SEARCHING FOR NON-UNITARY NEUTRINO OSCILLATION IN THE PRESENT T2K AND NOvA DATA

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

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Abstract: The mixing of three active neutrino flavors is parameterized by the unitary PMNS matrix. If there are more than three neutrino flavors and if the extra generations are heavy isosinglets, the effective 3×3 mixing matrix for the three active neutrinos will be non-unitary. We have analyzed the latest T2K and NOνA data with the hypothesis of non-unitary mixing of the active neutrinos. We found that the NOνA data slightly (at $\sim 1\,\sigma$ C.L.) prefer the non-unitary mixing over unitary mixing. In fact, allowing the non-unitary mixing brings the NOνA best-fit point in the $\sin^2\theta_{23} - \delta_{\rm CP}$ plane closer to the T2K best-fit point. The T2K data, on the other hand, prefer unitary mixing. A combined analysis of the NOνA and T2K data also prefers the unitary mixing but cannot rule out the $1\,\sigma$ C.L. non-unitary region derived from the NOνA data alone. We derive constraints on the non-unitary mixing parameters using the best-fit to the combined NOνA and T2K data. These constraints are similar or slightly more restrictive than previously found.

Keywords: Neutrino Mass Hierarchy, Leptonic CP-violation, non-unitarity


300 TRILLION NEUTRINOS WALK INTO A BAR
BAR
THEN WALK THROUGH THE BAR
BAR
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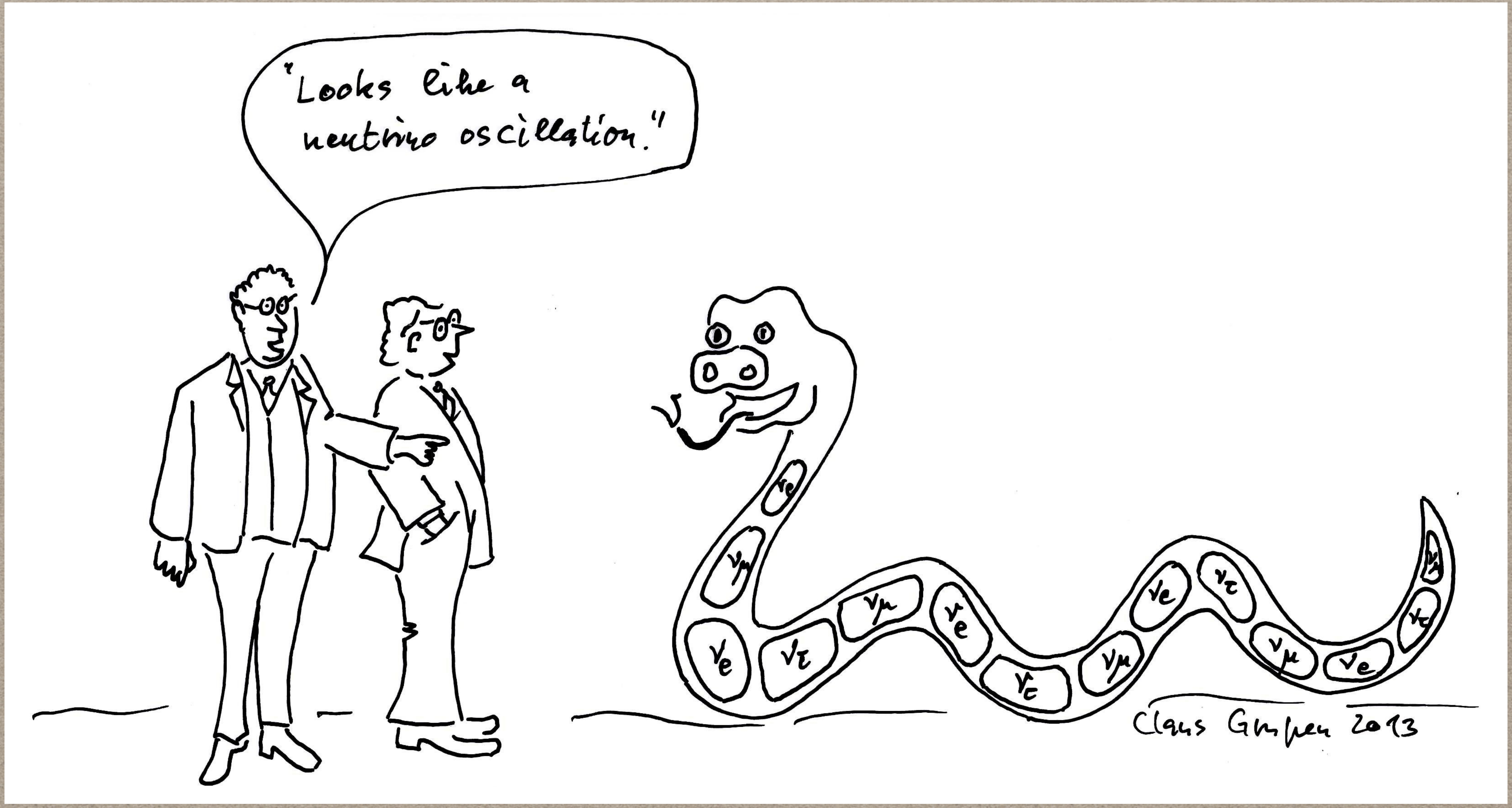
OUTLINE

1. Neutrino oscillation
    - Neutrino oscillation in vacuum
    - Neutrino oscillation in matter
2. Long baseline neutrino oscillation experiments
    - NOνA and T2K
    - Current best-fit points from NOvA and T2K

3. Problem
    - Background
    - Statement
    - Probability calculations with non-unitary mixing
    - Simulation details
    - Results
    - Conclusions

NEUTRINO OSCILLATION



NEUTRINO FLAVOUR AND MIXING

- Three neutrino flavours: ν_e, ν_μ, ν_τ
- They are produced in interactions
- They are called flavour or interaction eigenstates

VACUUM OSCILLATION

THREE FLAVOUR

- Three flavour states ν_e, ν_μ, ν_τ mix to form three mass eigenstates ν_1, ν_2, ν_3 with masses respectively m_1, m_2, m_3
- $$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = U^\dagger \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$
- U is a 3*3 unitary matrix

- $$U = \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$
- $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$
- The oscillation probability depends on three mixing angles $\theta_{12},\theta_{13,}\theta_{23}$, two independent mass squared differences and one CP violating phase δ_{CP}

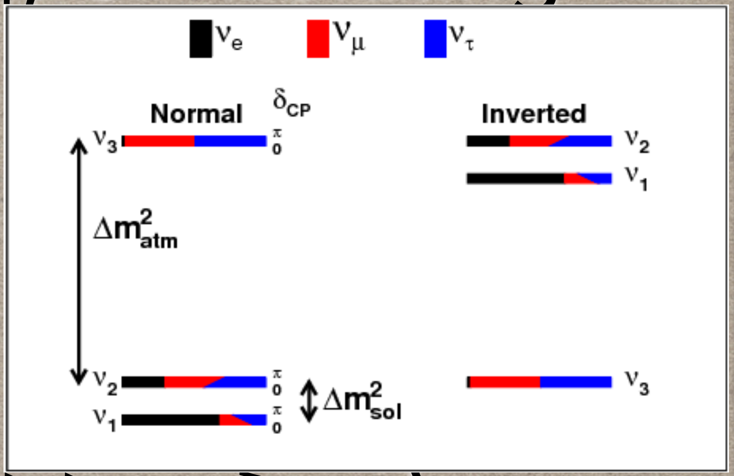
VALUES OF NEUTRINO OSCILLATION PARAMETERS AS OF JUNE, 2012

[Gonzalez-Garcia et al., arXiv: 1209.3023]

Parameters	(Best fit±1σ)
$\sin^2\theta_{12}$	$0.306^{+0.013}_{-0.012}$
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus \left[0.594^{+0.021}_{-0.022}\right]$
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$
$\delta_{CP}/°$	300^{+66}_{-138}
Δ_{21}	$7.50^{+0.18}_{-0.19}\ \mathrm{eV}^2$
$\Delta_{31}(N)$	$+2.473^{+0.070}_{-0.067}\ \mathrm{eV}^2$
$\Delta_{32}(I)$	$-2.427^{+0.042}_{-0.065}\ \mathrm{eV}^2$

THE UNKNOWN PARAMETERS

- The unknown quantities are: sign of Δ_{31}, CP violating phase δ_{CP} and octant of θ_{23}



- There can be two mass ordering:

1. Normal hierarchy (NH): $\Delta_{31}>0$ ($m_3>>m_2\gtrapprox m_1$)

2. Inverted hierarchy (IH): $\Delta 31<0$ ($m_2\gtrapprox m_1>>m_1$)

NEUTRINO OSCILLATION IN MATTER

- While passing through dense matter, neutrinos undergo forward elastic scattering, parameterised by a potential V, which changes the dispersion relation to $E = \sqrt{p^2 + m^2} + V$
- This extra potential modifies the neutrino oscillation probability
- While propagating, ν_e can have both CC and NC interactions
- ν_μ and ν_τ can have only NC interactions.
- The potential matrix in flavour basis, in two flavour approximation is

$$V = \begin{pmatrix} V_{CC} + V_{NC} & 0 \\ 0 & V_{NC} \end{pmatrix} = \begin{pmatrix} V_{CC} & 0 \\ 0 & 0 \end{pmatrix} + V_{NC} I$$

- Therefore, the CC potential is what contributes to the neutrino propagation

- It can be shown that the, under the influence of matter potential, upto the second order of $\boldsymbol{\alpha}=\Delta_{21}/\Delta_{31}$, oscillation probability $P_{\mu e}$ gets modified to [Cervera et al., arXiv: hep-ph/0002018]

$$\boxed{\begin{aligned} P_{\mu e} &= \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2\left[\hat{\Delta}(1-\hat{A})\right]}{(1-\hat{A})^2} \\ &+\alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\hat{\Delta}+\delta_{CP}) \frac{\sin(\hat{\Delta}\hat{A})}{\hat{A}} \frac{\sin\left[\hat{\Delta}(1-\hat{A})\right]}{(1-\hat{A})} \\ &+\alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{13} \cos^2\theta_{23} \frac{\sin^2(\hat{\Delta}\hat{A})}{\hat{A}^2} \end{aligned}}$$

$$\hat{\Delta} = \Delta_{31} L / 4E,\ \hat{A} = A / \Delta_{31},\ A = 2EV_{\mathrm{CC}}$$

THE LONG BASELINE NEUTRINO OSCILLATION EXPERIMENTS

- The current long baseline experiments like NOνA and T2K are the ones where matter affected three flavour oscillation can be observed.
- These experiments are sensitive to mass hierarchy, δ_{CP} and octant of θ_{23}
- These experiments can measure four probabilities:

A. Two disappearance probabilities $P_{\mu\mu}$ and $P_{\overline{\mu}\overline{\mu}}$: improve precision in $|\Delta_{31}|$ and $\sin 2\theta_{23}$

B. Two appearance probabilities $P_{\mu e}$ and $P_{\overline{\mu}\overline{e}}$: give information on CP violation, hierarchy and octant of θ_{23}

T2K

- T2K is a long baseline neutrino oscillation experiment, based in Japan
- J-PARC accelerator in Tokai is the source and the detector is the Super-Kamiokande water Cerenkov detector, 295 km away from the source
- The accelerator is oriented such that the detector is at 2.5^{o} off-axis
- Fiducial volume of the detector: 22.5 kt, capable of good discrimination between electron and muon
- Flux peaks at 0.7 GeV, which is also the first oscillation maximum

