Non-Standard Interactions and Tau-Neutrino Detection at DUNE

Presented by:

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October 02, 2025

Based on JHEP07(2025)245

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Outline

- The Deep Underground Neutrino Experiment (DUNE)
- Why ν_τ at a long baseline; **High Energy beam** vs regular beam
- Neutrino **Non-Standard interactions** (NSI) framework and event rates at DUNE
- Headline **sensitivities**
- Short detour: PMNS row-3 non-unitary & role of ν_τ
- Conclusions

Key Messages

- The NSI parameter $\epsilon_{\mu\tau}$ is most sensitive to tau-neutrino detection at DUNE.
- If **mass hierarchy** is known, ν_τ detection helps determine $\phi_{\mu\tau}$, complex phase of $\epsilon_{\mu\tau}$.
- ν_τ detection has **very limited improvements** on Mass Hierarchy / $\delta_{\rm cp}$/ Octant measurements.

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The Deep Underground Neutrino Experiment (DUNE)

Dreams Are Messages from the Deep

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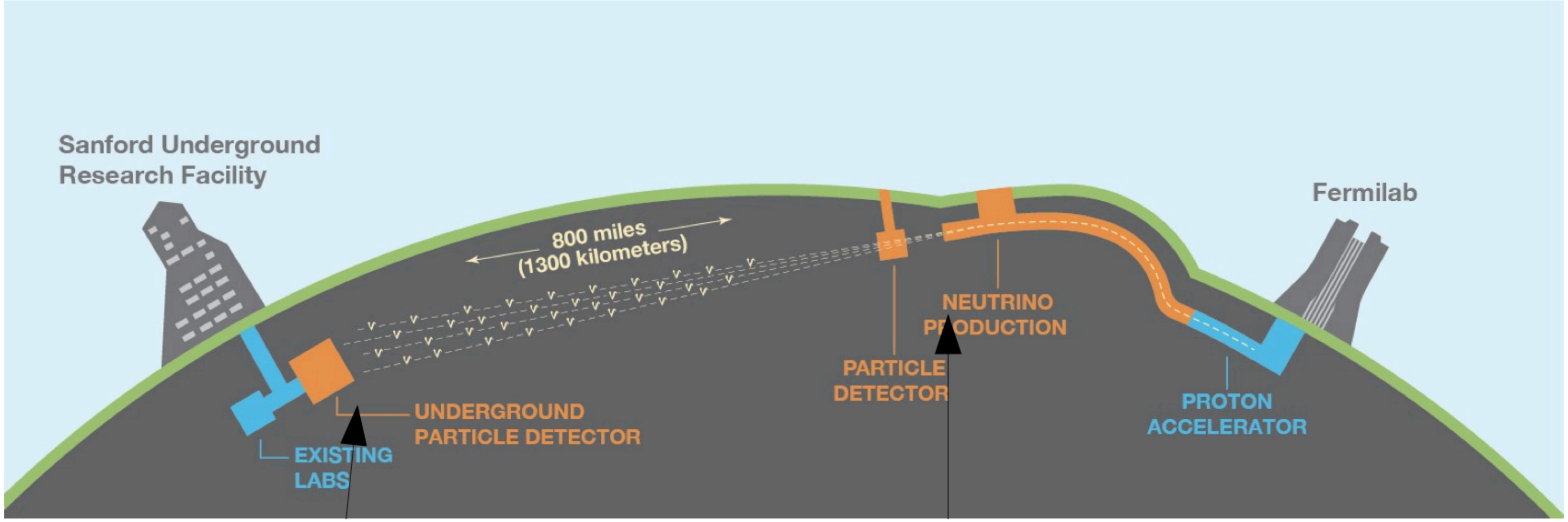
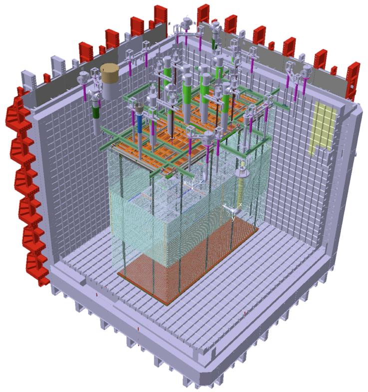
Deep Underground Neutrino Experiment

- DUNE is a **next-generation long-baseline** (LBL) neutrino experiment under construction.
- Far Detector (FD): two liquid argon time-projection chamber (LArTPC), **total fiducial mass starts with 20 kt**.



Source: DUNE collaboration



arXiv:2002.02967

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Scientific objectives of DUNE

Unravel the mysteries in Standard Model and our universe through neutrinos

- **Measuring neutrino oscillation parameters**
  - neutrino mass hierarchy, CP violating phase (δ_{cp}), mixing angles, and testing three-flavour model.
- **Neutrino astronomy**
  - Record **Supernovae Neutrino Bursts** and astronomical neutrinos from other sources.
- **Search for beyond the Standard Model Physics (this talk)**
  - Look for deviations from Standard Model predictions, such as those described by **non-standard interactions.**

In this work, we study the capabilities of DUNE as outlined in its technical design report.

arXiv:2002.02967, 2103.04797

High Energy Beam and tau-neutrino at DUNE

In search of the elusive flavour

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Reasons to study tau-neutrino appearance

Tau-neutrino data provides unique view into BSM new physics.

- **Testing the three-flavour oscillation framework and matter effects**
- **Direct test of PMNS unitarity (row 3)**
  - Confirm that missing ν_μ reappear as ν_τ with the **expected rate**
  - (Otherwise) Shed light on **sterile-neutrino** or **heavy neutral leptons**.
- **Test of BSM theories of neutrino physics**
  - Providing constraints on theories such as **non-unitary neutrino mixing** or **non-standard interactions (NSI)**

arXiv:1904.07265, arXiv:1906.06212

Challenges at LBL experiments

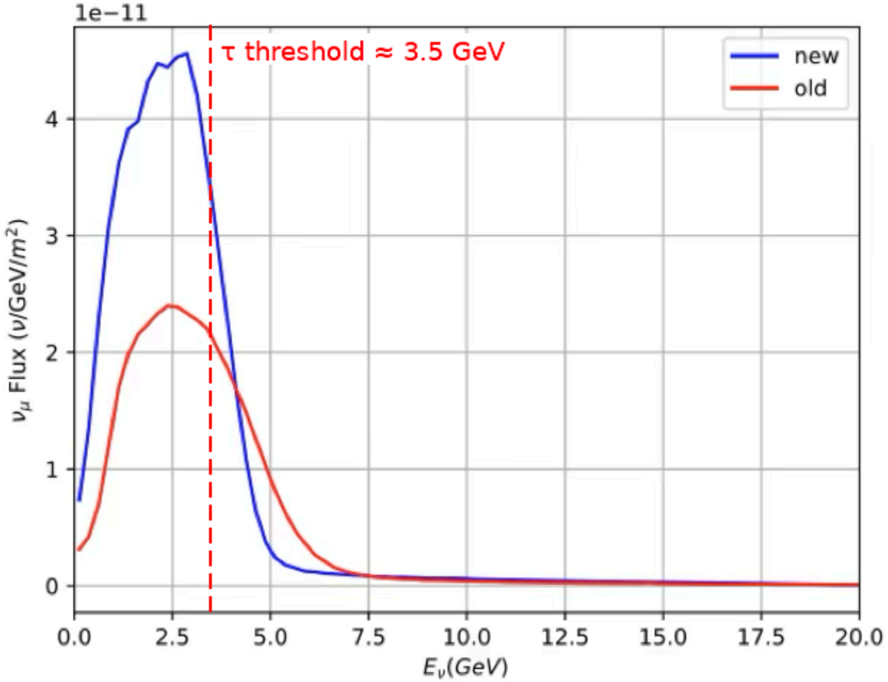
Tau-neutrinos are more difficult to study than electron and muon neutrinos.

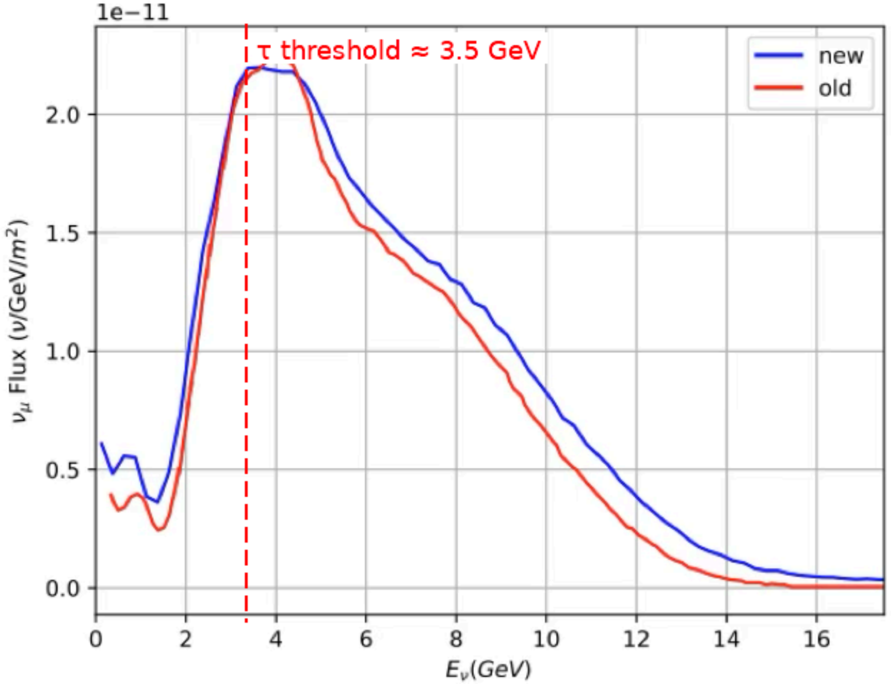
- **High threshold for production**
  - Production of a tau lepton requires neutrino energy **threshold of 3.5 GeV**
- **Lifetime of Tau lepton is very short**
  - Requires very high **spatial resolution** for the detector
- **Not focused on previous LBL experiments:**
  - NOvA and T2K use beam **below threshold**, also limited by detector resolution.
  - OPERA and ICARUS in CNGS project successfully optimized for tau appearance, not oscillation parameter precision.

arXiv:1507.01417, 10.1038/s41597-021-00991-y, arXiv:1901.03750, arXiv:1110.0112

Neutrino beam at DUNE

- Top plot: regular beam, bottom: high-energy beam
- “New” is **flux profile used in our study**, “old” is outdated **flux from previous works**.
- Peak of the regular beam **< 3.5 GeV** Tau lepton production threshold.
- Achieved through replacement of three baseline horns with two parabolic horns (NuMI-like).





