Searching for non-unitary neutrino oscillations in the present T2K and NOνA data

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1. The tension between NOνA and T2K data
2. Looking for non-unitary mixing in far detector data
3. Non-unitary mixing in near detector data

1. The tension between NOνA and T2K data
   - Brief introduction to neutrino oscillation
   - NOνA and T2K
   - 2020 data
2. Looking for non-unitary mixing in far detector data
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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

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

- $c_{ij} = \cos\theta_{ij}$, 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}.

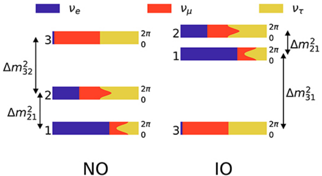
Values of neutrino oscillation parameters as of June, 2012

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}.

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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. 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]

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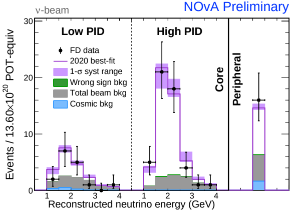
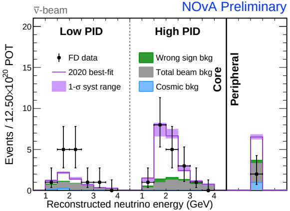
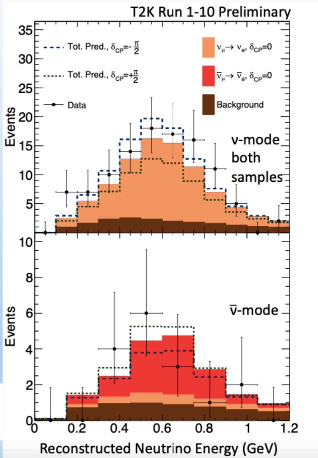
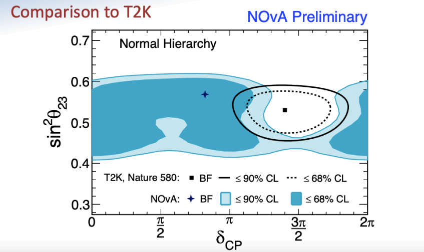

ν-beam
NOvA Preliminary
Low PID
High PID
Core
Peripheral
FD data
2020 best-fit
1-σ syst range
Wrong sign bkg
Total beam bkg
Cosmic bkg
Events / 13.60×10^20 POT-equiv
0
10
20
30
1 2 3 4 1 2 3 4
Reconstructed neutrino energy (GeV)


ν̄-beam
NOvA Preliminary
Low PID
High PID
Core
Peripheral
FD data
2020 best-fit
1-σ syst range
Wrong sign bkg
Total beam bkg
Cosmic bkg
Events / 12.50×10^20 POT
0
5
10
15
20
1 2 3 4 1 2 3 4
Reconstructed neutrino energy (GeV)


T2K Run 1-10 Preliminary
Tot. Pred., δCP=-π/2
Tot. Pred., δCP=+π/2
Data
νμ→νe, δCP=0
ν̄μ→ν̄e, δCP=0
Background
ν-mode both samples
ν̄-mode
Events
5
10
15
20
25
30
35
Events
0
2
4
6
8
10
0
0.2
0.4
0.6
0.8
1
1.2
Reconstructed Neutrino Energy (GeV)

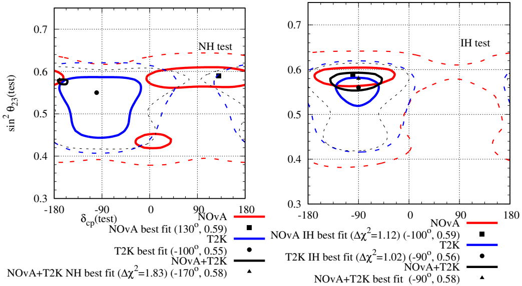
Analysis of 2020 data from NOνA and T2K

- 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.



Our analysis

LS Miranda, P. Pasquini, U. Rahaman, S. Razzaque, Eur.Phys.J.C 81 (2021) 5, 444, arXiv:1911.09398



1. The tension between NOνA and T2K data

2. Looking for non-unitary mixing in far detector data
    - Non-unitary mixing of 3 active neutrinos
    - Non-unitary mixing in 2020 data

3. Non-unitary mixing in near detector data

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

$$N = N_{NP} U_{3\times3} = \begin{bmatrix} \alpha_{00} & 0 & 0 \\ \alpha_{10} & \alpha_{11} & 0 \\ \alpha_{20} & \alpha_{21} & \alpha_{22} \end{bmatrix} U_{\mathrm{PMNS}} \,, \tag{2.3}$$

