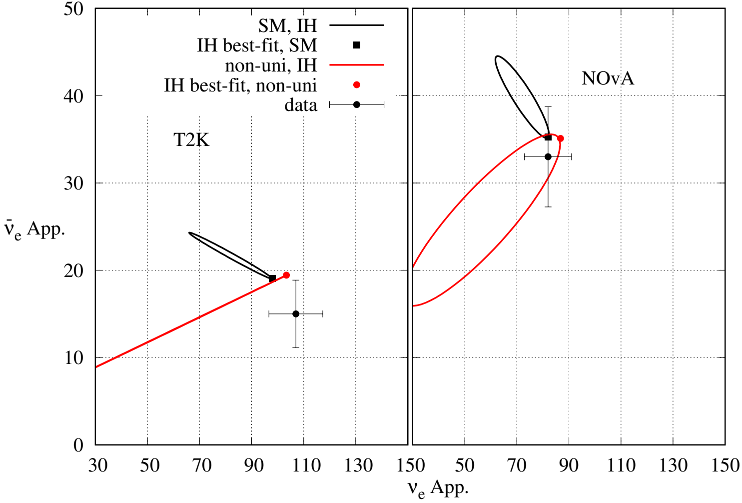
$$N = N_{NP} U_{3\times 3} = \begin{bmatrix} \alpha_{00} & 0 & 0 \\ \alpha_{10} & \alpha_{11} & 0 \\ \alpha_{20} & \alpha_{21} & \alpha_{22} \end{bmatrix} U_{\mathrm{PMNS}}\,, \tag{2.4}$$

We will consider the effects of α_{00}, $\alpha_{10} = |\alpha_{10}| e^{i\phi_{10}}$ and α_{11} only.

Resolution of the tension

- We analysed the NOνA and T2K data with both unitary and non-unitary hypotheses. [Miranda, Paquini,Rahaman, Razzaque, arXiv: 1911.09398; Rahaman, Razzaque, Sankar, arXiv: 2201.03250]
- We fix all the parameter at the combined best-fit of NOνA and T2K, and vary δ_{CP} in the range $[-180^\circ : 180^\circ]$.
- The result will be represented as bi-event plots.


SM, NH
NH best-fit, SM
non-uni, NH
NH best-fit, non-uni
data
T2K
NOvA
$\bar{\nu}_e$ App.
ν_e App.
50
40
30
20
10
0
30
50
70
90
110
130
150
50
70
90
110
130
150


SM, IH
IH best-fit, SM
non-uni, IH
IH best-fit, non-uni
data
T2K
NOvA
$\bar{\nu}_e$ App.
ν_e App.
50
40
30
20
10
0
30
50
70
90
110
130
150
50
70
90
110
130
150

1. Evolution of the tension between NOνA and T2K data
2. Resolution of the tension with BSM physics
   - Non-unitary mixing of 3 active neutrinos
   - Non-standard NC interaction during propagation of neutrino through matter
3. Conclusions

Theoretical background

- Non-standard interactions can arise as a low energy manifestation of new heavy states of a more complete model at high energy, or it can arise due to light mediators.
- NC NSI during propagation is represented by dimension 6 operator:

$$\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\epsilon^{fC}_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right)\left(\bar{f}\gamma_\mu P_C f\right), \tag{2.5}$$

The effective Hamiltonian for neutrino propagation in matter in presence of NSI can be written in the flavour basis as

$$H = H_{\rm vac} + H_{\rm mat} + H_{\rm NSI}, \tag{2.6}$$

where

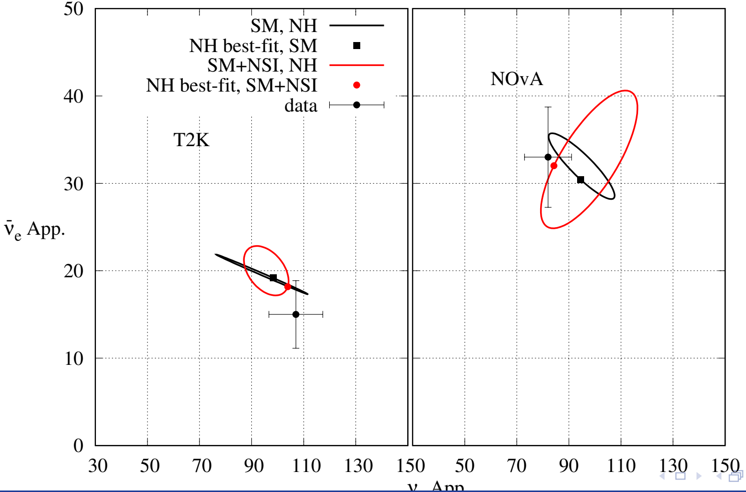
$$H_{\rm vac} = \frac{1}{2E} U \begin{bmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{bmatrix} U^\dagger ; H_{\rm mat} = \sqrt{2} G_F N_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} ; \tag{2.7}$$