- Started taking data in 2009
- 2013: first neutrino data in both disappearance and appearance mode with 6.6×10^{20} protons on target (POT) [Abe et al., arXiv: 1311.4750, 1403.1532]
- 2015: First anti-neutrino data in both disappearance and disappearance mode with 4×10^{20} POT [Salzgeber et al., arXiv: 1508.0615]
- 2017: neutrino data with 7.252×10^{20} POT and anti-neutrino data with 7.531×10^{20} POT [Haegel et al., arXiv: 1709.0418]
- 2019: (anti-) neutrino appearance data with 1.49 $(1.64)\times10^{21}$ POT and (anti-) neutrino disappearance data with 14.7 $(7.6)\times10^{20}$ POT (arXiv:1910.03887, 1807.07891)

NOνA

- The source for NOνA experiment is NuMI beam from Fermilab [Ayres et al, The NOνA Technical Design Report]
- The detector is a 14 kt Totally Active Scintillator Detector (TASD), located 810 km away from Fermilab, at 0.8^{o} off-axis
- The flux peaks sharply at 2 GeV, close to oscillation maxima 1.4 GeV
- 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: Published neutrino data in both disappearance and appearance mode with 6.05×10^{20} POT [Adamson et al., arXiv: 1701.0589, 1703.0332]
- 2018: Published neutrino data in both disappearance and appearance mode with 8.85×10^{20} POT [Acero et al., 1806.00096]
- 2019: Published (anti-) neutrino data in both disappearance and appearance mode with 8.85 (12.33)$\times10^{20}$ POT [arXiv: 1906.04907]

BEST FIT FROM LATEST T2K AND NOvA DATA

- T2K: $\delta_{CP}/\pi = -1.89^{+0.70}_{-0.58}(-1.38^{+0.48}_{-0.54})$ $\sin^2\theta_{23} = 0.53^{+0.03}_{-0.04}$ for NH (IH) [arXiv:1910.03887]
- NOvA: $\delta_{CP}/\pi = 0^{+1.3}_{-0.4}(1.5)$ $\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}(0.56)$ for NH (IH)[arXiv: 1906.04907]
- There are discrepancies between two experiments

PROBLEM

BACKGROUND: REACTOR ANOMALIES

- Deficit of observed $\bar{\nu}_e$ events in different detectors placed at a few meters distance from the reactor sources, compared to the predicted event numbers.
- $R_{\text{avg}} = 0.938 \pm 0.023$: $2.7\,\sigma$ deviation from unity

- Similar indication of electron neutrino disappearance from SAGE and GALEX solar neutrino experiments
- $R = 0.86 \pm 0.05$: another $2.7\,\sigma$ deviation from unity
- Both deficits can be explained by an oscillation over very short base line at $\Delta m^2 \geq 1\,\mathrm{eV}^2$

BACKGROUND: LSND AND MiniBooNE ANOMALIES

- LSND at Los Alamos was developed to observe $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation over a baseline of 30 m.
- After 5 years it observed $89.7 \pm 22.4 \pm 6.0\, \bar{\nu}_e$ events over background: $3.8\,\sigma$ signal of $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation at $\Delta m^2 \sim 1\,\mathrm{eV}^2$

- MiniBooNE at Fermilab was designed to observe $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

- Baseline= 540 m.

- It has confirmed a $4.7\,\sigma$ excess of ν_e and $\bar{\nu}_e$ events

- Combined analysis of LSND and MiniBooNE shows a $6\,\sigma$ excess.

BACKGROUND: EXPLANATION

- Most common explanation is the existence of one or more ‘sterile’ neutrinos.
- Simplest model consists of 3+1 neutrino mixing
- 4 mass eigen states:

$\nu_1, \nu_2, \nu_3, \nu_4$ with masses m_1, m_2, m_3, m_4 such that $m_1, m_2, m_3 << m_4$ and $\Delta_{41} = [0.1 - 10]\ \mathrm{eV}^2$

- If extra neutrino exists as isosinglet neutral heavy leptons (NHL), in the minimal extension of the standard model, they would not take part in neutrino oscillations.
- The admixture of such leptons in the charged current weak interactions would affect the neutrino oscillation, and the neutrino oscillation would be described by an effective 3*3 non-unitary matrix.

STATEMENT OF PROBLEM

- Do the present data from NOvA and T2K exclude non-unitarity?
- If not, can we reach a better agreement between NOvA and T2K using non-unitary hypothesis?

PROBABILITY WITH NON-UNITARY MIXING

- Mixing matrix $N = N^{\mathrm{NP}} U$
- U is the standard PMNS matrix.
- $N^{\mathrm{NP}} = \begin{pmatrix} \alpha_{00} & 0 & 0 \\ \alpha_{10} & \alpha_{11} & 0 \\ \alpha_{20} & \alpha_{21} & \alpha_{22} \end{pmatrix}$

[arXiv: 1503.08879]

- The theory of probability calculation has been discussed in details in our paper arXiv: 1911.09398.

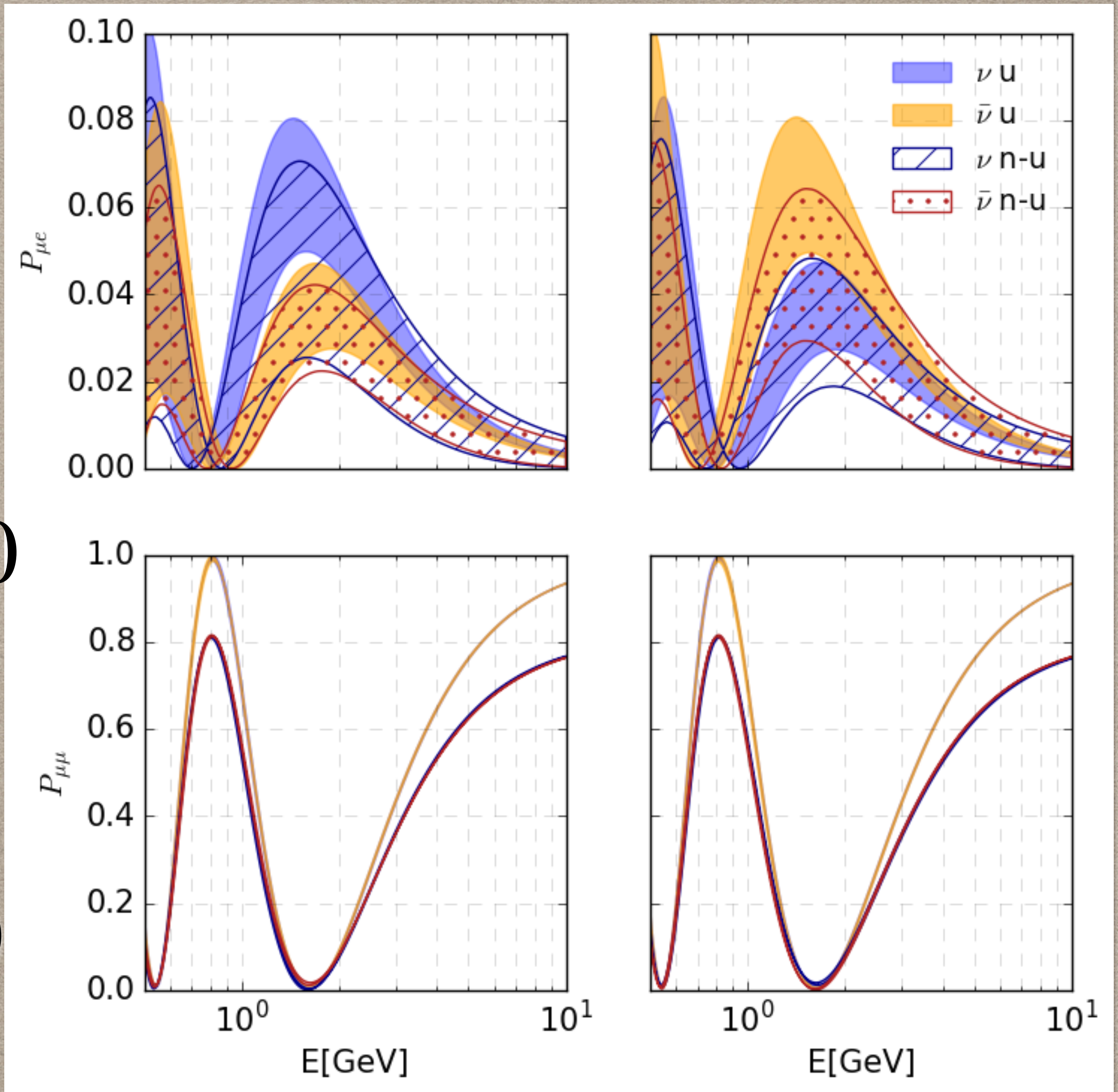
GLOBAL 3σ LIMIT ON ALPHA PARAMETERS

- $\alpha_{00} > 0.93, \alpha_{11} > 0.95, \alpha_{22} > 0.61, |\alpha_{10}| < 3.6 \times 10^{-2}, |\alpha_{20}| < 1.3 \times 10^{-1}, |\alpha_{21}| < 2.1 \times 10^{-2}$

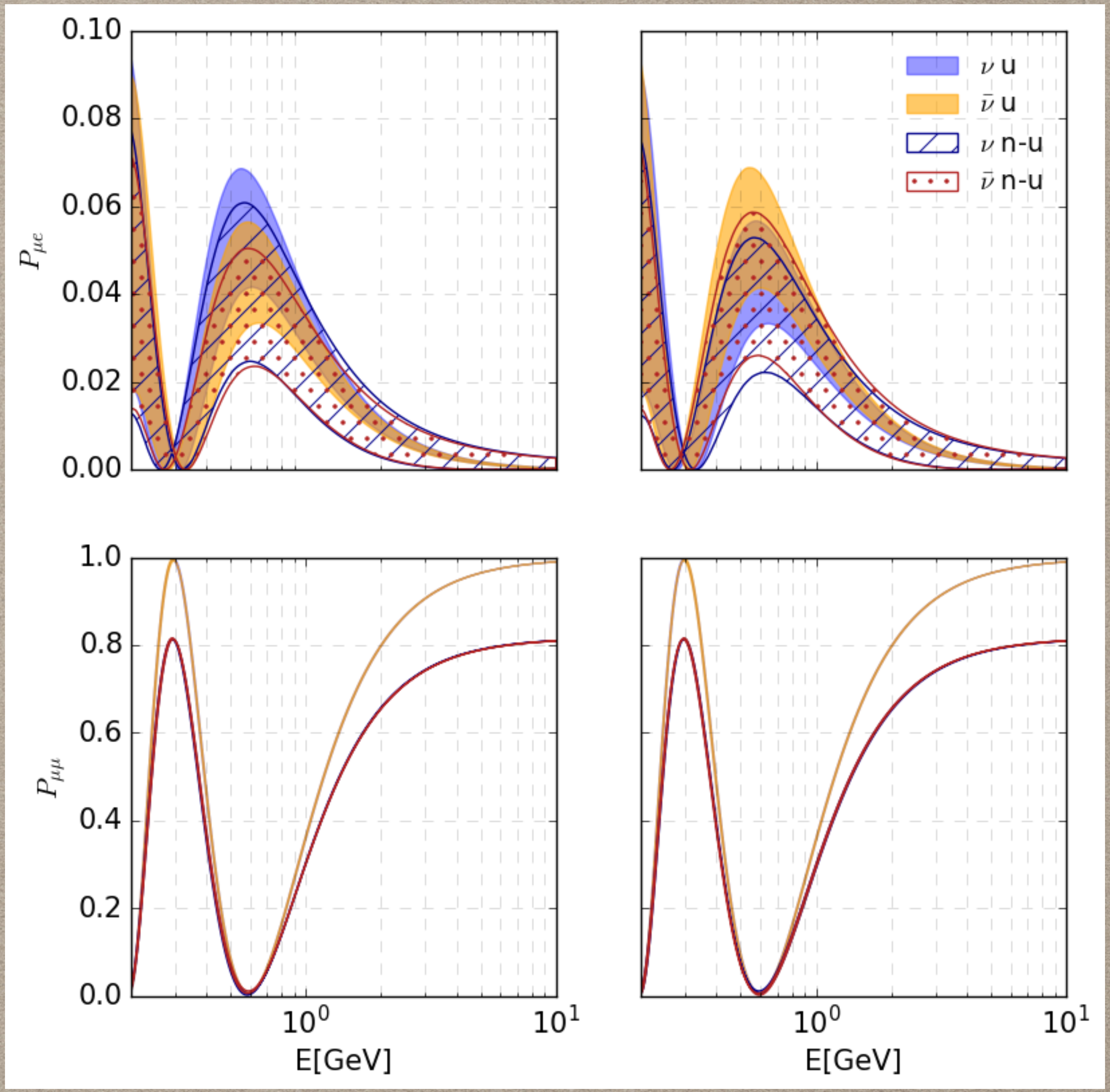
[arXiv:1503.08879]