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arXiv:2503.16124, 2103.04797, 1606.09550, 2002.03005

Neutrino Non-Standard interactions (NSI)

Echoes of hidden interactions

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How NSI affects neutrino oscillation in matter

NSI = additional matter potential with off-diagonal flavour terms

$$H = H_{\text{vac}} + H_{\text{mat}} + H_{\text{NSI}},$$

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

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

$$\mathscr{L}_{\text{NC-NSI}} = -2\sqrt{2} G_F \epsilon_{\alpha\beta}^{fC} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f} \gamma_\mu P_C f)$$

The NSI interaction Lagrangian operator

- α, β denotes neutrino flavours (electron, muon, tau)
- f denotes fermion type in matter (e, u, d)
- C is L or R handed projection operator.
- Very general parameterization of a neutrino flavour changing interaction, at a dimension 6 four particle vertex.

Effective term from NSI in the Hamiltonian

- NSI enters as an **addition effective matter potential** term
- Six degrees of freedom from 3 diagonal and 3 off-diagonal terms
- Off-diagonal term introduces **flavour-changing neutral-current effects** in propagation through matter.

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NSI Modification to $\nu_\mu \to \nu_\tau$ oscillation probability (1/2)

Expanding probability, treating NSI as perturbative term

For 3-flavour oscillation, we can expand to second order

$$P_{\mu\tau}^{\rm NSI} = P_{\mu\tau}^{\rm 2vac} + P_{\mu\tau}^{\epsilon_{e\mu},\epsilon_{e\tau}} + P_{\mu\tau}^{\epsilon_{\mu\mu},\epsilon_{\mu\tau},\epsilon_{\tau\tau}} + \ldots$$

The leading term is **vacuum oscillation probability** in 2-flavour model, which is

$$P_{\mu\tau}^{\rm 2vac} = 4\cos^2\theta_{23}\sin^2\theta_{23}\sin^2\frac{\Delta_{31}L}{4E}$$

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NSI Modification to $\nu_\mu \rightarrow \nu_\tau$ oscillation probability (2/2)

Examine the contribution from $\epsilon_{\mu\tau}$ term

At order $O(\epsilon)$, the contribution from $\epsilon_{\mu\tau}$ is

$$\Delta_{\mu\tau} \propto \sin^2(2\theta_{23})\,|\epsilon_{\mu\tau}|\cos(\phi_{\mu\tau})\sin(\Delta_{31}L/2E)$$

At $|\epsilon_{\mu\tau}| = 0.2, \phi_{\mu\tau} = 0$, this term is **~ 10 times larger than the subleading term**

This term is sensitive to hierarchy, but no octant sensitivity.

$\epsilon_{\mu\mu}$ and $\epsilon_{\tau\tau}$ terms proportional to $\cos^2 2\theta_{23} \sim 0$, $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ terms always 2nd order -> Both negligible

Observing NSI at DUNE

Signals beneath the Dunes

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Simulation Details

Key assumptions and sources from the simulation

The χ^2 values are calculated using GLoBES, through comparison of true experimental event rates and test theoretical rates in each energy bin.

Energy resolution, energy-dependent detector efficiencies, and systematic uncertainties are from DUNE TDR.

In particular, used bin based energy smearing suggested by arXiv:1904.07265:

$$R^c(E, E') = \frac{1}{\sqrt{2\pi}\sigma(E)} \exp(-\frac{(E - E')^2}{2\sigma^2(E)})$$

Where

$$\sigma(E) = 0.25E$$

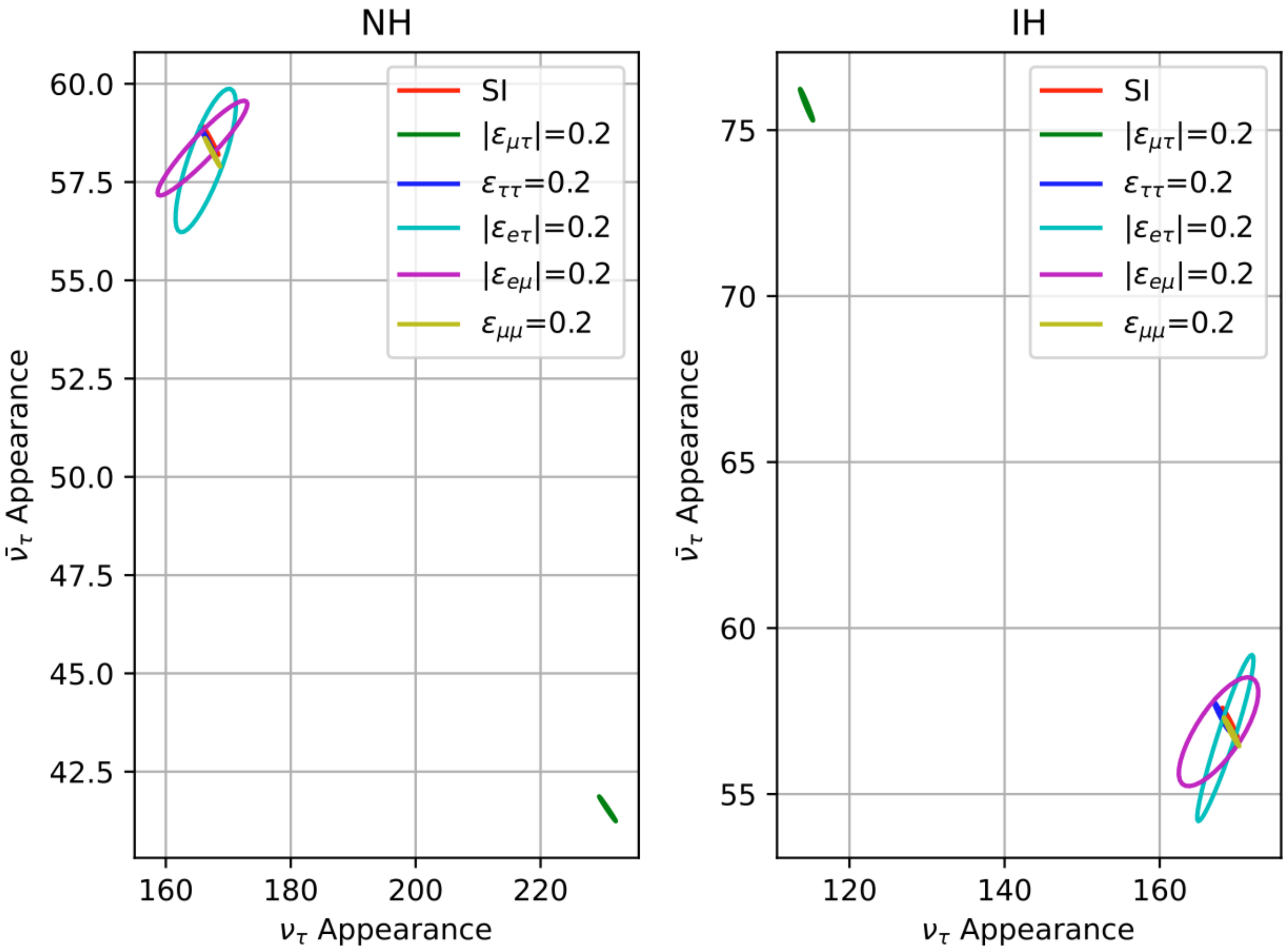
arXiv:2503.16124, 2103.04797, arXiv:hep-ph/0701187

Beam running schemes at DUNE

Exposure & Channels	Beam / Mode	Description
5 + 5 (μ + e)	Regular beam; ν & ν̄: 5 years each	Muon disappearance and electron appearance with DUNE regular beam; 5 years in ν-mode and 5 years in ν̄-mode.
5 + 5 (μ + τ)	Regular beam; ν & ν̄: 5 years each	Same as above, but τ appearance instead of e.
5 + 5 (μ + e + τ)	Regular beam; ν & ν̄: 5 years each	Combine all three channels from above.
5 + 5 + 1 + 1 (μ + τ)	Regular: ν & ν̄ 5y each High-energy: ν & ν̄ 1y each	Same as μ+τ case, plus 1 year each in ν and ν̄ with the DUNE high-energy beam.
5 + 5 + 1 + 1 (μ + e + τ)	Regular: ν & ν̄ 5y each High-energy: ν & ν̄ 1y each	Combining everything above (all channels and both beams).

1.1e21 POT per year for both regular and high-energy beam.