We will consider the effects of α_{00}, $\alpha_{10} = |\alpha_{10}|e^{i\phi_{10}}$ and α_{11} only.
$3\,\sigma$ boundary values: $\alpha_{00} > 0.93$, $\alpha_{11} > 0.95$, $|\alpha_{10}| < 3.6 \times 10^{-2}$ [Escrihuela et al., arXiv: 1612.07377]

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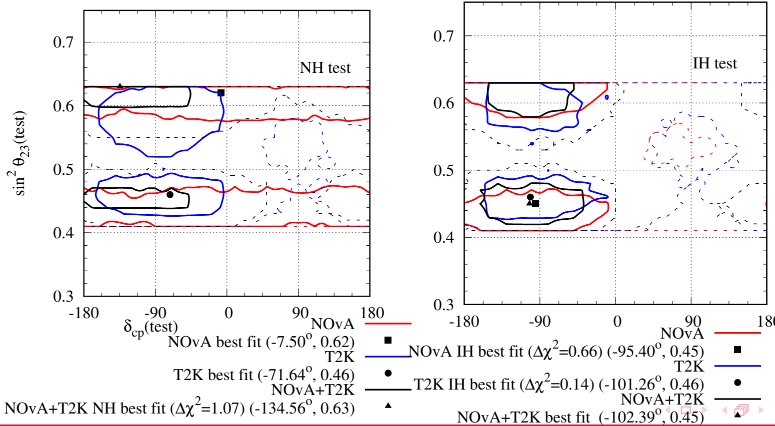
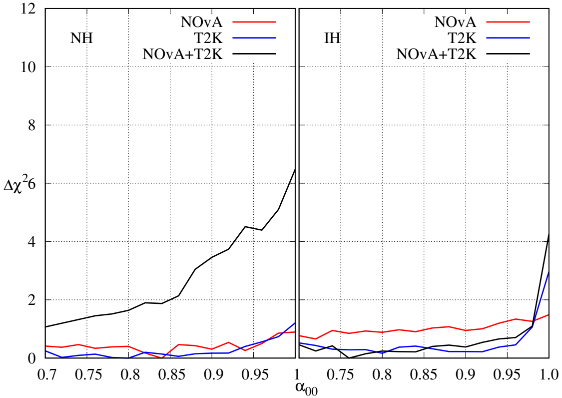
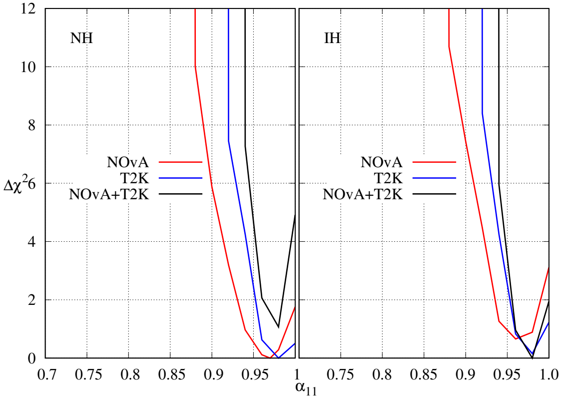
Analysis of 2020 data with non-unitary hypothesis



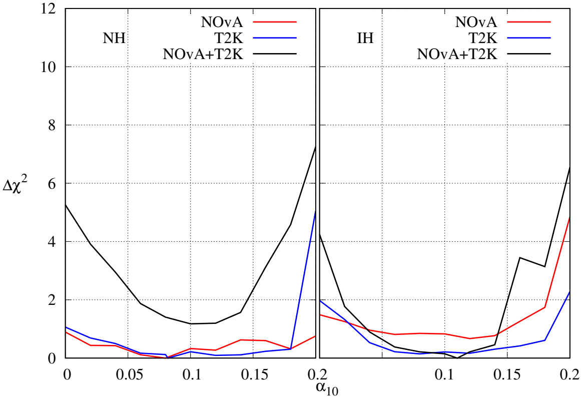
Constrain on α_{00} from 2020 data



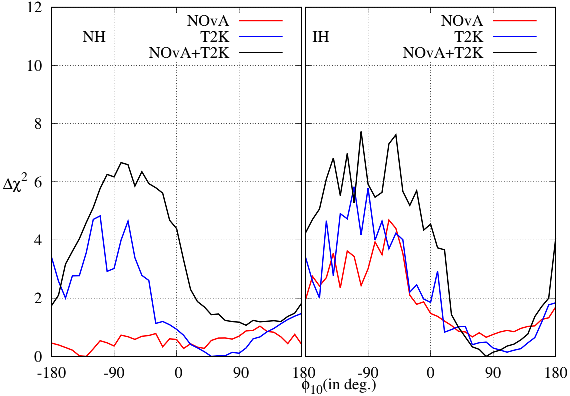
Constrain on $|\alpha_{10}|$ from 2020 data