Probability plots for NOvA for $\phi_{10} = 0$

Appearance (Disappearance) probability in upper (lower panel) NH (IH) in left (right) panel

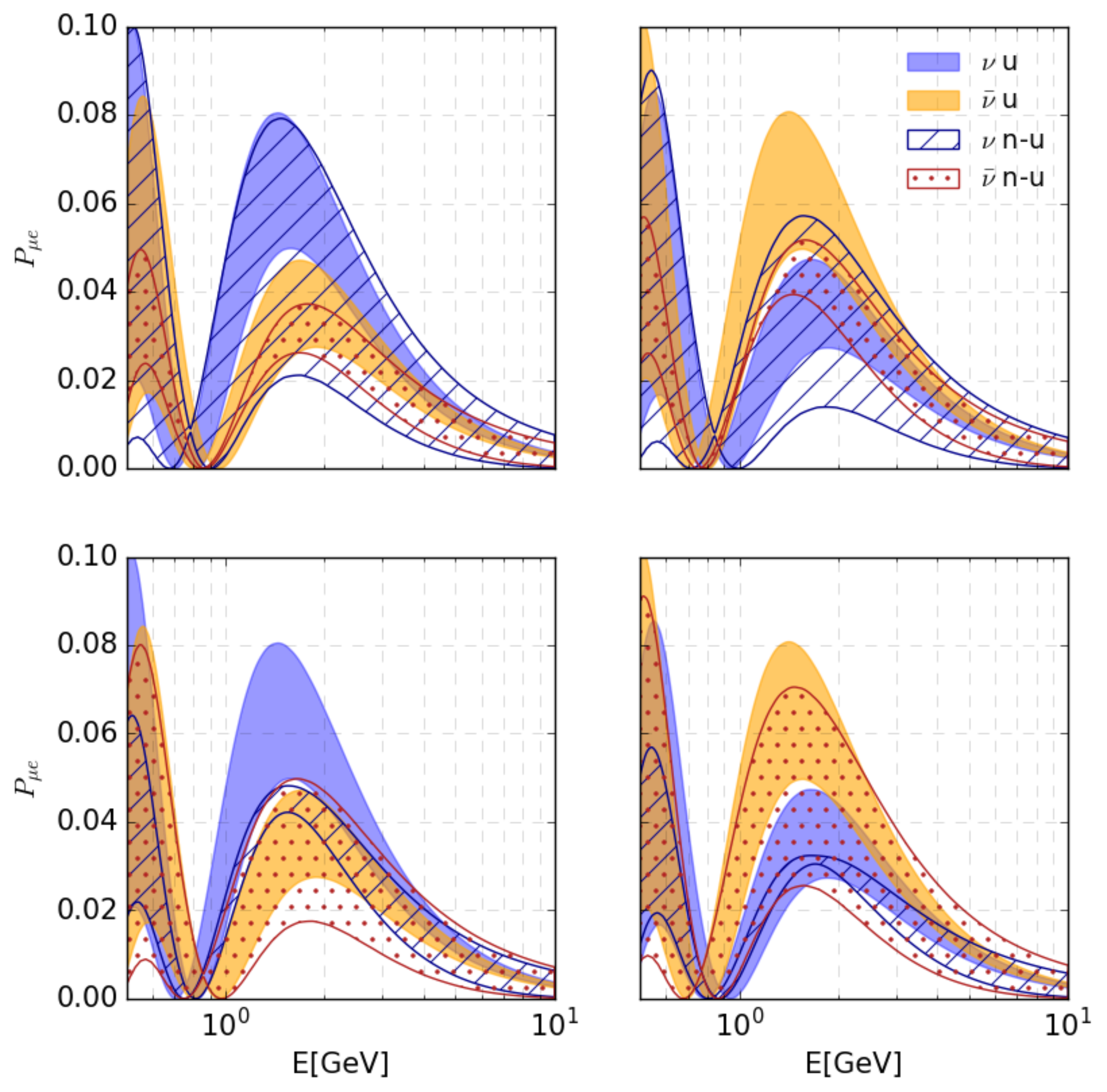


Probability plots for T2K for $\phi_{10} = 0$



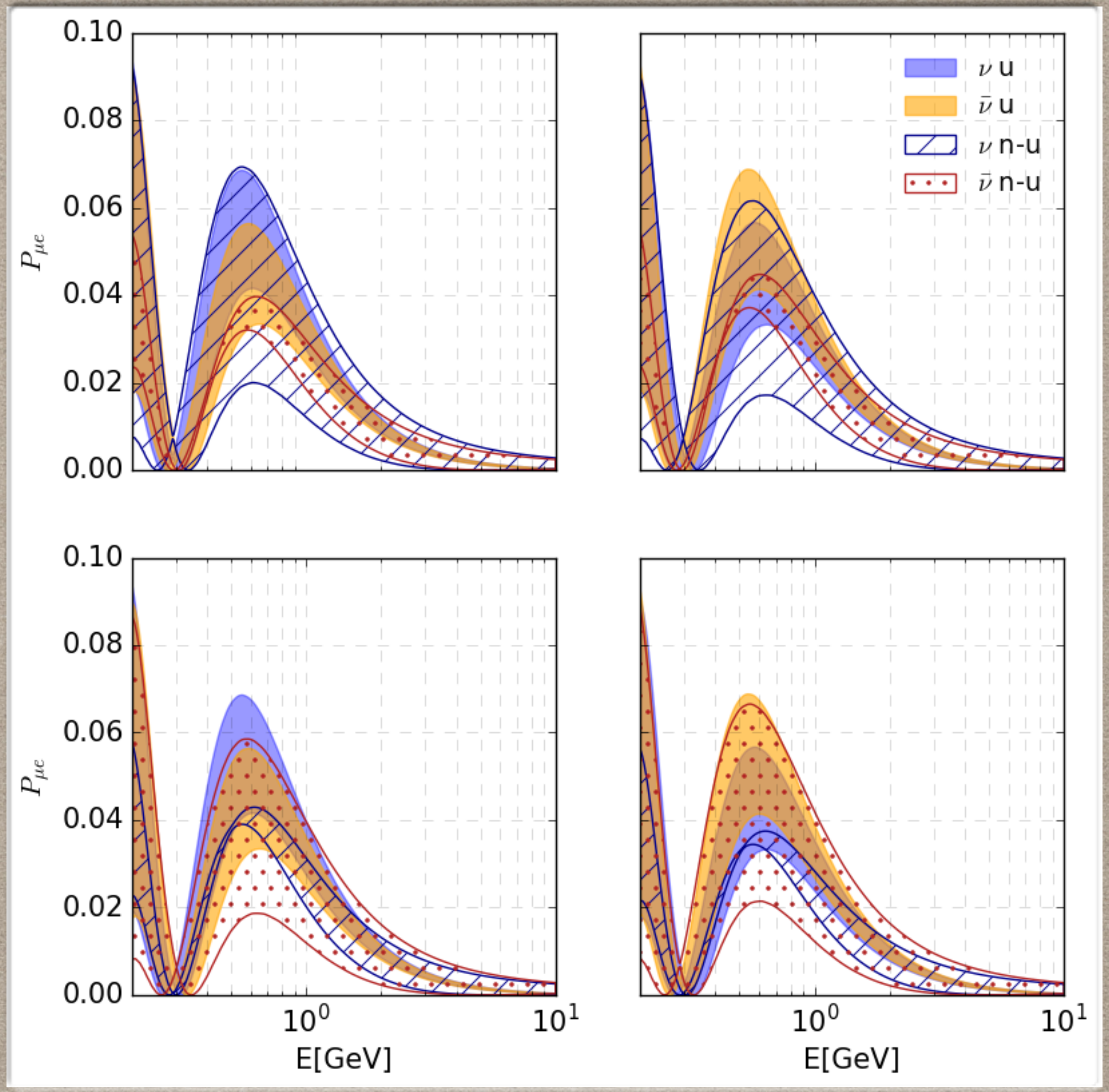
Probability plots for NOvA $\phi_{10} = -\pi/2(+\pi/2)$ in upper (lower) panel

NH (IH) in left (right) panel



Probability plots for T2K $\phi_{10} = -\pi/2(+\pi/2)$ in upper (lower) panel

NH (IH) in left (right) panel



ANALYSIS DETAILS

- For analysis, we used GLoBES: a sophisticated C language based software packages, designed to simulate long baseline neutrino oscillation experiments [arXiv: hep-ph/0407333]
- We use GLoBES to calculate theoretical event spectrum (test events) as a function of reconstructed binned energy
- We extracted data from the publication of NOvA and T2K collaborations
- For i-th energy bin:
  - data– N_i^{exp}
  - test events– N_i^{th}
- Test values of oscillation parameters to generate test event rates– test values

- Choosing test values:
  - For standard oscillation parameters, except $\delta_{\rm CP}$, test values are chosen within the 3σ range determined by the previous experiments.
  - For atmospheric mass squared difference, we varied $\Delta m^2_{\rm eff}$ around its MINOS central value $2.32 \times 10^{-3}\,{\rm eV}^2$

$$\Delta m^2_{\rm eff} = \sin^2\theta_{23}\Delta_{31} + \cos^2\theta_{12}\Delta_{32} + \cos\delta_{\rm CP}\sin 2\theta_{12}\sin\theta_{13}\tan\theta_{12}\Delta_{21}$$

  - We varied $\delta_{\rm CP}$ in the range $[-180^o : 180^o]$
  - For non standard parameters, test values are varied within a likely 3σ range
- We used 10% systematics error for each of the experiments.