Modification to (expected) event rates at DUNE



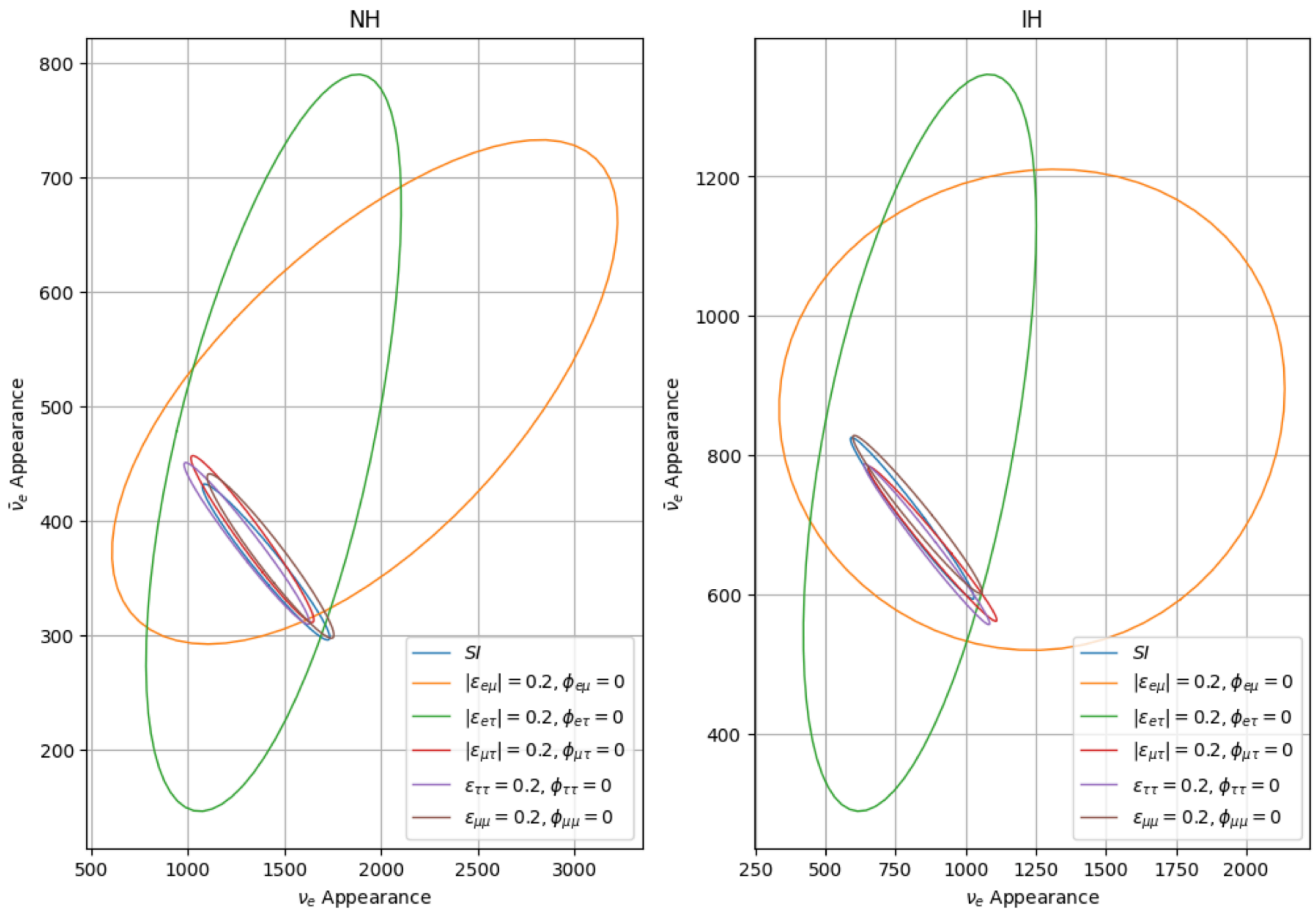
$\nu_\tau + \bar{\nu}_\tau$ **event numbers** after DUNE 5+5 regular beam.

Ellipse is from varying δ_{cp} in $[-\pi, \pi]$

Event rates includes background

Suggests that when hierarchy is given, there should be good sensitivity for existence of $\epsilon_{\mu\tau}$.

Modification to (expected) event rates at DUNE



ν_e + $\bar{\nu}_e$ event numbers DUNE 5+5 regular beam.

Ellipse is from varying CP violation phase in $[-\pi, \pi]$

Larger Ellipse distinct from SI suggests **good δ_{cp} sensitivity in presence of $\epsilon_{e\mu}$ or $\epsilon_{e\tau}$.**

Not very good sensitivity for distinction between the two.

$\phi_{\mu\tau}$-Hierarchy degeneracy

Degeneracy arising from the perturbative term

Hierarchy sensitivity with $\epsilon_{\mu\tau}$ present comes from

$$\Delta_{\mu\tau} \propto \sin^2(2\theta_{23})\,|\,\epsilon_{\mu\tau}\,|\cos(\phi_{\mu\tau})\sin(\Delta_{31}L/2E)$$

A consequence is that NH, $\phi_{\mu\tau} = 0$ is mimicked by IH,$\phi_{\mu\tau} = \pi$.

Therefore, when the phase and mass hierarchy is **simultaneously unknown**, this degeneracy affects sensitivity in attempts to measure either of them.

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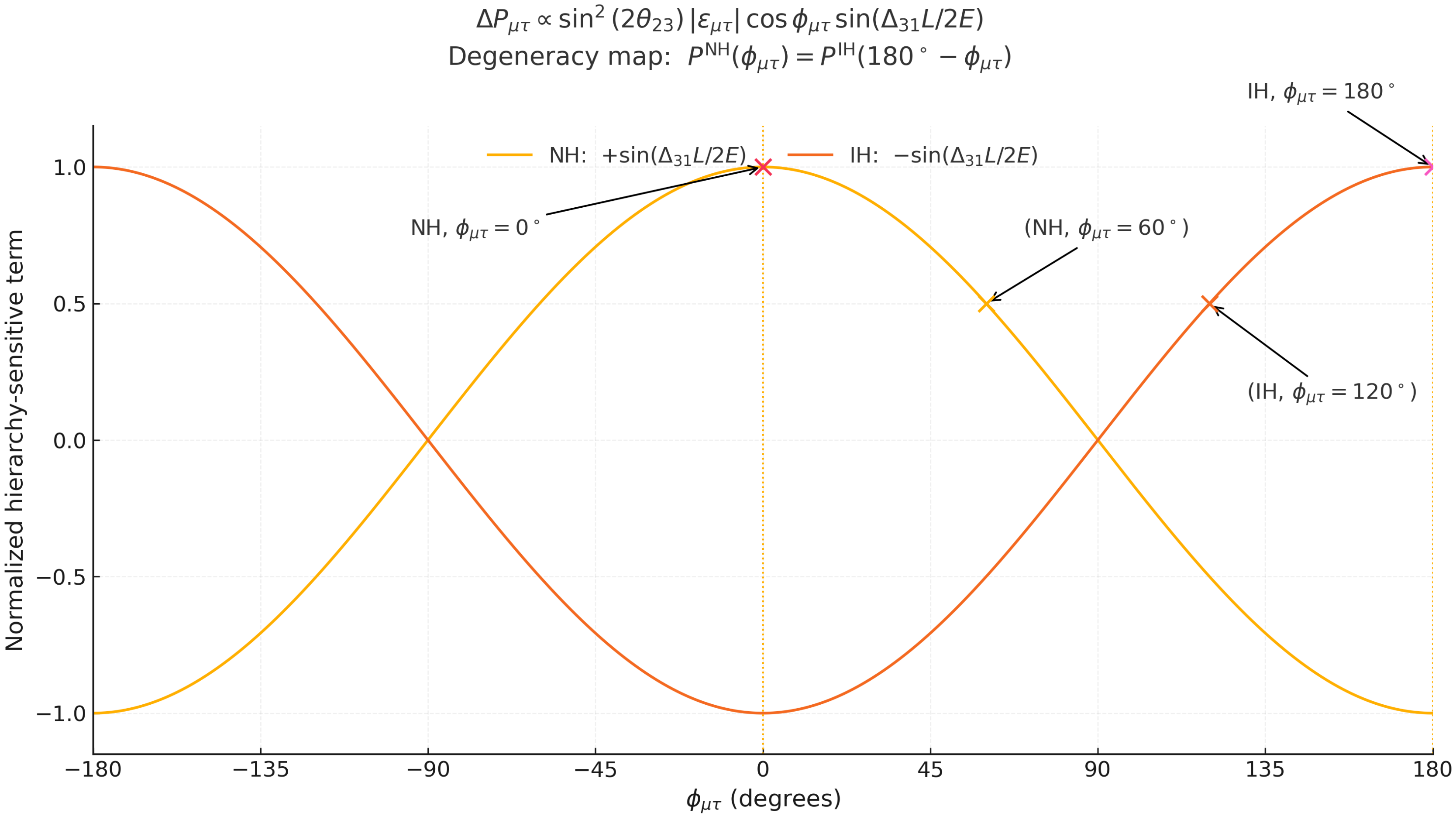
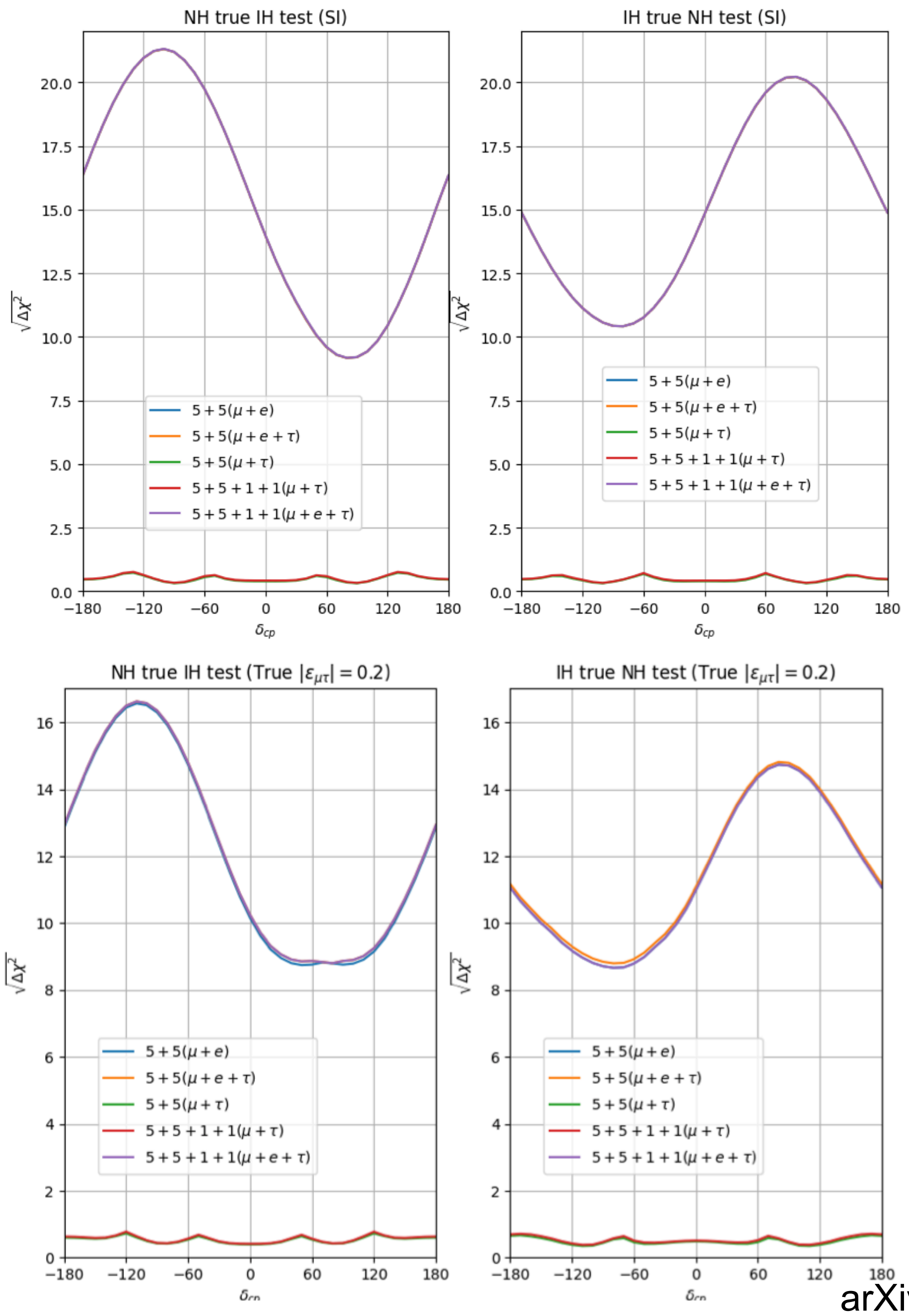
$\phi_{\mu\tau}$-Hierarchy degeneracy