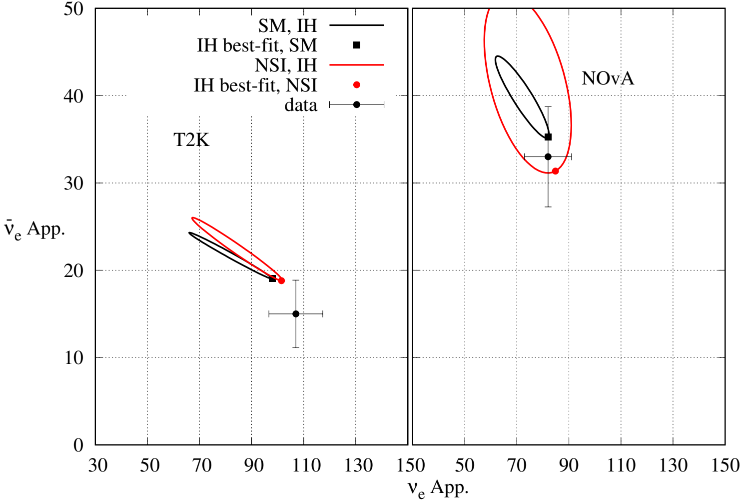
$$H_{\rm NSI} = \sqrt{2} G_F N_e \begin{bmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{bmatrix} . \tag{2.8}$$

Resolution of the tension

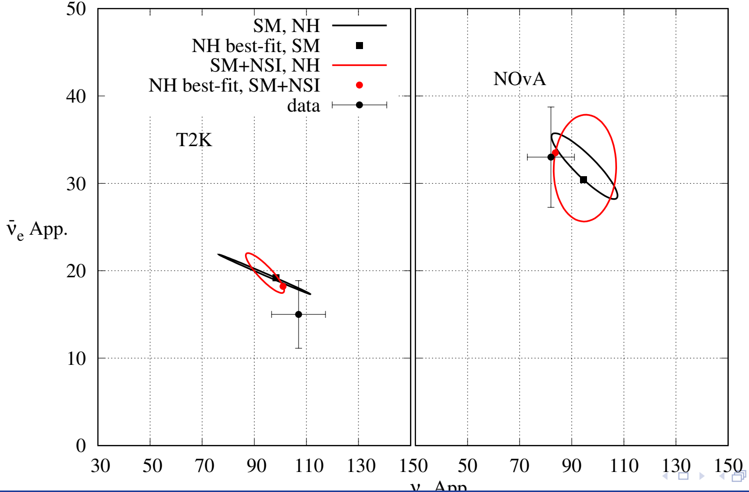
- We considered the effects of $\epsilon_{e\mu} = |\epsilon_{e\mu}|e^{i\phi_{e\mu}}$, and $\epsilon_{e\tau} = |\epsilon_{e\tau}|e^{i\phi_{e\tau}}$ one at a time.
- NOνA and T2K data were analysed with NSI hypothesis.[Chatterjee, Palazzo, arXiv: 2008.04161; Denton et al.,arXiv: 2008.01110; Rahaman et al., arXiv: 2201.03250]
- The results will be presented as bi-event plots.

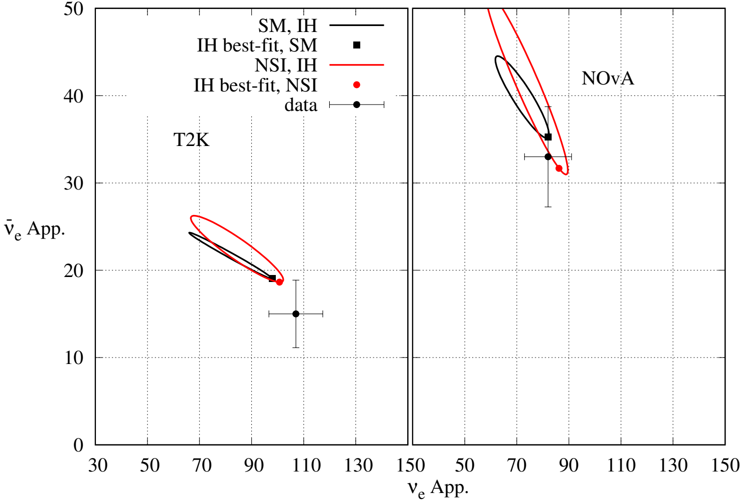
$\epsilon_{e\mu}$


SM, NH
NH best-fit, SM
SM+NSI, NH
NH best-fit, SM+NSI
data
T2K
NOvA
$\bar{\nu}_e$ App.
ν_e App.
0
10
20
30
40
50
30
50
70
90
110
130
150
50
70
90
110
130
150


SM, IH
IH best-fit, SM ■
NSI, IH
IH best-fit, NSI ●
data
T2K
NOvA
50
40
30
20
10
0
$\bar{\nu}_e$ App.
30
50
70
90
110
130
150
50
70
90
110
130
150
ν_e App.

$\epsilon_{e\tau}$




SM, IH
IH best-fit, SM
NSI, IH
IH best-fit, NSI
data
T2K
NOvA
$\bar{\nu}_e$ App.
ν_e App.
0
10
20
30
40
50
30
50
70
90
110
130
150
50
70
90
110
130
150

- The tension between T2K and NOνA only grew stronger with time.
- T2K observes a large excess in its observed ν_e appearance event number, as compared to the expected event number at the reference point 000.
- This excess can be only explained by the solution $+++$.
- NOνA sees a moderate excess in its ν_e appearance events, compared to the expected events at 000.This moderate excess, combined with the $\bar{\nu}_e$ appearance data, can be only explained by the solutions $++-$,and $-++$
- This tension can be resolved by BSM physics like non-unitary mixing or NSI
- Lorentz invariance violation can also be a possible way to resolve the tension. [Rahaman, arXiv: 2103.04576; Rahaman et al., arXiv: 2201.03250]

Thank You!