- To minimise the difference between N_i^{exp} and N_i^{th}, χ^2 is calculated between them [Coloma et al., arXiv: 1209.5973]

$$\boxed{\begin{aligned}\chi^2 = \sum_i 2[(N_i^{\text{th}} - N_i^{\text{exp}}) + N_i^{\text{exp}} \times \ln(N_i^{\text{exp}} / N_i^{\text{th}})] + \sum_j [2N_j^{\text{th}}] \\ +\chi^2(\text{prior})\end{aligned}}$$

- Prior is added to take care of the deviation of the test values of measured oscillation parameters from their measured values

$$\boxed{\begin{aligned}\chi^2(\text{prior}) = &\left(\frac{\sin^2 2\theta_{13}(\text{test}) - \sin^2 2\theta_{13}(\text{true})}{0.05 \times \sin^2 2\theta_{13}(\text{true})}\right)^2 \\ &+ \left(\frac{\sin^2 2\theta_{23}(\text{test}) - \sin^2 2\theta_{23}(\text{true})}{0.02 \times \sin^2 2\theta_{23}(\text{true})}\right)^2 \\ &+ \left(\frac{|\Delta m^2_{\mu\mu}|(\text{test}) - |\Delta m^2_{\mu\mu}|(\text{true})}{0.03 \times |\Delta m^2_{\mu\mu}|(\text{true})}\right)^2\end{aligned}}$$

- We find out minimum χ^2 and subtract it from all χ^2 to calculate $\Delta\chi^2$
- 1σ, 2σ, 3σ parameter values are defined by the constraints $\Delta\chi^2 < \Delta\chi^2_{1,2,3}$

No. of parameter fittings	1σ	2σ	3σ
1	1	4	9
2	2.28	5.99	11.83

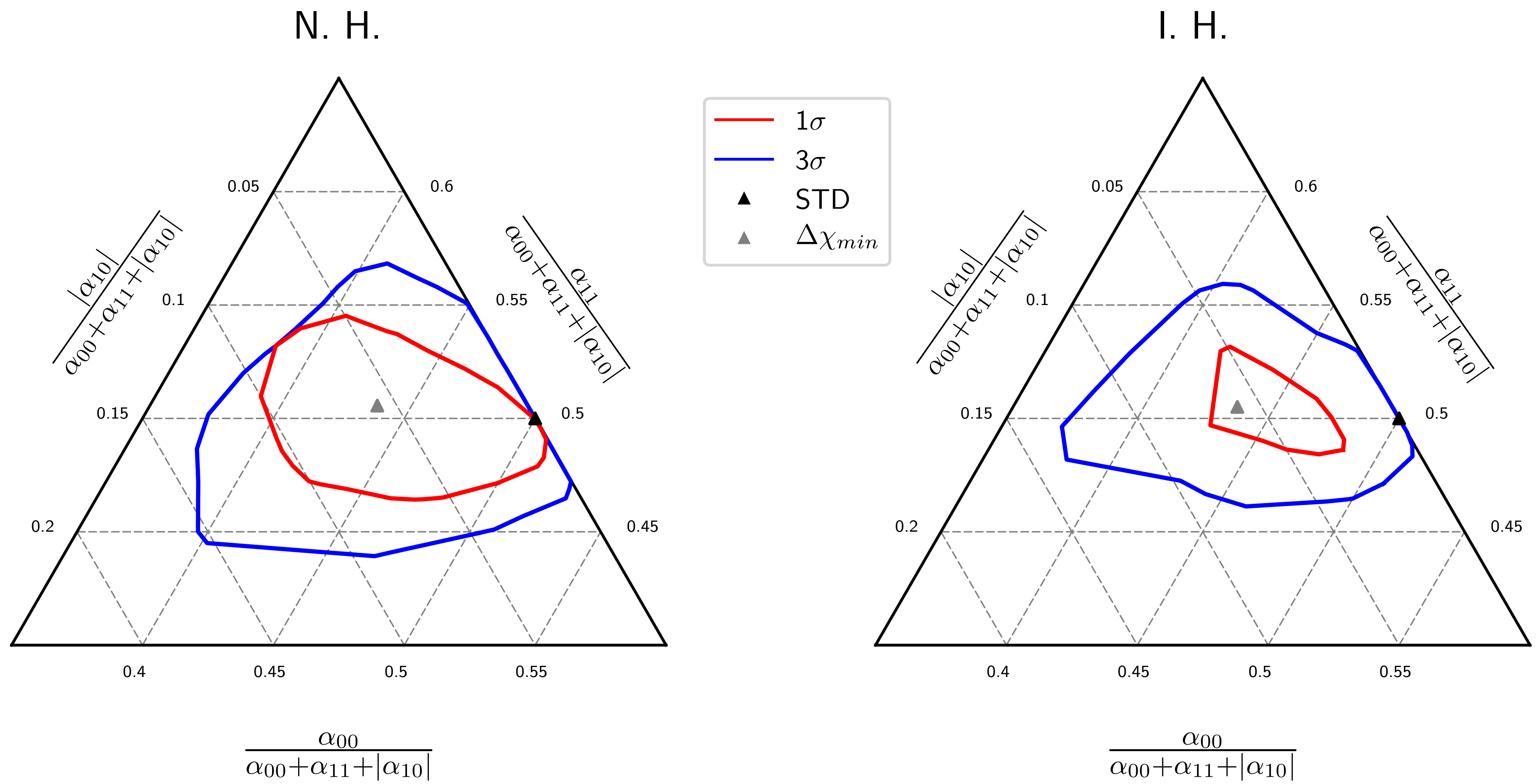
RESULTS

- Minimum $\chi^2 = 44.32(47.92)$ for NOvA non-unitary (standard) mixing for 50 energy bins.
- Minimum $\chi^2 = 121.37(123.71)$ for T2K non-unitary (standard) mixing for 104 energy bins.
- Minimum $\chi^2 = 170.90(173.40)$ for NOvA+T2K non-unitary (standard) mixing for 154 energy bins.