Constrain on α_{11} from 2020 data



Constrain on ϕ_{10} from 2020 data



Inference from 2020 data [Miranda, Pasquini, Rahaman, Razzaque, arXiv: 1911.09398]

- Both the experiments individually prefer non-unitary mixing over the unitary one at $1\,\sigma$ C.L., preferring NH in both cases.
- The combined analysis, however, prefers IH both for unitary and non-unitary mixing but the non-unitary mixing is favored over unitary mixing at more than $2\,\sigma$ C.L.
- The tension between the two experiments is also reduced when analysed with non-unitary hypothesis.
- Both the experiments lose θ_{23} octant and hierarchy sensitivity when analysed with non-unitarity.
- The constraints on the non-unitary parameters are even weaker with the 2020 data as compared to the 2019 data. As a consequence, the preference for non-unitarity is stronger with the 2020 data.

- NOνA and T2K FD data rule out unitary mixing at $1\,\sigma$ C.L. [Miranda et al., arXiv: 1911.09387]
- Short baseline reactor neutrino experiments strongly prefer unitary mixing. [Forero et al., arXiv: 2103.01998]
- Further analysis of more available data are required to look for non-unitary mixing.

Zero distance effect

- $$P_{\mu e}^{\mathrm{NU}}(L = 0) = \alpha_{00}|\alpha_{10}|^2 \tag{3.4}$$

  [Escrihuela et al., arXiv: 1503.08879]
- Possible to observe flavour transformation even at zero distance.
- Short baseline neutrino oscillation experiments as well as the NDs od long baseline experiments are good candidates to look for non-unitary mixing.
- T2K ND data are not available in public domain

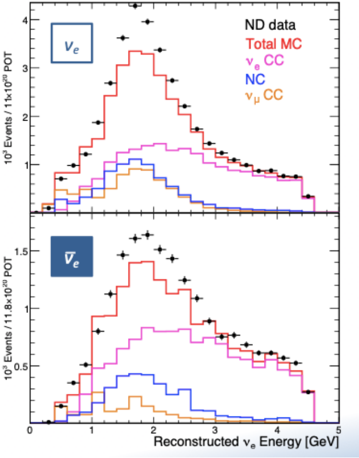
But NOνA ND data are!

NOνA ND

[Acero et al., arXiv:1806.00096]

- 290 ton TASD
- distance from source is 1 km.
- Placed at 100 m underground and 0.8° off-axis.
- Cannot observe flavour change for unitary mixing, but can do the same for non-unitary mixing.
- The non-unitary oscillation at ND is sensitive to α_{00}, $|\alpha_{10}|$. Also $|\alpha_{10}| \leq \sqrt{(1-\alpha_{00}^2)(1-\alpha_{11}^2)}$
- In 2020, NOνA near detector (ND) data with 11×10^{20} (11.8×10^{20}) protons on target (POTs) in (anti-) neutrino mode have been published. [A. Himmel, Talk given at Neutrino 2020]
- Gives an unique opportunity to explore non-unitary mixing at the ND and FD of the same experiment.

[A. Himmel, Talk given at Neutrino 2020]



there is an excess in observed electron and positron events compared to the expected event rates in the standard case.

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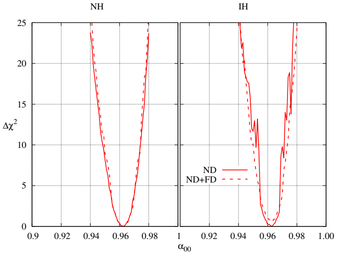
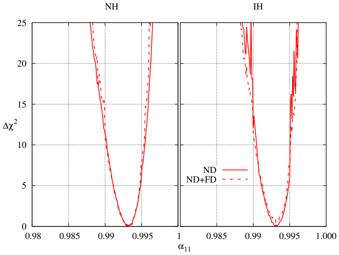
    - Motivation
    - Analysis of ND data

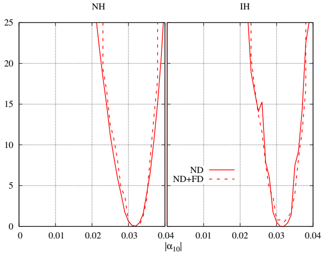
Result

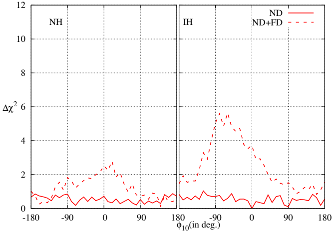
[Paper to be available on arXiv by 30th August, 2021]