Degeneracy arising from the perturbative term

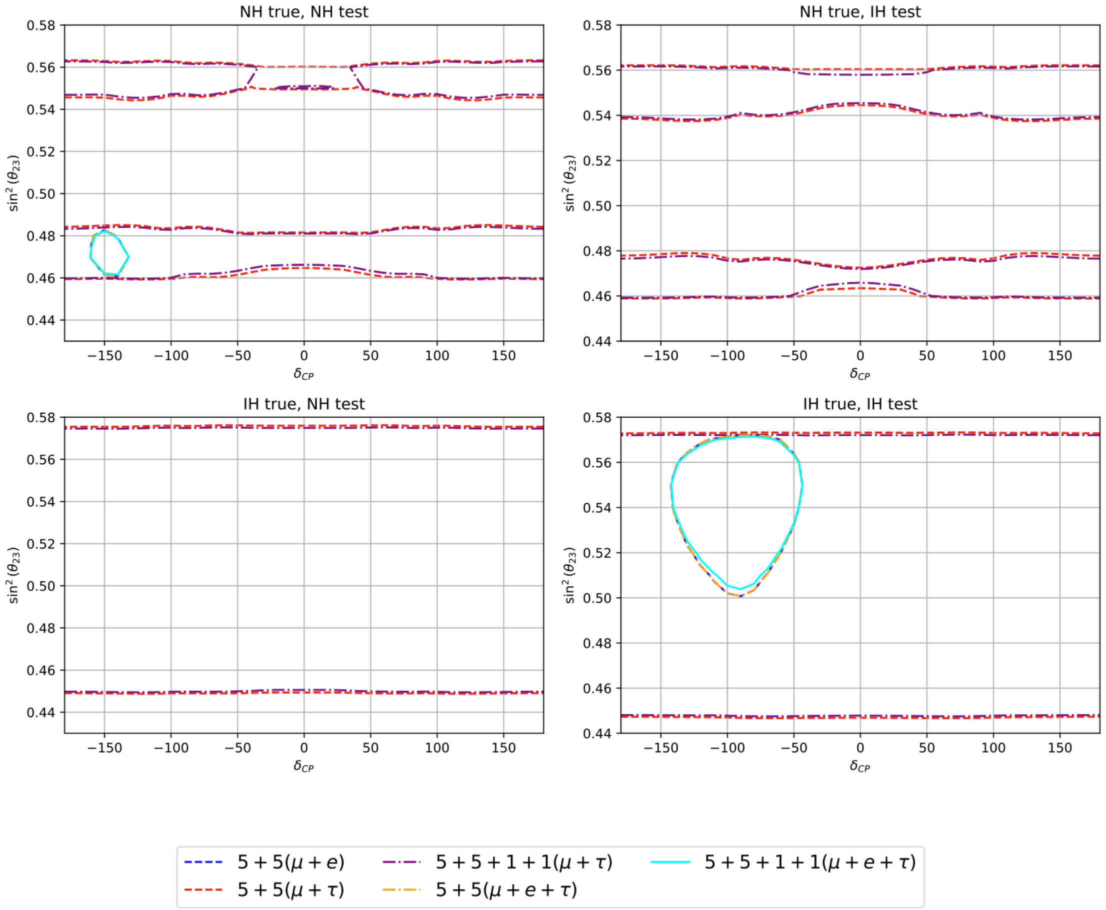


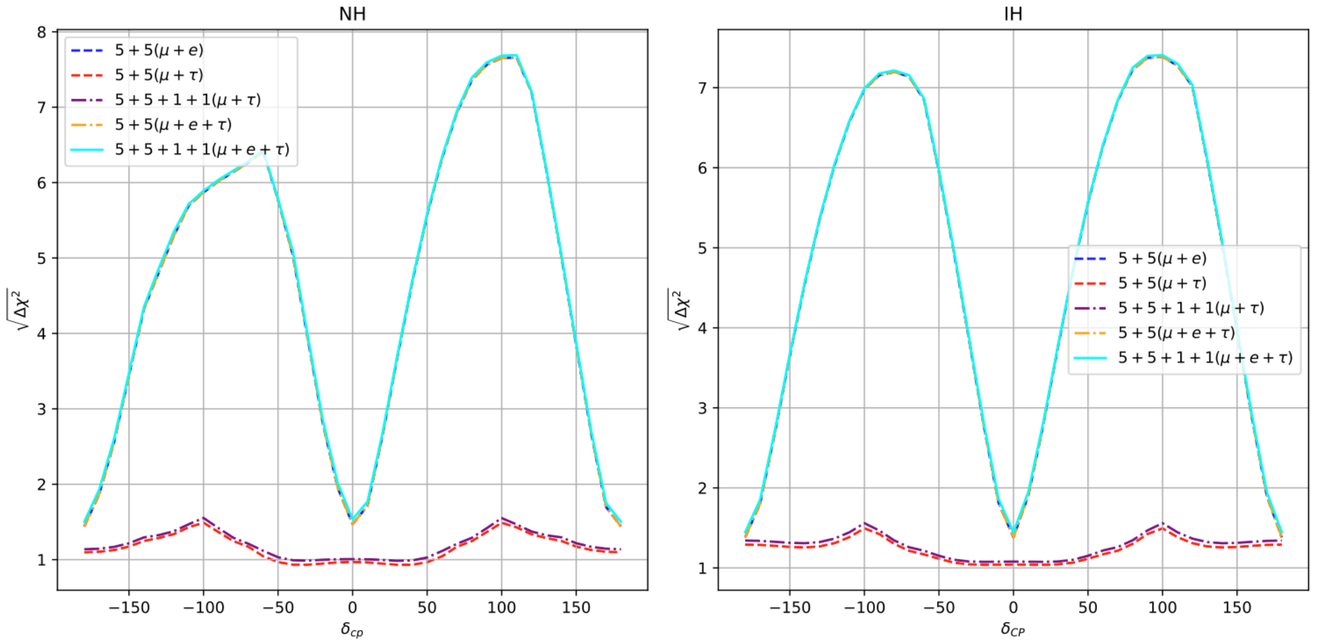
Mass hierarchy sensitivity with NSI

- Reduction in sensitivity with $\epsilon_{\mu\tau}$
- $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ case also see reduction, due to δ_{cp} and NSI phase interference.



δ_{cp} and Octant sensitivity





No significant impact from NSI and/or tau-neutrino detection, as it is mainly driven by electron-neutrino appearance.