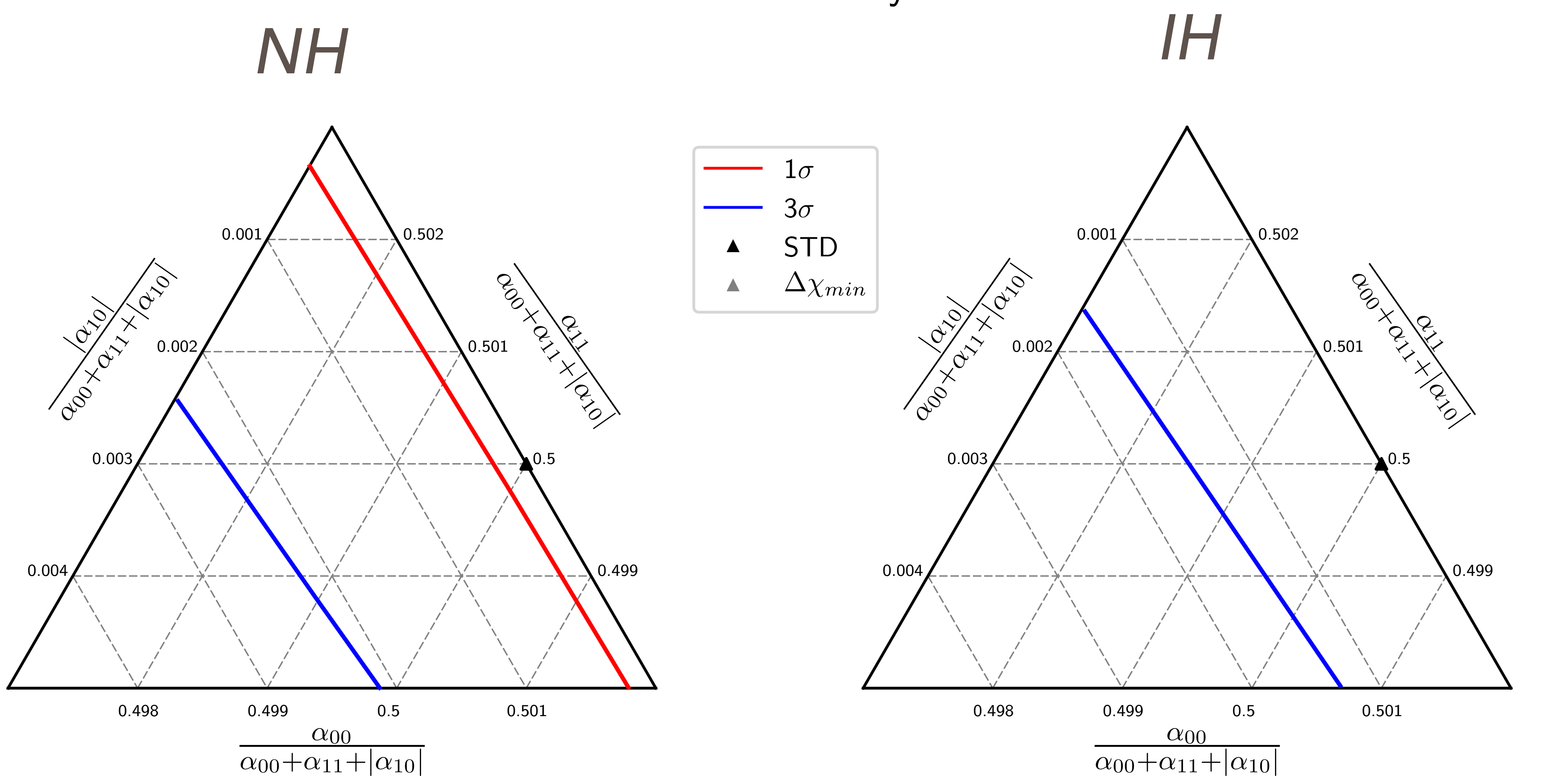
RESULTS

TRIANGULAR PLOTS

NOνA - Non-Unitary



T2K - Non-Unitary

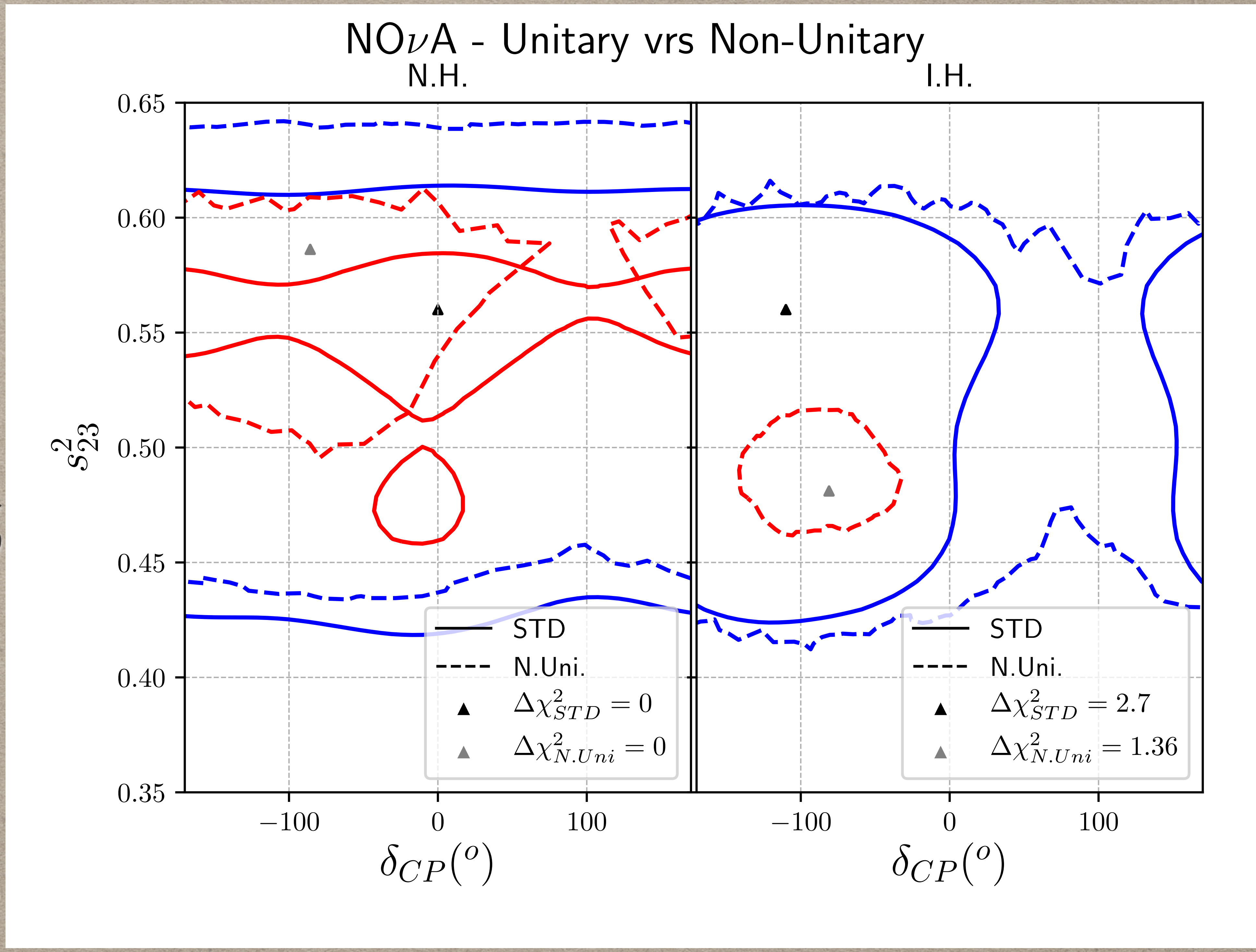


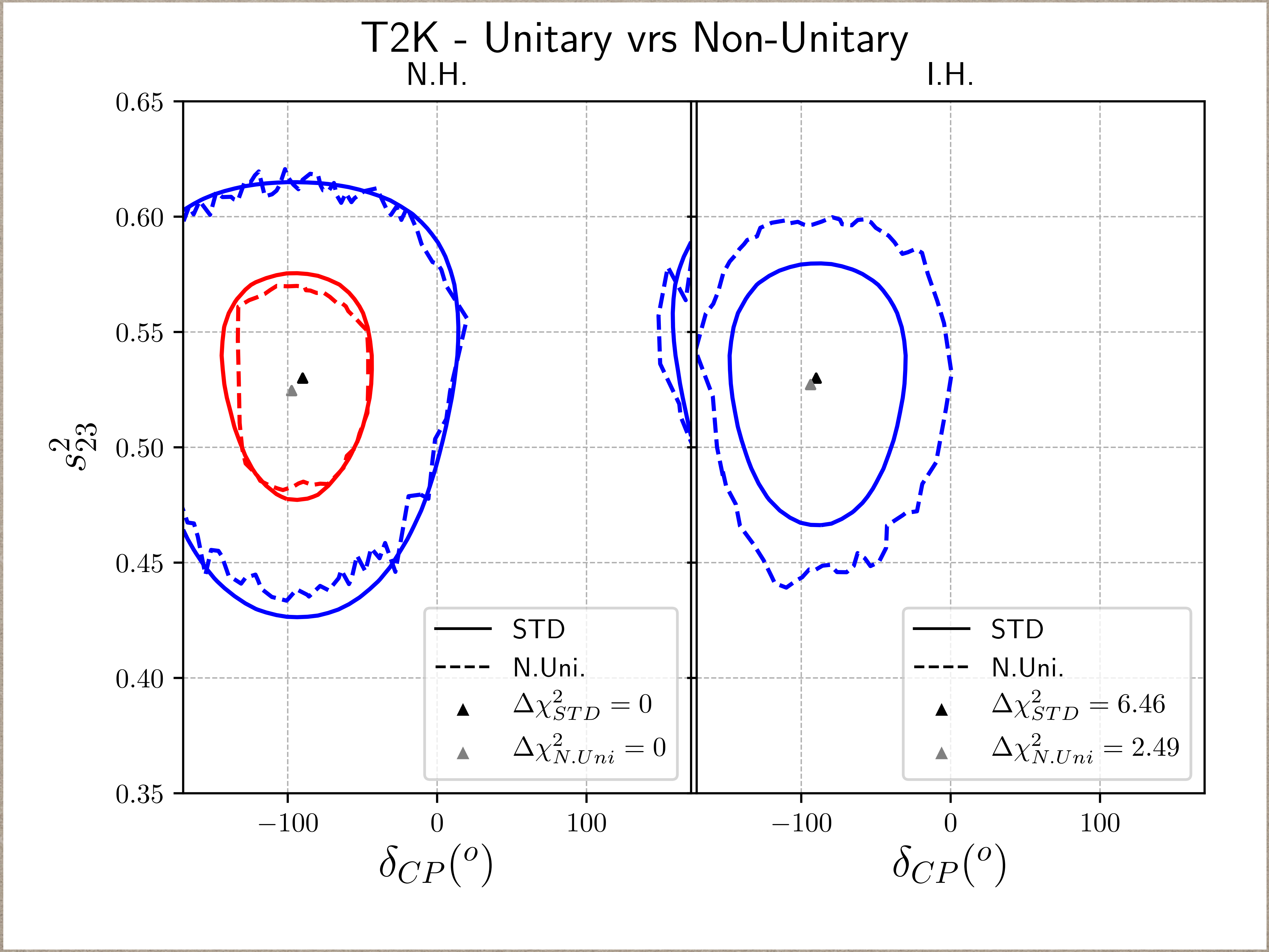
RESULTS

$\sin^2\theta_{23} - \delta_{\text{CP}}$ Plane

Red curve: 1σ

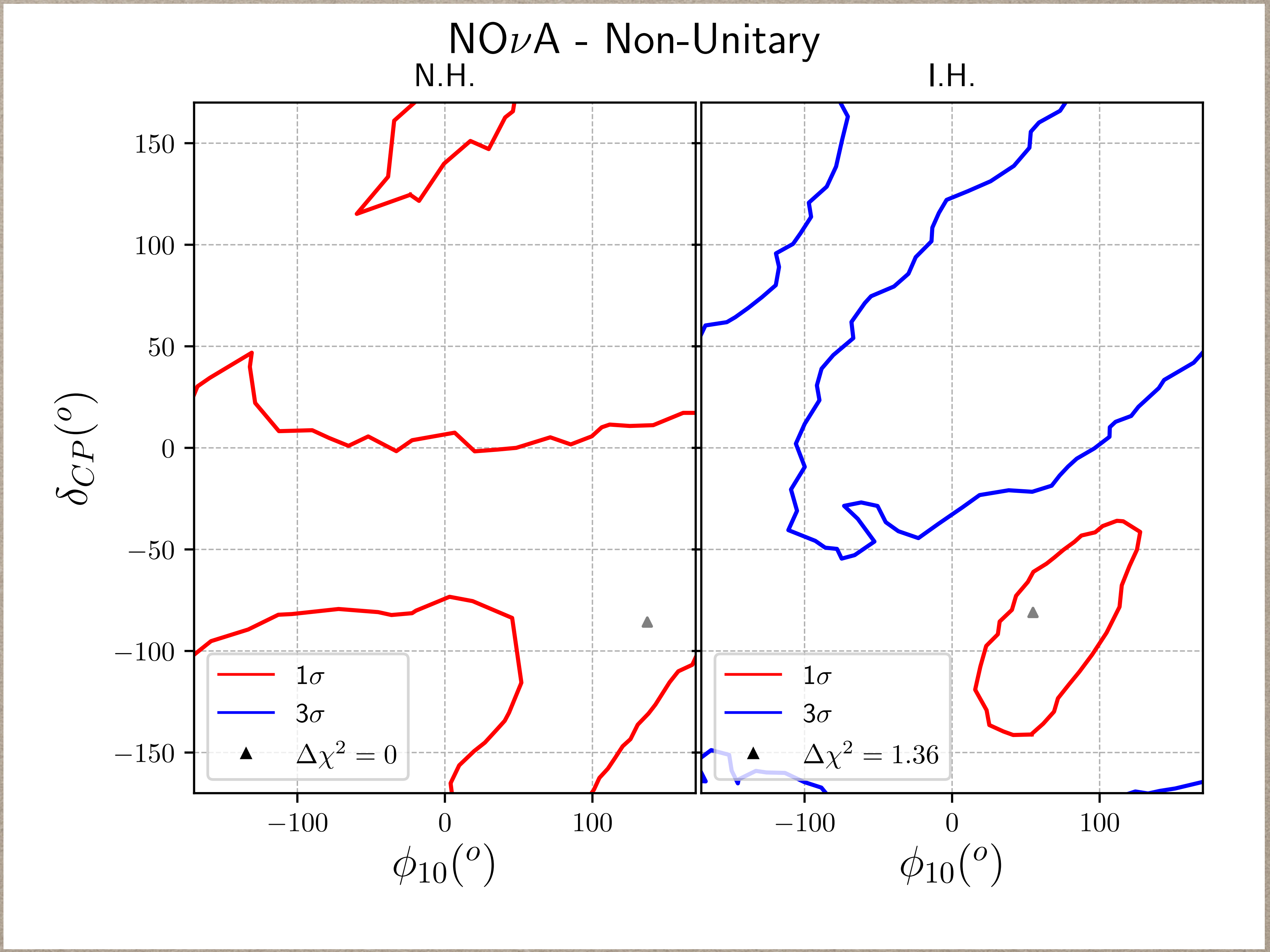
Blue curve: 3σ

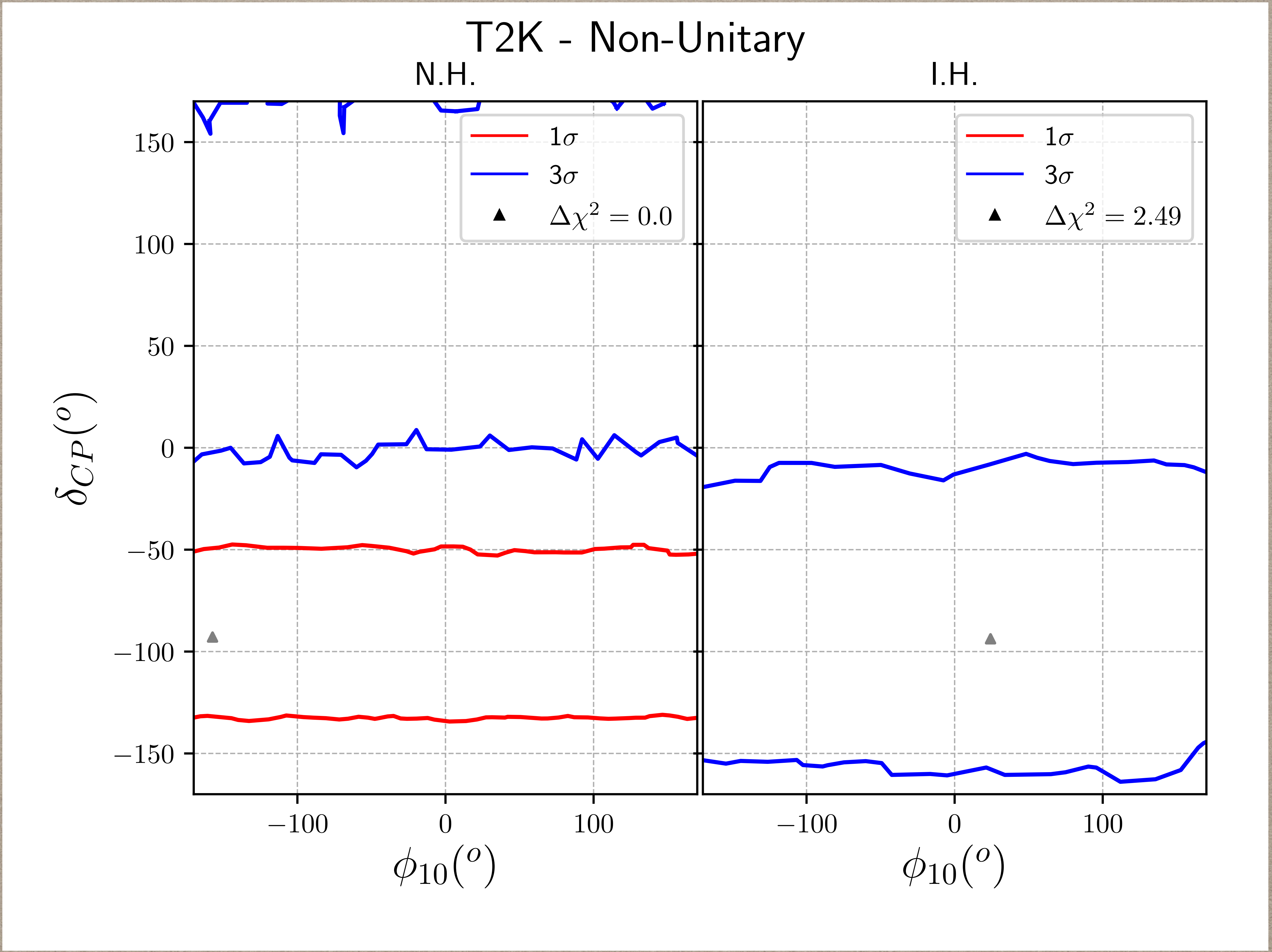



T2K - Unitary vrs Non-Unitary
N.H.
I.H.
0.65
0.60
0.55
0.50
0.45
0.40
0.35
s^2_{23}
−100
0
100
$\delta_{CP}(^o)$
STD
N.Uni.
$\Delta\chi^2_{STD} = 0$
$\Delta\chi^2_{N.Uni} = 0$
$\Delta\chi^2_{STD} = 6.46$
$\Delta\chi^2_{N.Uni} = 2.49$