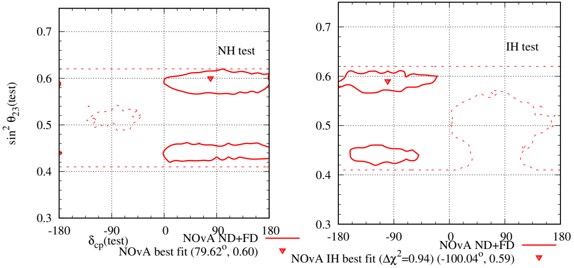
Result


NH
IH
25
20
15
10
5
0
0
0.01
0.02
0.03
0.04
0.01
0.02
0.03
0.04
$|\alpha_{10}|$
ND
ND+FD

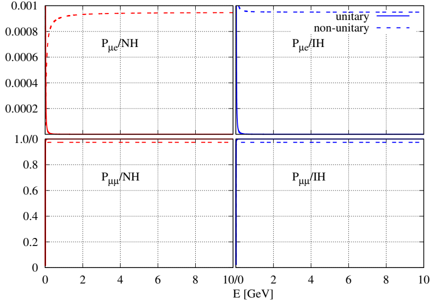

12
10
8
$\Delta\chi^2$ 6
4
2
0
NH
IH
ND
ND+FD
-180
-90
0
90
180
-90
0
90
180
ϕ_{10}(in deg.)

Result

- ND data are not sensitive to standard unitary parameters.
- After combining with FD data, they become sensitive to standard parameters.

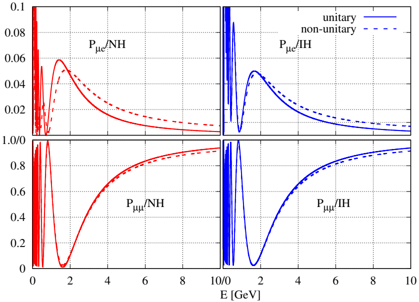


Probability plots



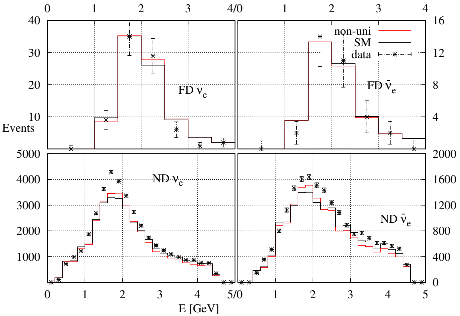
$\nu_\mu \to \nu_e$ transformation ($\nu_\mu \to \nu_\mu$ survival) probability as a function of energy at the ND in the upper (lower) panel. The left (right) panel is for NH (IH). The solid (dashed) line represents (non-) unitary mixing.

Probability plots



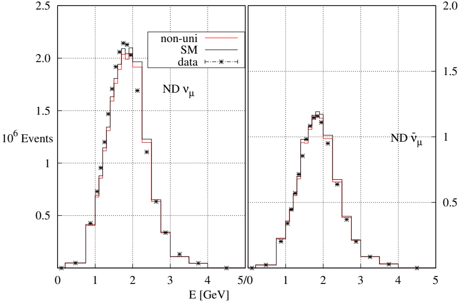
$\nu_\mu \to \nu_e$ transformation ($\nu_\mu \to \nu_\mu$ survival) probability as a function of energy at the FD in the upper (lower) panel. The left (right) panel is for NH (IH). The solid (dashed) line represents (non-) unitary mixing.

Event number plots



Comparison between observed and expected ν_e and $\bar{\nu}_e$ events at the best-fit points for both unitary and non-unitary mixing at ND and FD.

Event number plots



Comparison between observed and expected ν_μ and $\bar{\nu}_\mu$ events at the best-fit points for both unitary and non-unitary mixing at ND.

Inference from NOνA ND data

- NOνA ND data rule out unitary mixing at more than $5\,\sigma$ C.L. and give a precise measurement of the non-unitary parameters.
- Although the deviation from unitarity is small, this is the **first strong signature of BSM** physics at accelerator neutrino long baseline experiments.
- when ND data are combined with FD data, the allowed values of δ_{CP} are same as those found after analysing FD data with unitary mixing hypothesis. However the octant of θ_{23} cannot be resolved.
- It is very important for T2K and future experiments DUNE and T2HK to look for non-unitary mixing at their ND data.

Thank You!