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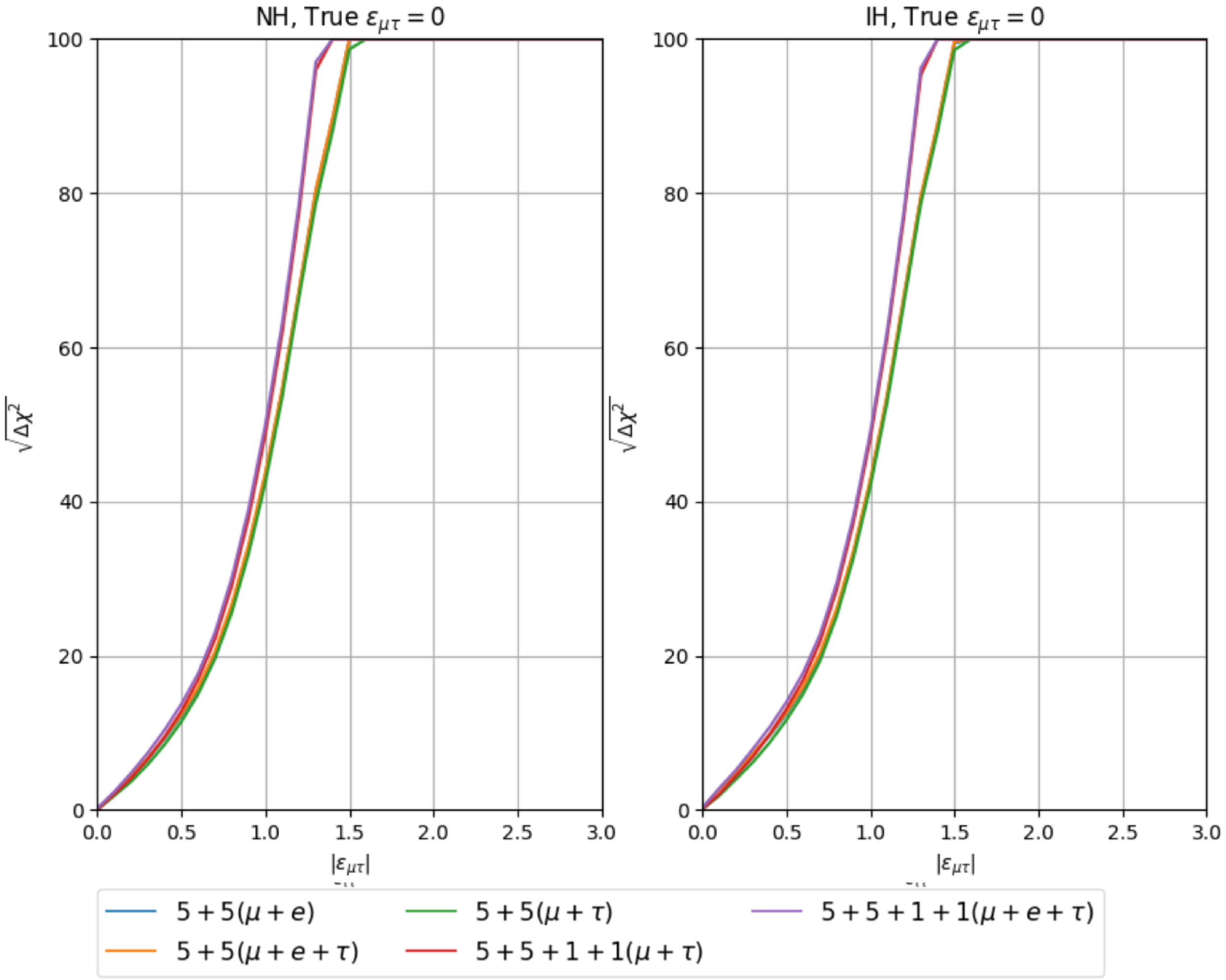
NSI term sensitivity

In truth SI case, can DUNE rule out NSI existence



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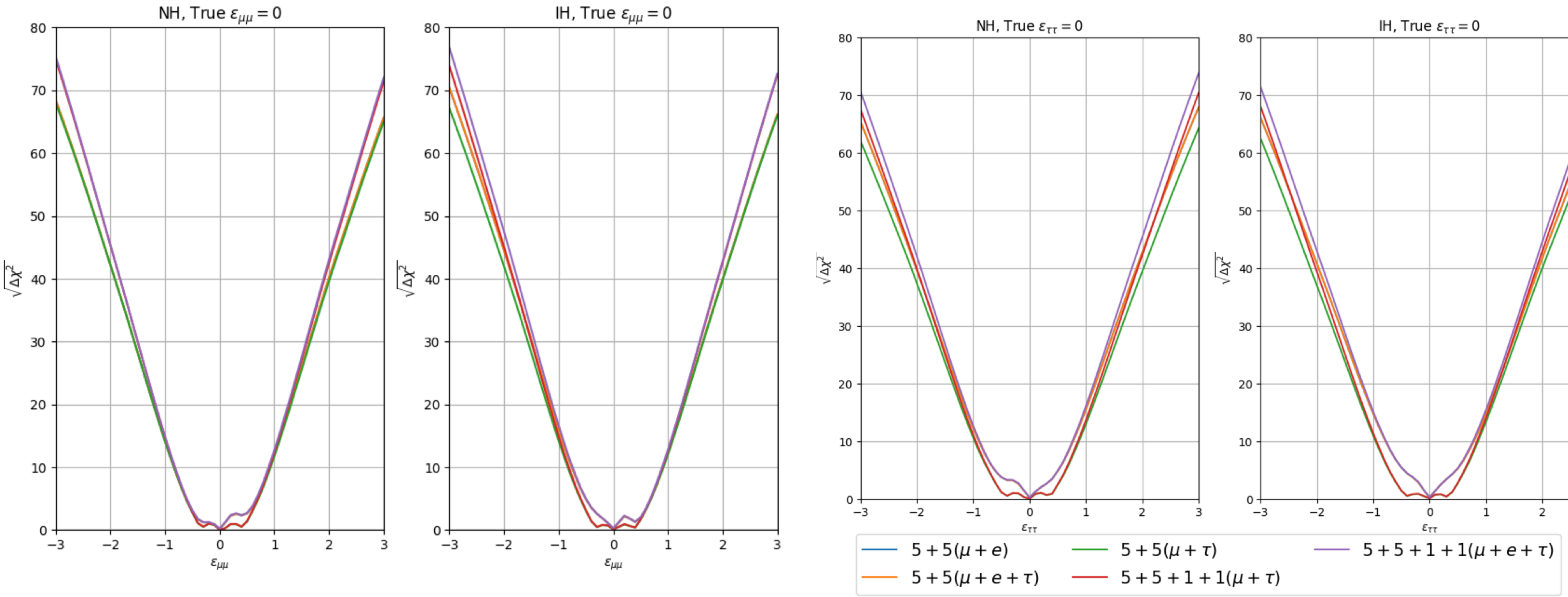
arXiv:2503.16124

NSI term sensitivity

In truth SI case, can DUNE rule out NSI existence (subleading terms)



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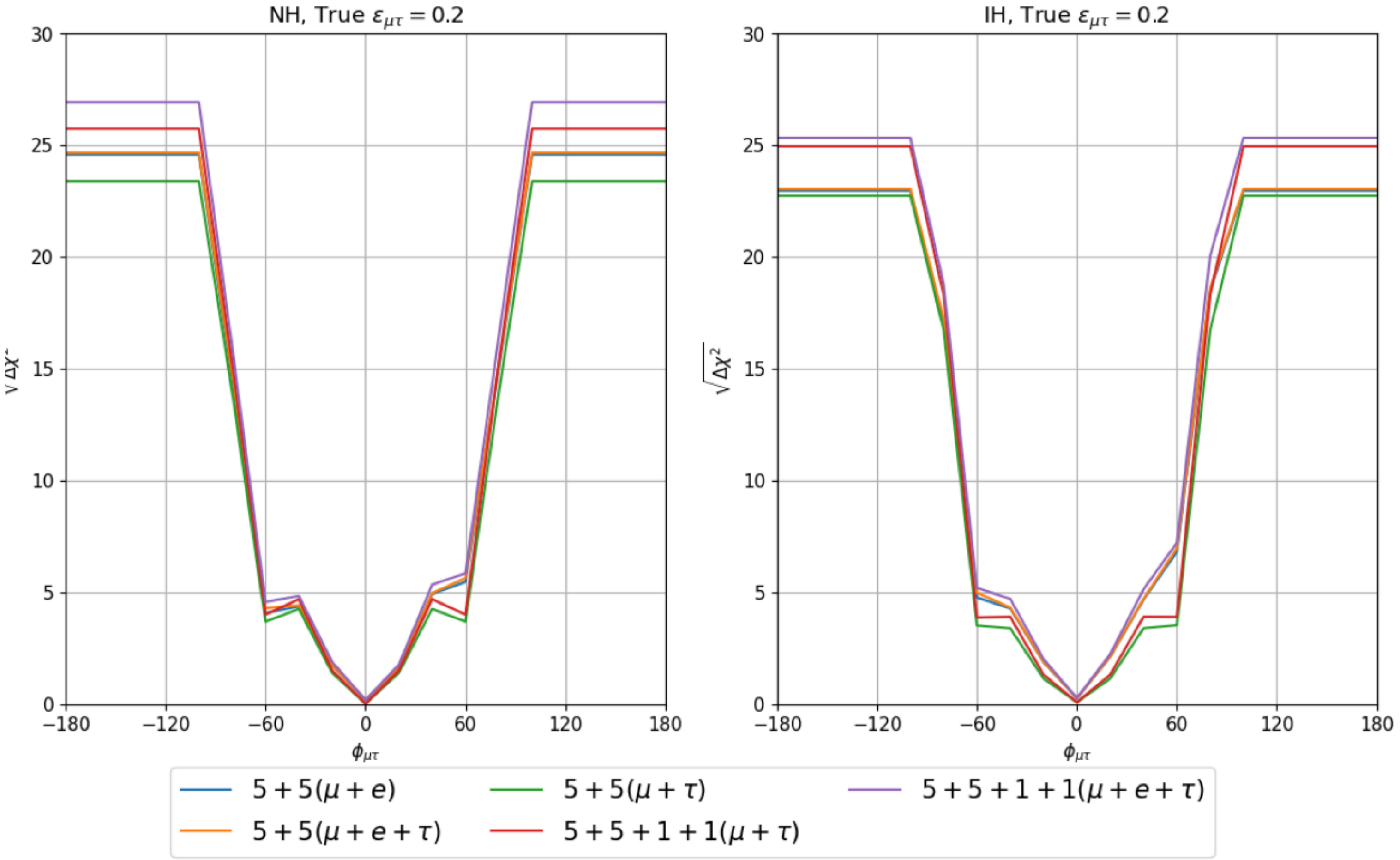
NSI phase sensitivity

If NSI phase in nature is 0, how precisely can DUNE measure it?