RESULTS

$\phi_{10} - \delta_{CP}$ Plane

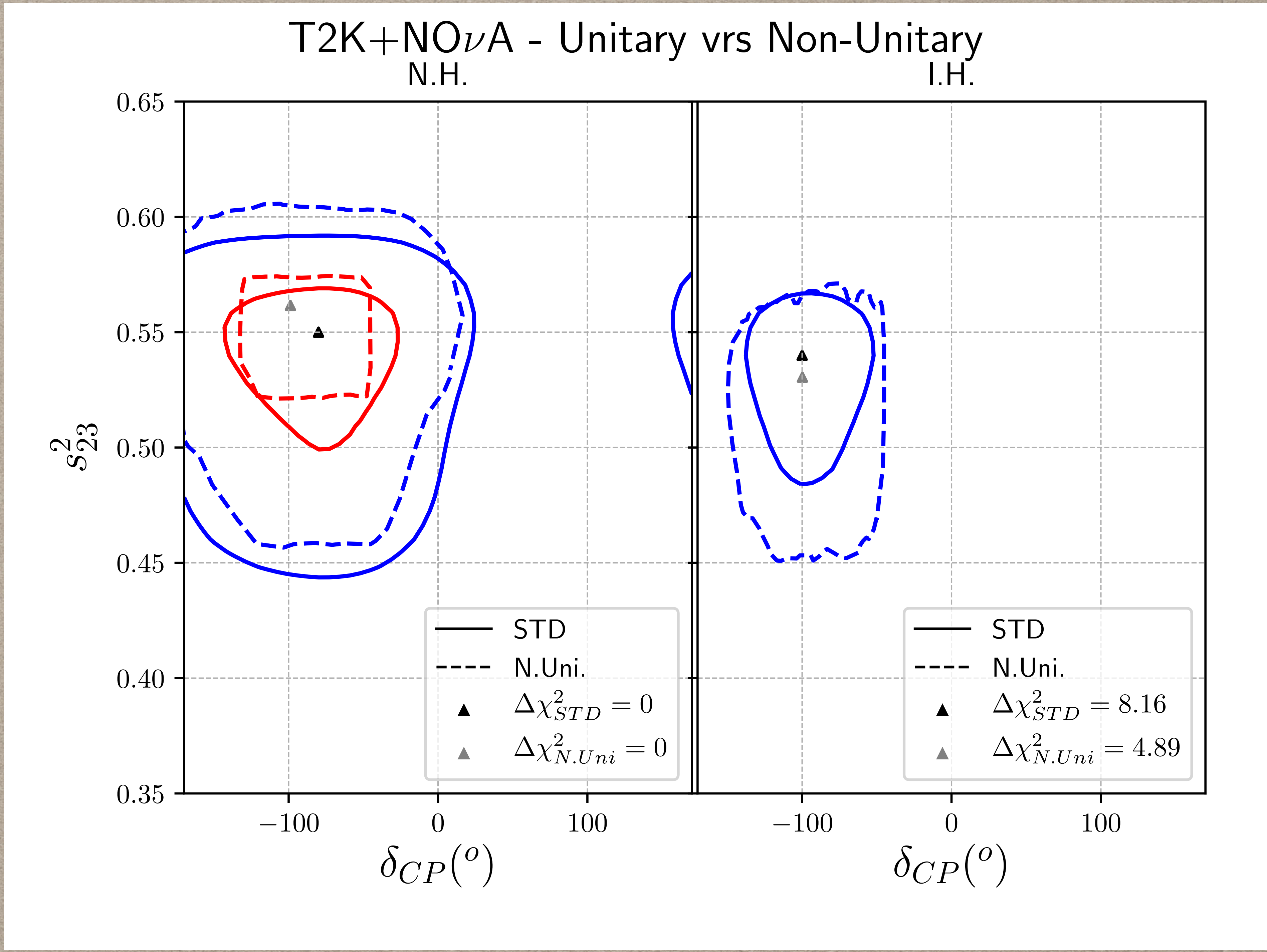


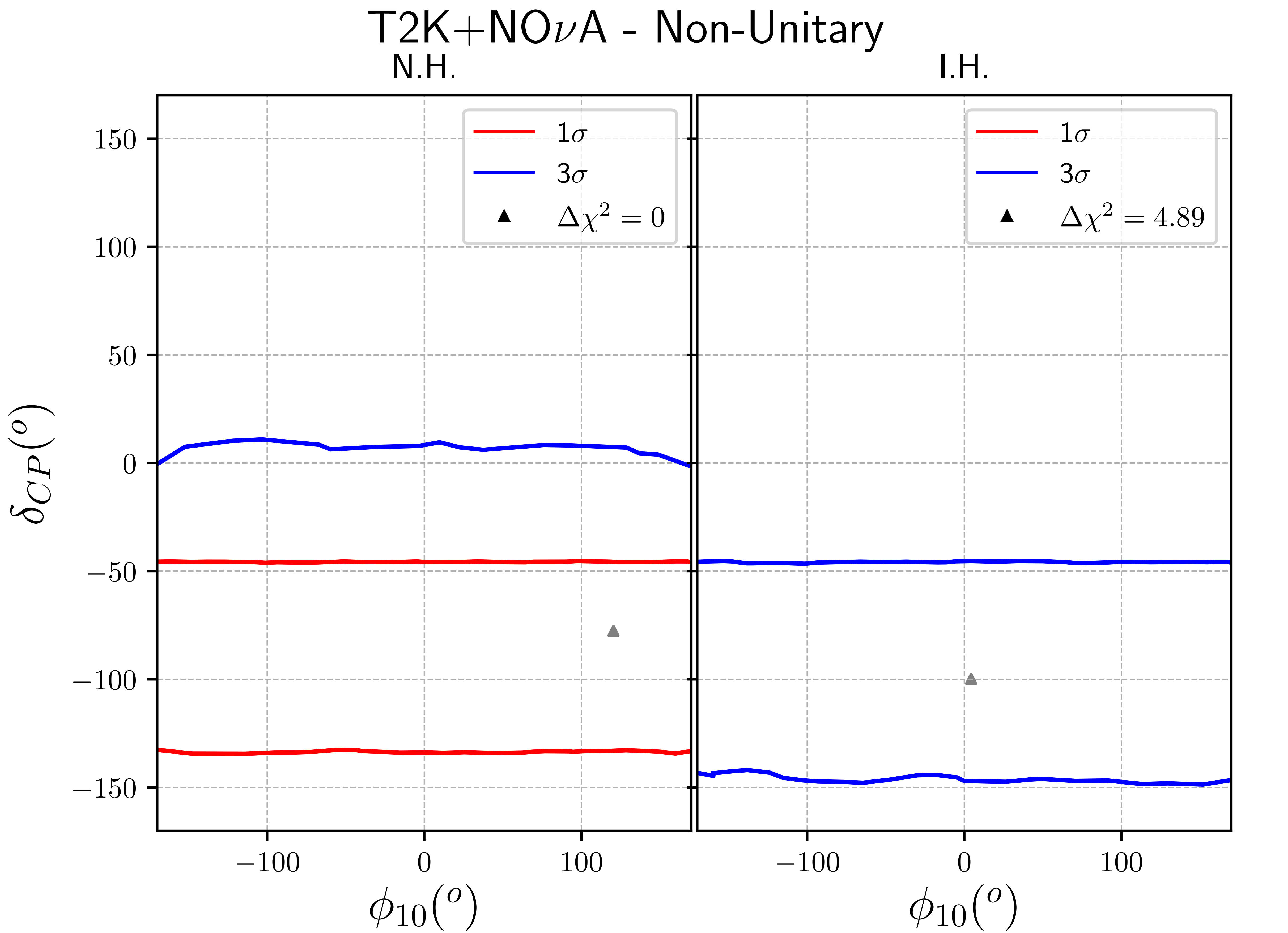


T2K - Non-Unitary
N.H.
I.H.
1σ
3σ
$\Delta\chi^2 = 0.0$
$\Delta\chi^2 = 2.49$
$\delta_{CP}(^o)$
$\phi_{10}(^o)$
150
100
50
0
-50
-100
-150
-100
0
100

RESULTS

NOvA+T2K

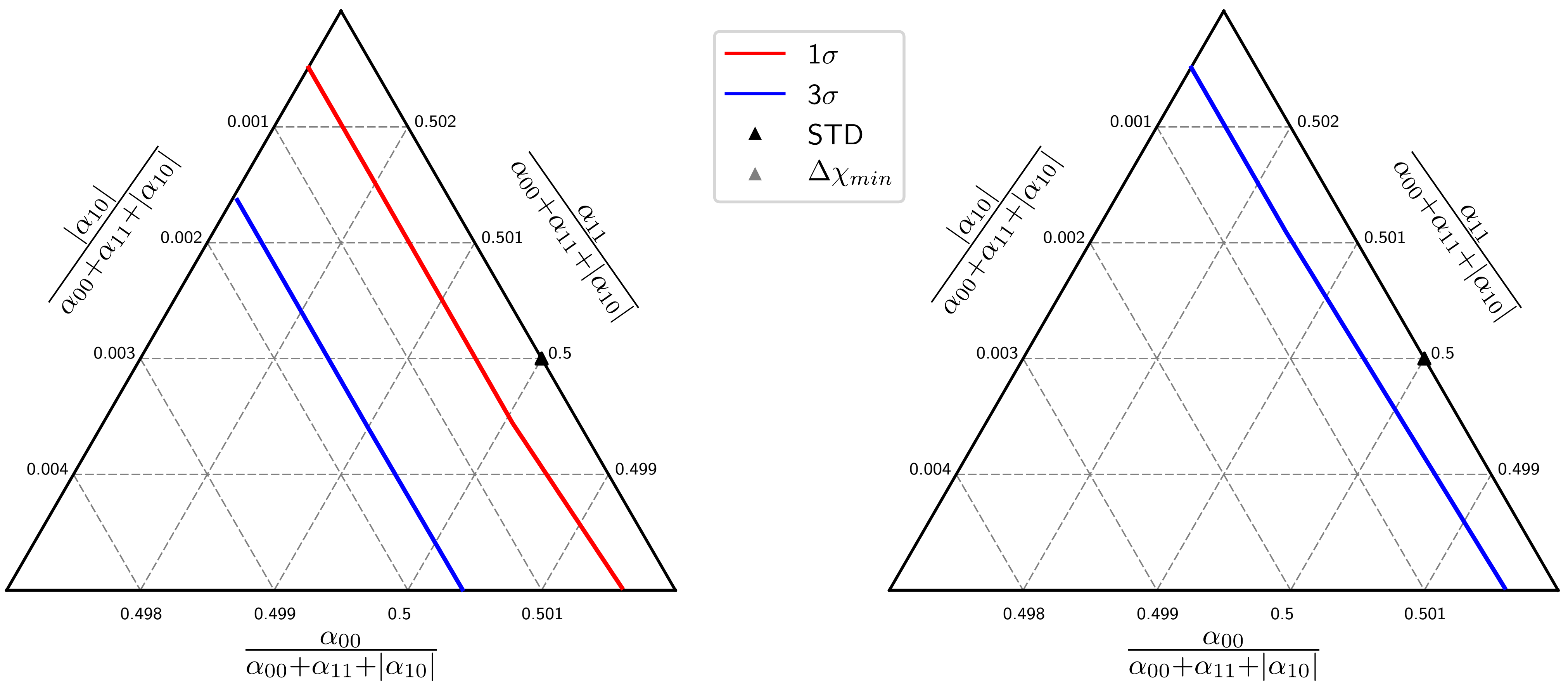



T2K+NOνA - Non-Unitary
N.H.
I.H.
1σ
3σ
$\Delta\chi^2 = 0$
$\Delta\chi^2 = 4.89$
150
100
50
0
−50
−100
−150
$\delta_{CP}(^o)$
−100
0
100
$\phi_{10}(^o)$

RESULTS

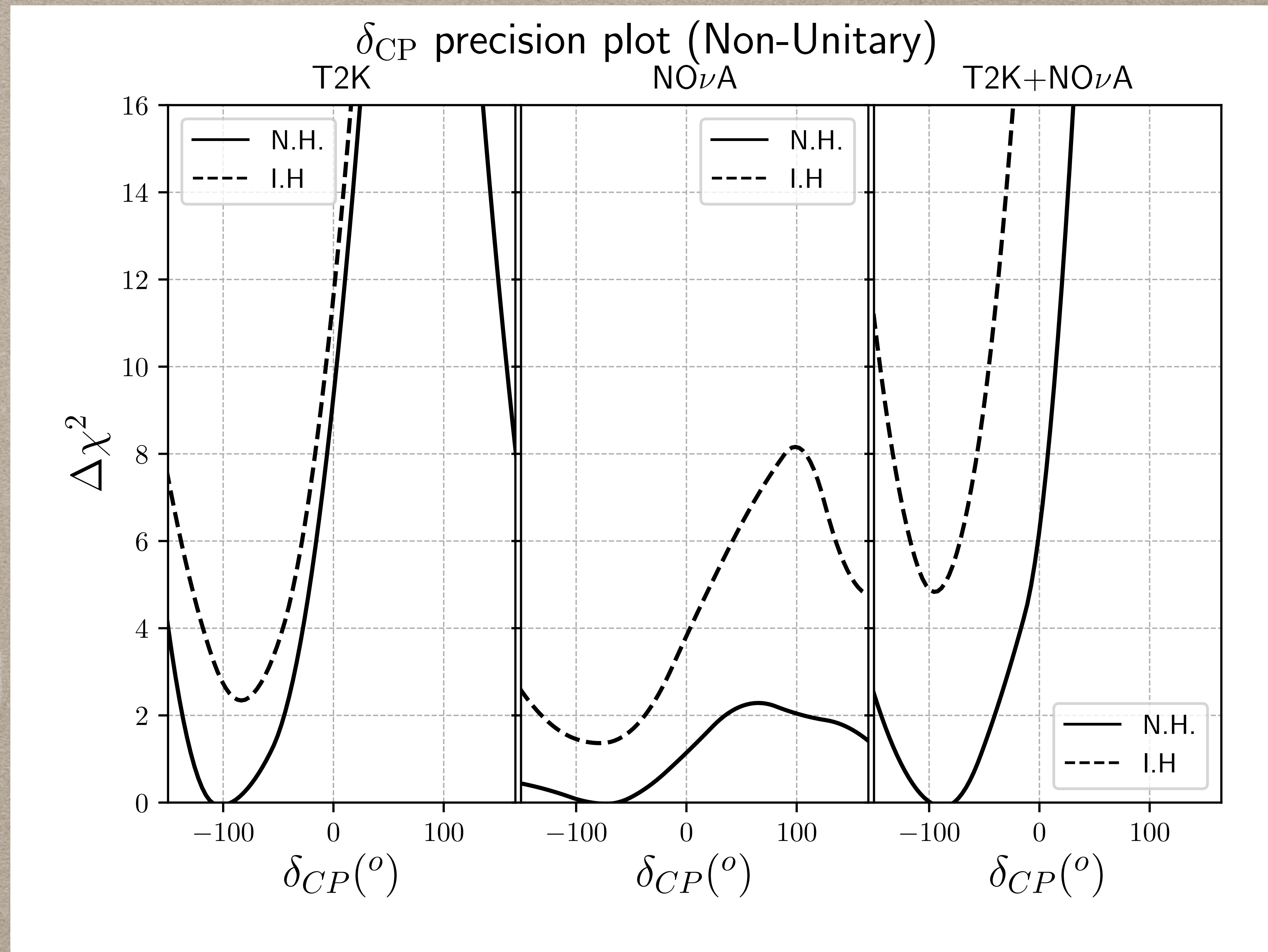
NOvA+T2K
Triangular
Plots

T2K+NOνA - Non-Unitary



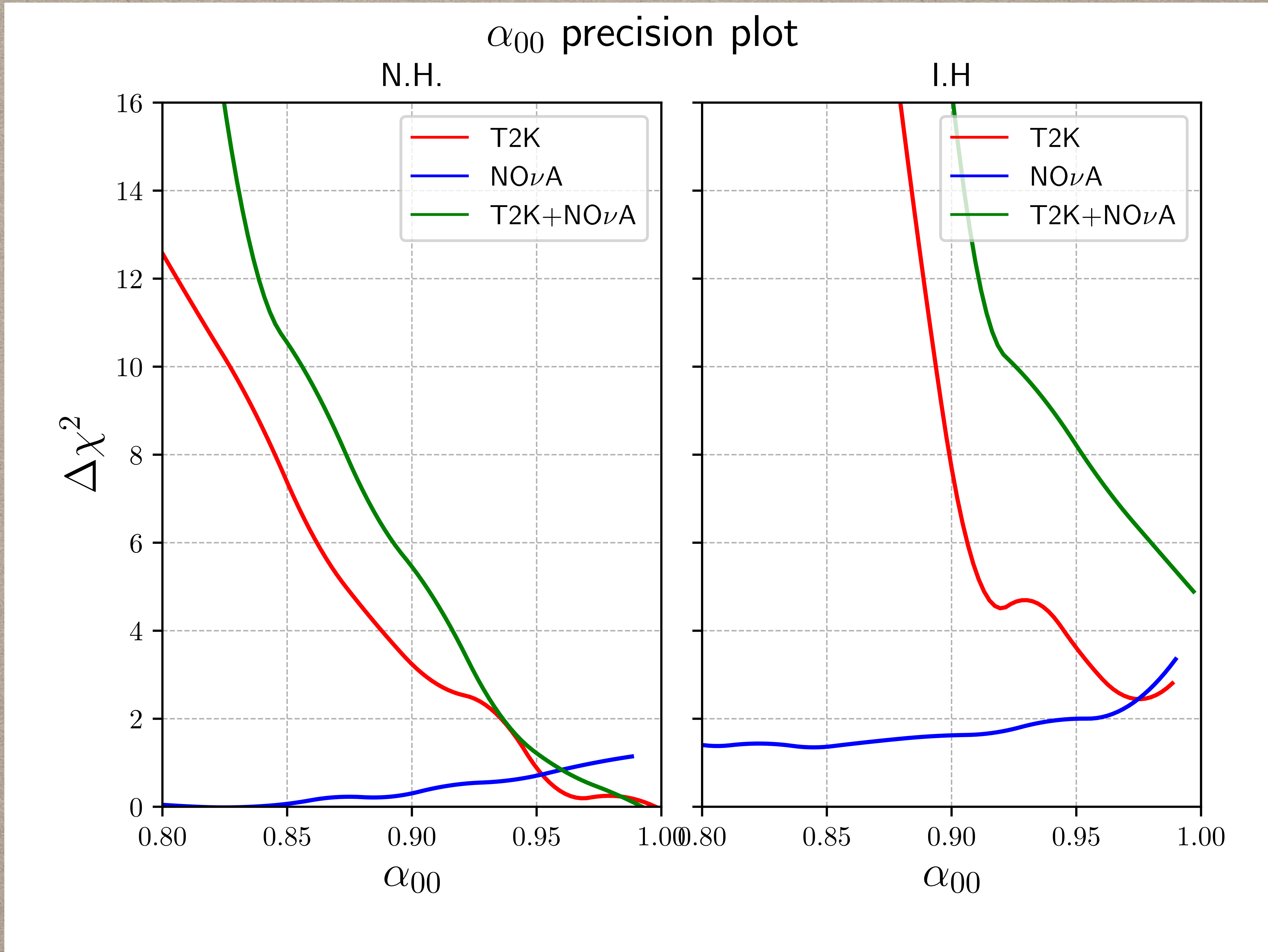
RESULTS

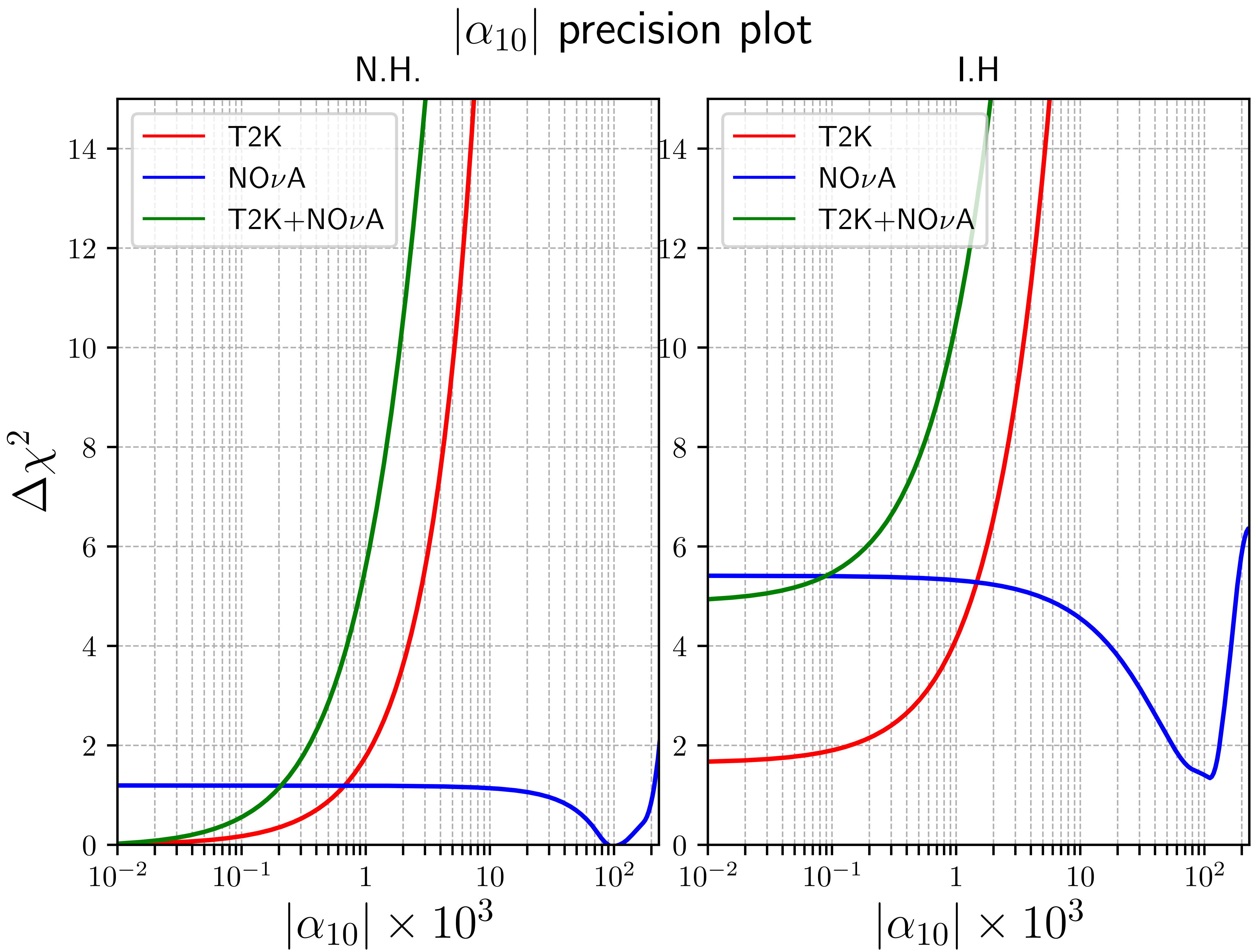
Hierarchy and δ_{CP} sensitivity



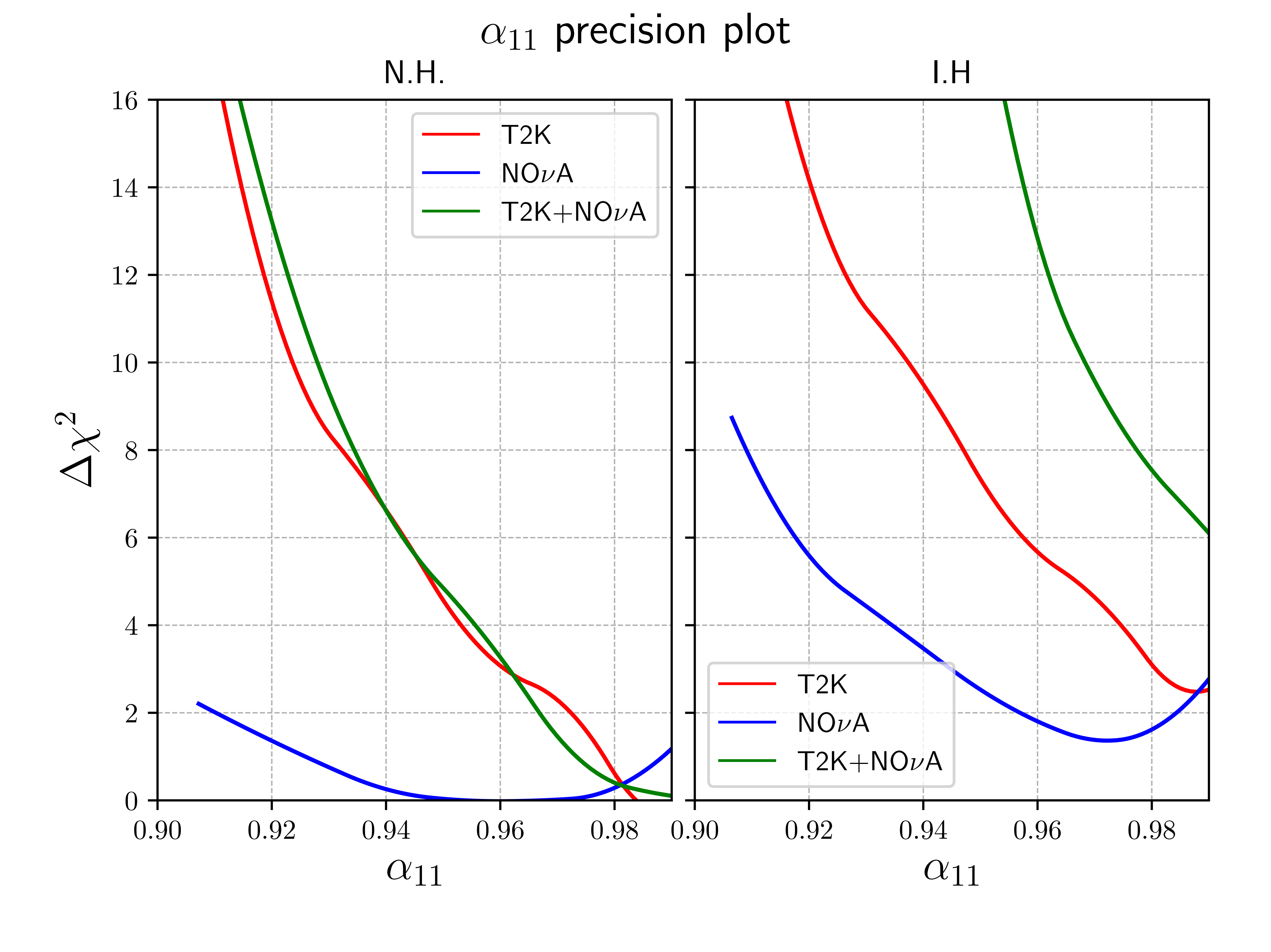
RESULTS

Constraints on non-standard parameters


α_{00} precision plot
N.H.
I.H
T2K
NOνA
T2K+NOνA
$\Delta\chi^2$
α_{00}
0
2
4
6
8
10
12
14
16
0.80
0.85
0.90
0.95
1.00



$|\alpha_{10}|$ precision plot
N.H.
I.H
T2K
NOνA
T2K+NOνA
$\Delta\chi^2$
0
2
4
6
8
10
12
14
10^{-2}
10^{-1}
1
10
10^2
$|\alpha_{10}| \times 10^3$


α_{11} precision plot
N.H.
I.H
T2K
NOνA
T2K+NOνA
$\Delta\chi^2$
α_{11}
0
2
4
6
8
10
12
14
16
0.90
0.92
0.94
0.96
0.98

Parameters	unitary		non-unitary	
	NH	IH	NH	IH
$\frac{\Delta m^2_{\rm eff}}{10^{-3}\,{\rm eV}^2}$	$2.44^{+0.02}_{-0.048}$	$-2.44^{+0.02}_{-0.048}$	$2.396^{+0.004}_{-0.026}$	$-(2.41^{+0.01}_{-0.05})$
$\sin^2\theta_{23}$	$0.56^{+0.01}_{-0.02}$	$0.56^{+0.01}_{-0.02}$	$0.57^{+0.01}_{-0.03}$	$0.48^{+0.04}_{-0.02}$
$\sin^2 2\theta_{13}$ (u)	$0.084^{+0.002}_{-0.002}$	$0.084^{+0.003}_{-0.002}$	$0.084^{+0.002}_{-0.003}$	$0.084^{+0.002}_{-0.003}$
$\delta_{\rm CP}/^\circ$ (u)	0^{+40}_{-50}	$-(110^{+30}_{-50})$	$-(72.42^{+106.57}_{-60.55})$	$-(81.02^{+60.77}_{-30.01})$
α_{00}			$0.83^{+0.14}_{-0.05}$	$0.84^{+0.06}_{-0.07}$
$\lvert\alpha_{10}\rvert$			$0.107^{+0.090}_{-0.069}$	$0.114^{+0.028}_{-0.064}$
α_{11}			$0.95^{+0.04}_{-0.03}$	$0.97^{+0.01}_{-0.02}$
$\phi_{10}/^\circ$			$164.32^{+15.68}_{-135.77}$	$54.84^{+69.63}_{-32.57}$

Table 1. Parameter values at the best-fit points for NOνA.

Parameters	unitary		non-unitary (best-fit)		90% (3σ)	
	NH	IH	NH	IH	NH	IH
$\frac{\Delta m^2_{\rm eff}}{10^{-3}\,{\rm eV}^2}$	$2.512^{+0.048}_{-0.048}$	$-(2.512^{-0.048}_{+0.048})$	$2.50^{+0.04}_{-0.04}$	$-(2.49^{+0.05}_{-0.03})$		
$\sin^2\theta_{23}$	$0.53^{+0.03}_{-0.04}$	$0.53^{+0.02}_{-0.03}$	$0.52^{+0.03}_{-0.03}$	$0.53^{+0.03}_{-0.03}$		
$\sin^2 2\theta_{13}$	$0.085^{+0.003}_{-0.002}$	$0.085^{+0.002}_{-0.003}$	$0.086^{+0.001}_{-0.004}$	$0.084^{+0.004}_{-0.001}$		
$\delta_{\rm CP}/^\circ$	$-(90^{+30}_{-20})$	$-(90^{+20}_{-20})$	$-(92.88^{+31.56}_{-30.17})$	$-(93.74^{+21.75}_{-20.46})$		
α_{00}			0.998	0.971	>0.91 (0.84)	>0.91 (0.89)
$\lvert\alpha_{10}\rvert$			0.000	0.000	<0.001 (0.005)	<0.001 (0.0052)