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NSI phase sensitivity

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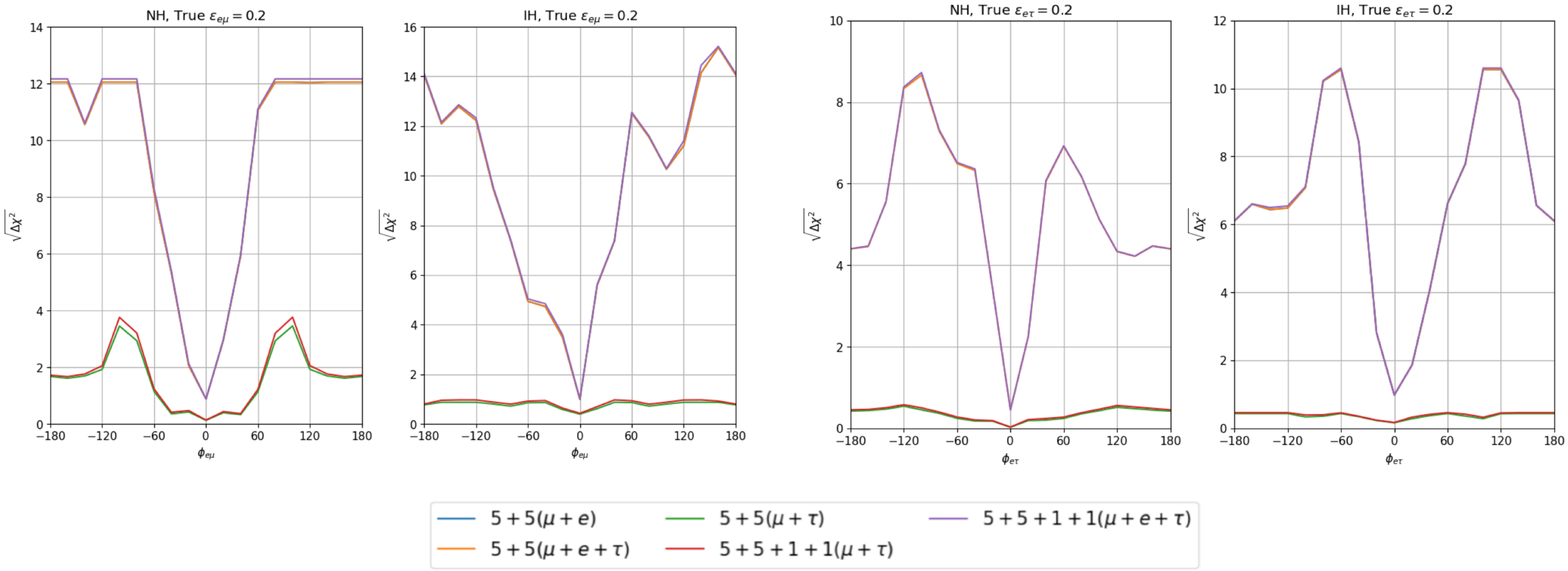

arXiv:2503.16124

Final Future Constraints on NSI parameter from DUNE

Parameters	$5+5$ $(\mu+e)$	$5+5$ $(\mu+\tau)$	$5+5$ $(\mu+e+\tau)$	$5+5+1+1$ $(\mu+\tau)$	$5+5+1+1$ $(\mu+e+\tau)$
$\lvert\epsilon_{e\mu}\rvert$ NH	$< 0.04\ (0.10)$	$< 0.31\ (0.43)$	$< 0.04\ (0.10)$	$< 0.31\ (0.43)$	$< 0.04\ (0.10)$
IH	$< 0.04\ (0.09)$	$< 0.25\ (0.38)$	$< 0.0.04\ (0.09)$	$< 0.25\ (0.38)$	$< 0.04\ (0.09)$
$\lvert\epsilon_{e\tau}\rvert$ NH	$< 0.07\ (0.20)$	$< 0.83\ (1.02)$	$< 0.07\ (0.20)$	$< 0.83\ (1.02)$	$< 0.07\ (0.20)$
IH	$< 0.09\ (0.13)$	$< 0.78\ (0.98)$	$< 0.0.09\ (0.13)$	$< 0.78\ (0.98)$	$< 0.09\ (0.13)$
$\lvert\epsilon_{\mu\tau}\rvert$ NH	$< 0.08\ (0.14)$	$< 0.09\ (0.17)$	$< 0.08\ (0.14)$	$< 0.09\ (0.15)$	$< 0.07\ (0.13)$
IH	$< 0.07\ (0.12)$	$< 0.10\ (0.16)$	$< 0.07\ (0.12)$	$< 0.09\ (0.14)$	$< 0.06\ (0.11)$
$\epsilon_{\mu\mu}$ NH	$> -0.40\ (-0.50)$ $< 0.11\ (0.48)$	$> -0.43\ (-0.50)$ $< 0.50\ (0.57)$	$> -0.40\ (-0.50)$ $< 0.11\ (0.48)$	$> -0.43\ (-0.50)$ $< 0.50\ (0.57)$	$> -0.40\ (-0.50)$ $< 0.11\ (0.48)$
IH	$> -0.17\ (-0.34)$ $< 0.14\ (0.56)$	$> -0.43\ (-0.50)$ $< 0.49\ (0.54)$	$> -0.17\ (-0.34)$ $< 0.14\ (0.56)$	$> -0.43\ (-0.50)$ $< 0.49\ (0.54)$	$> -0.17\ (-0.34)$ $< 0.14\ (0.56)$
$\epsilon_{\tau\tau}$ NH	$> -0.12\ (-0.26)$ $< 0.14\ (0.35)$	$> -0.54\ (-0.63)$ $< 0.45\ (0.51)$	$> -0.12\ (-0.26)$ $< 0.14\ (0.35)$	$> -0.54\ (-0.63)$ $< 0.45\ (0.51)$	$> -0.12\ (-0.26)$ $< 0.14\ (0.35)$
IH	$> -0.11\ (-0.20)$ $< 0.09\ (0.25)$	$> -0.51\ (-0.60)$ $< 0.42\ (0.51)$	$> -0.11\ (-0.20)$ $< 0.09\ (0.25)$	$> -0.51\ (-0.60)$ $< 0.42\ (0.51)$	$> -0.11\ (-0.20)$ $< 0.09\ (0.25)$

The 90% (3σ) constraints

PMNS row-3 unitarity: why ν_τ matters

Role of ν_τ detection in PMNS constraining PMNS third row unitarity

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Non-unitarity of PMNS matrix

General formula of a non-unitary mixing matrix

A model is when a **fourth neutrino flavour** ν_s exists, where ν_s is mainly of a heavy mass eigenstate m_4 such that $m_4 \gg m_1, m_2, m_3$.

Further the extra generation of sterile neutrino existing as **iso-singlet neutral heavy lepton** (NHL), where $\Delta_{41} \equiv m_4^2 - m_1^2 \gg O(\mathrm{eV}^2)$.

In this case, it **does not take part in neutrino oscillation**. Their involvement in weak interaction gives **effective 3-flavour mixing** that can be described by modified **non-unitary PMNS matrix**, namely

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

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Constraining the non-unitary mixing matrix

Current status and bounds

The **first two rows** of the mixing matrix can be constrained by **detecting electrons and** ν_μ at neutrino oscillation experiments.

Constraints on third row mostly from **charged lepton flavour violation (CLFV)**

3σ limit for 1 dof on third row unitarity violation from joint neutrino oscillation and CLFV fit (with neutrino oscillation only in brackets) from arXiv:1612.07377:

$$|\alpha_{20}| < 4.4 \times 10^{-3}\,(9.8 \times 10^{-2})\,; \quad |\alpha_{21}| < 2.0 \times 10^{-3}\,(1.7 \times 10^{-2})\,; \quad \alpha_{22} > 0.9976\,(0.76)$$

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Constraining the non-unitary mixing matrix

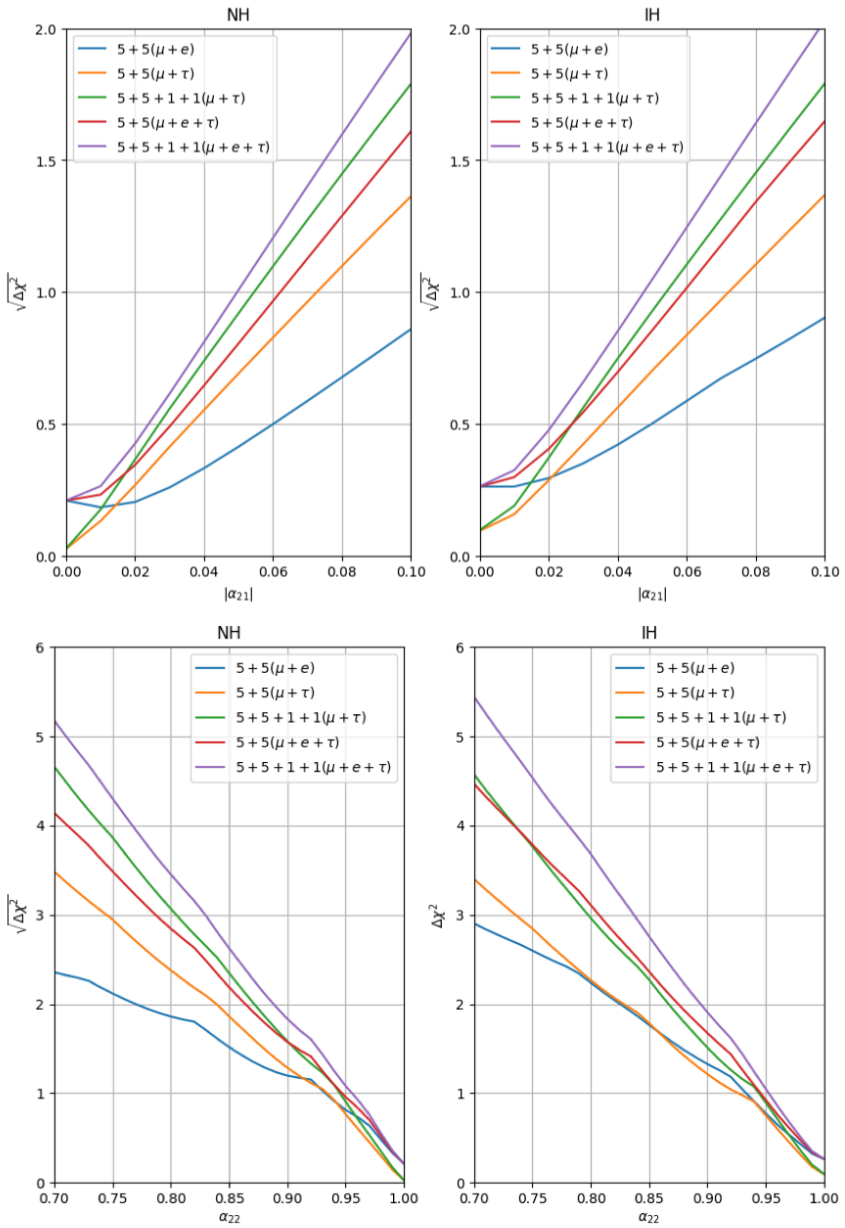
Capabilities of DUNE to constrain non-unitarity

The plots shows **sensitivity** under DUNE exposure

Considered unitary mixing to be truth, marginalized $|\Delta_{31}|$ and $\sin^2\theta_{23}$ in 3σ range, $\delta_{\rm cp}$ in $[-\pi, \pi]$.

Tested $|\alpha_{21}|$ in $[0 : 0.1]$, α_{22} in $[0.7 : 1]$, ϕ_{21} in $[-\pi, \pi]$

Better constraint in α_{22} than neutrino oscillation only fit (>0.76).



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arXiv:2503.16124

Conclusion

We considered the impact of ν_τ and $\bar{\nu}_\tau$ detection at DUNE in relation to NSI.

- **Tau-neutrino detection and NSI parameter $\epsilon_{\mu\tau}$**
  - Most significant contribution to tau event rates is from $\epsilon_{\mu\tau}$, for which ν_τ detection **boosts sensitivity in its existence**
  - If mass hierarchy is fixed, ν_τ **detection also help determine $\phi_{\mu\tau}$**
  - Strategically, can measure MH from ν_e appearance data, then determine $\epsilon_{\mu\tau}$
- **Oscillation parameter measurements**
  - Tau-neutrino detection **does not have significant improvement** to mass hierarchy, δ_{cp}, and octant measurements

Overall, tau appearance channels provides complementary constraint on NSI and BSM physics.

Backup Slides

Backup Slides

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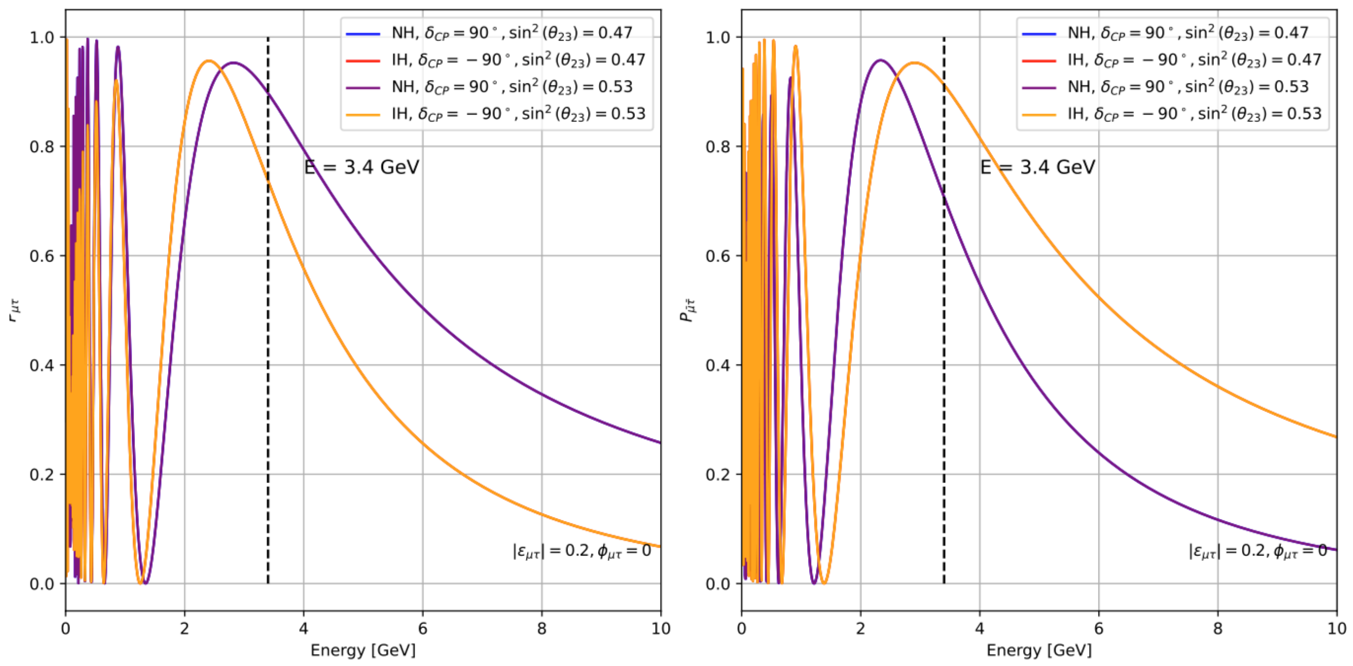
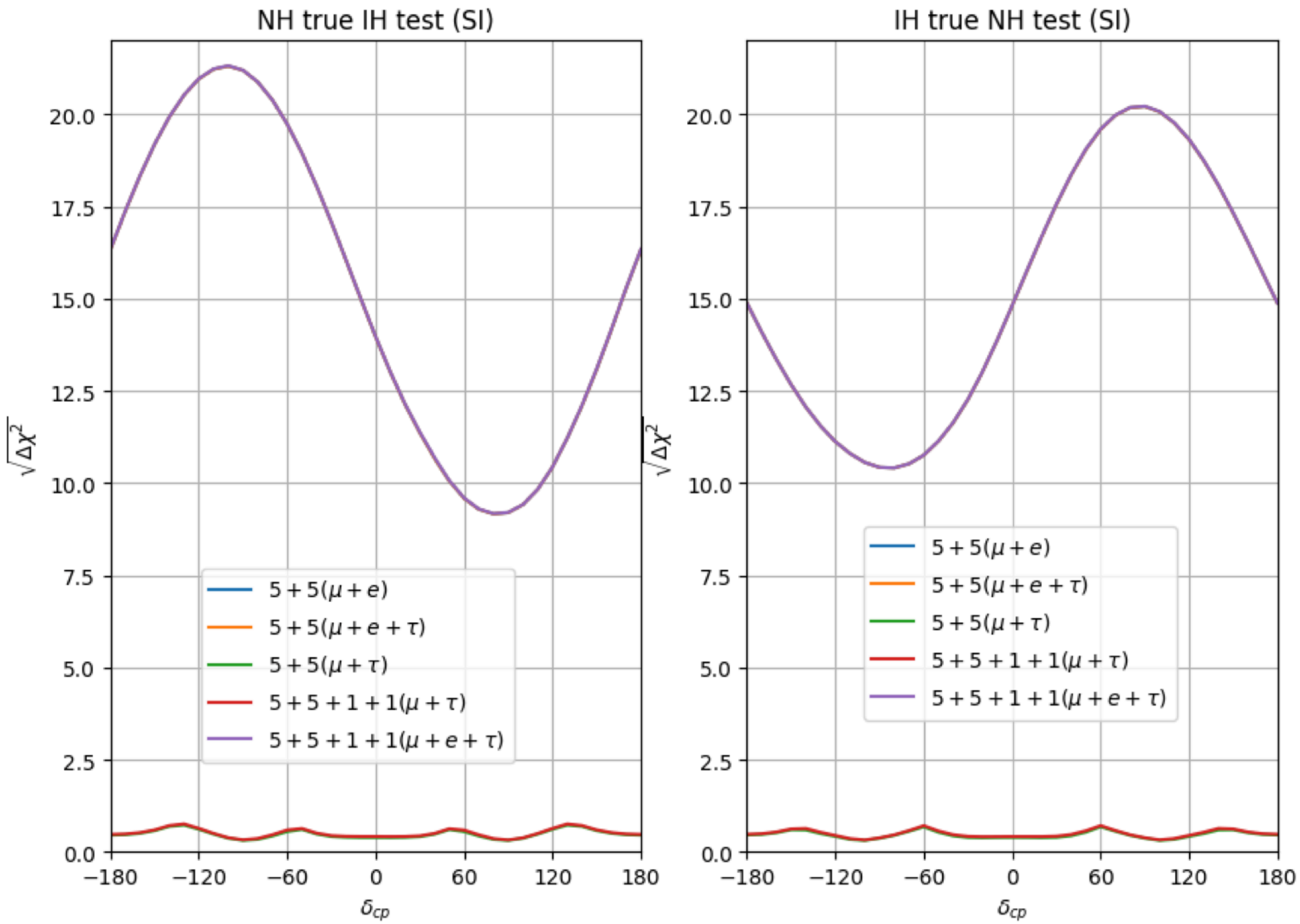
NSI Modification to $\nu_\mu \rightarrow \nu_\tau$ oscillation probability (3/3)

- The plot is produced with $|\epsilon_{\mu\tau}| = 0.2$ with 0 complex phase.
- The 0.2 magnitude is similar to best-fit values of $|\epsilon_{e\mu}|$ and $|\epsilon_{e\tau}|$ values from T2K and NOvA.
- The lack of octant sensitivity can be seen from the graph.



Mass hierarchy sensitivity

- Varied the CP Violating phase
- Marginalized $\sin^2\theta_{23}$ and $|\Delta_{31}|$ in their respective 3 sigma range
- DUNE has decisive sensitivity on mass hierarchy in the SI case.
- Does not change with inclusion of tau-neutrino appearance data.