α_{11}			0.997	0.987	>0.964 (0.93)	>0.97 (0.93)
$\phi_{10}/^\circ$			$-(157.27^{+22.65}_{-336.86})$	$24.24^{+151.29}_{-178.37}$		

Table 2. Parameter values at the best-fit points for T2K. The 90% and $3\,\sigma$ limits have also been

Parameters	unitary		non-unitary (best-fit)		90% (3σ)	
	NH	IH	NH	IH	NH	I H
$\frac{\Delta m^2_{\rm eff}}{10^{-3}\,{\rm eV}^2}$	$2.464^{+0.024}_{-0.048}$	$-(2.464^{+0.024}_{-0.048})$	$2.47^{+0.02}_{-0.04}$	$-(2.449^{+0.003}_{-0.023})$		
$\sin^2\theta_{23}$	$0.55^{+0.03}_{-0.02}$	$0.54^{+0.01}_{-0.03}$	$0.55^{+0.02}_{-0.02}$	$0.53^{+0.01}_{-0.02}$		
$\sin^2 2\theta_{13}$	$0.085^{+0.003}_{-0.002}$	$0.085^{+0.001}_{-0.004}$	$0.084^{+0.003}_{-0.002}$	$0.085^{+0.001}_{-0.002}$		
$\delta_{\rm CP}/^\circ$	$-(80^{+40}_{-30})$	$-(100^{+10}_{-20})$	$-(77.60^{+48.44}_{-31.05})$	$-(99.82^{+9.08}_{-23.50})$		
α_{00}			0.998	0.997	>0.93 (0.86)	>0.96 (0.90)
$\lvert\alpha_{10}\rvert$			0.000	0.000	<0.0005 (0.001)	<0.0005(0.0016)
α_{11}			0.993	0.998	>0.96 (0.93)	>0.98 (0.96)
$\phi_{10}/^\circ$			$120.41^{+59.57}_{-300.33})$	$4.31^{+162.71}_{-181.51}$		

Table 3. Parameter values at the best-fit points for combined data from NOνA and T2K. The 90% and $3\,\sigma$ limits have also been mentioned.

CONCLUSION

- NOvA disfavours unitary mixing in favour of non-unitary mixing at 1 σ confidence level
- At the best-fit point for T2K, the mixing matrix is effectively unitary, but T2K cannot exclude non-unitarity completely.
- The tension between the two experiments on $\sin^2\theta_{23}$-δ_{CP} plane is reduced when analysed with non-unitarity.
- With non-unitary hypothesis, NOvA can determine hierarchy only at 1σ C.L.
- T2K can determine hierarchy at 2σ C.L. for 90% of the δ_{CP} plane.
- The constraints on $|\alpha_{10}|$, obtained from T2K data is stronger than the ones given in arXiv:1612.07377.
- The bounds on diagonal α parameters are weaker than those reported in arXiv:1612.07377.
- Future data of NOvA and T2K should be analysed with non-unitary hypothesis, besides the analysis with standard unitary hypothesis. If there are tension between them on the decision of unitarity in future, it may lead to discovery of new physics.
- Future long baseline experiments like DUNE and T2HK may resolve the confusion.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