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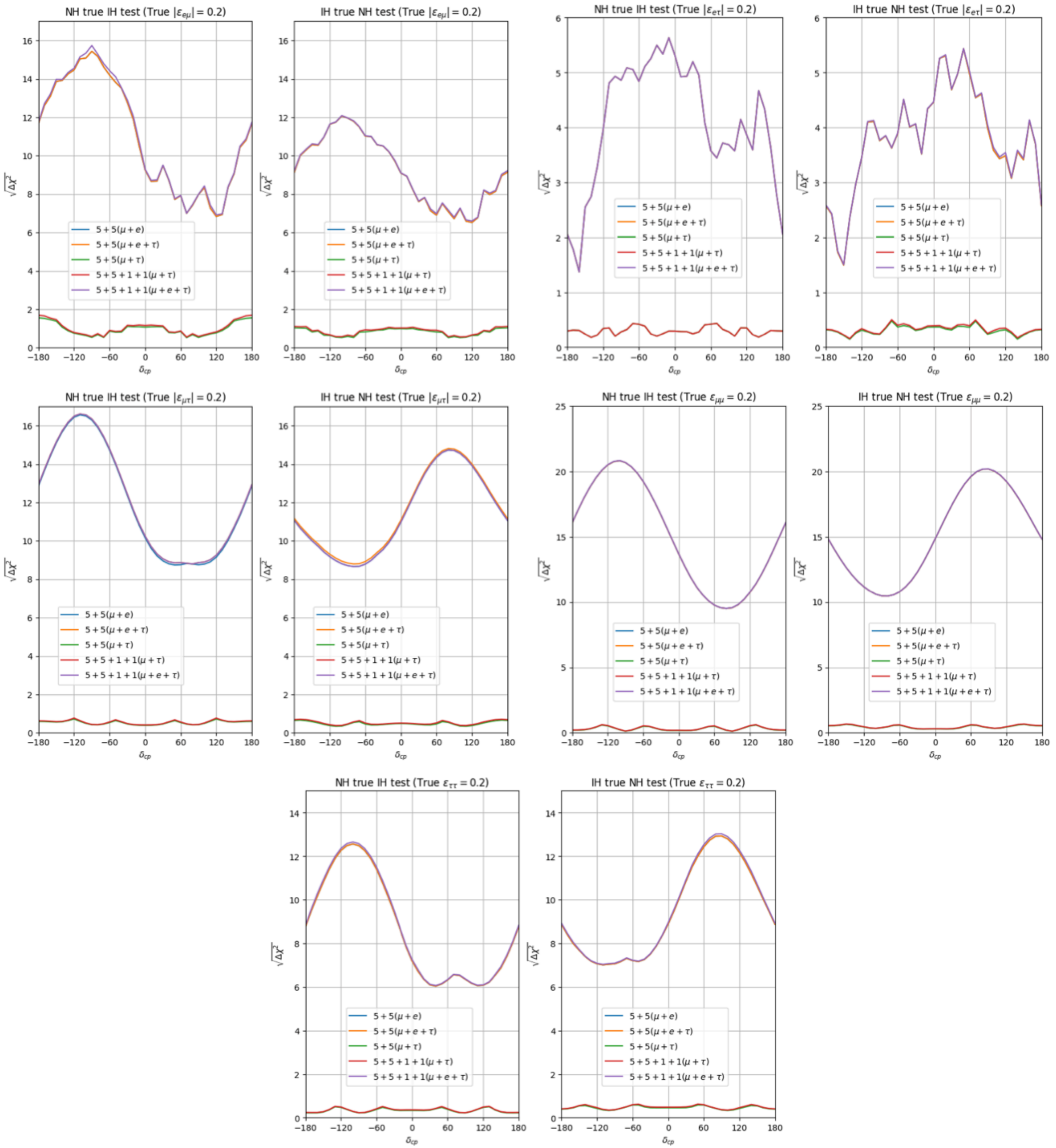
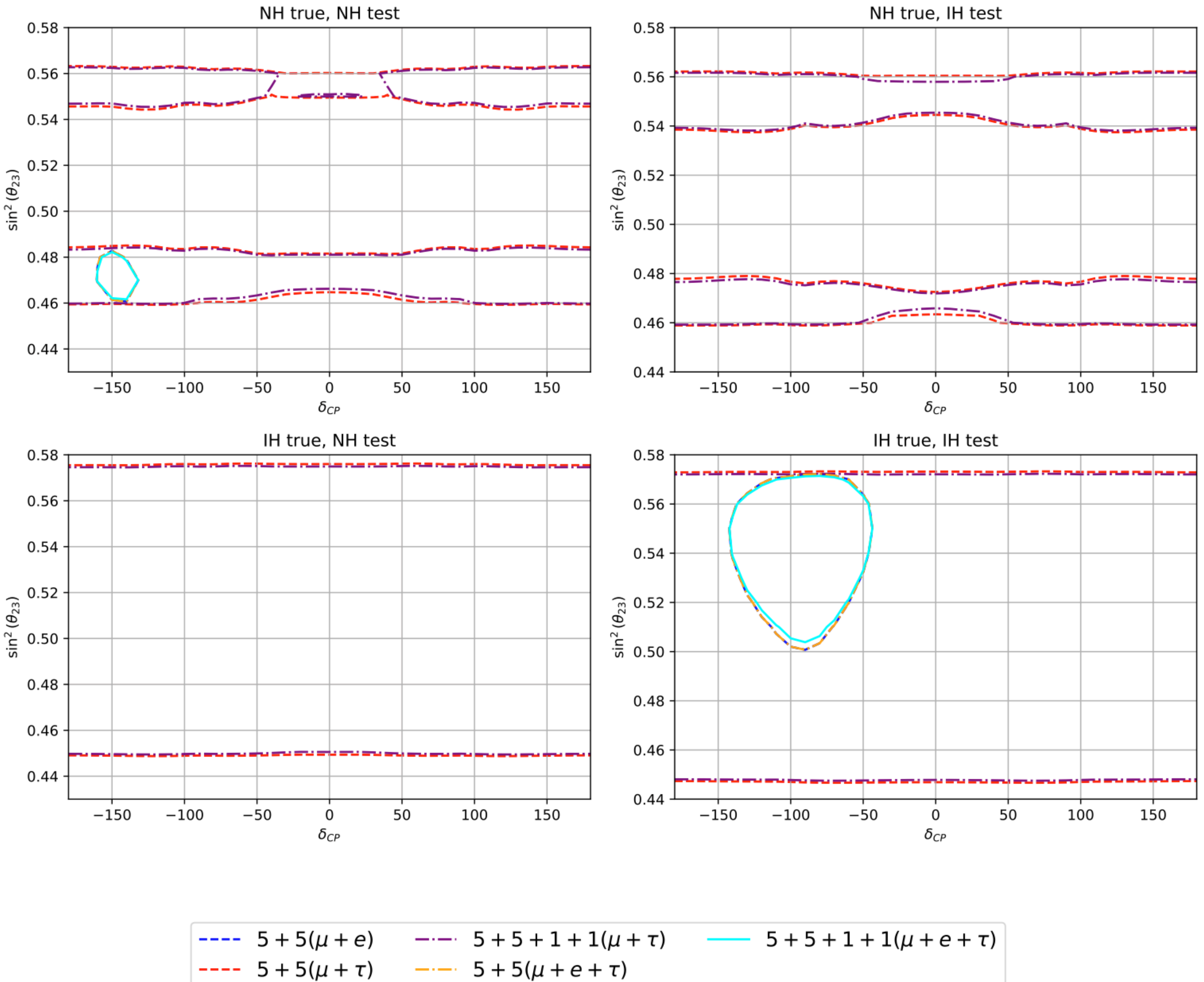
Mass hierarchy sensitivity



Octant sensitivity

- Allowed region in the SI case
- Inclusion of electron neutrino appearance is needed for any meaningful sensitivity.



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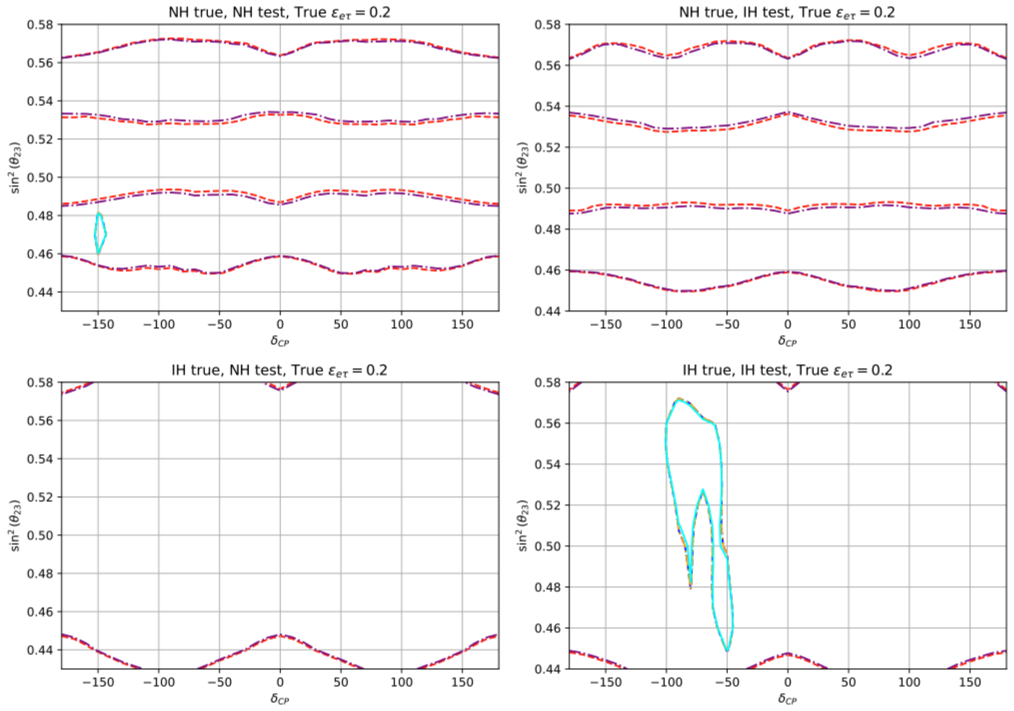
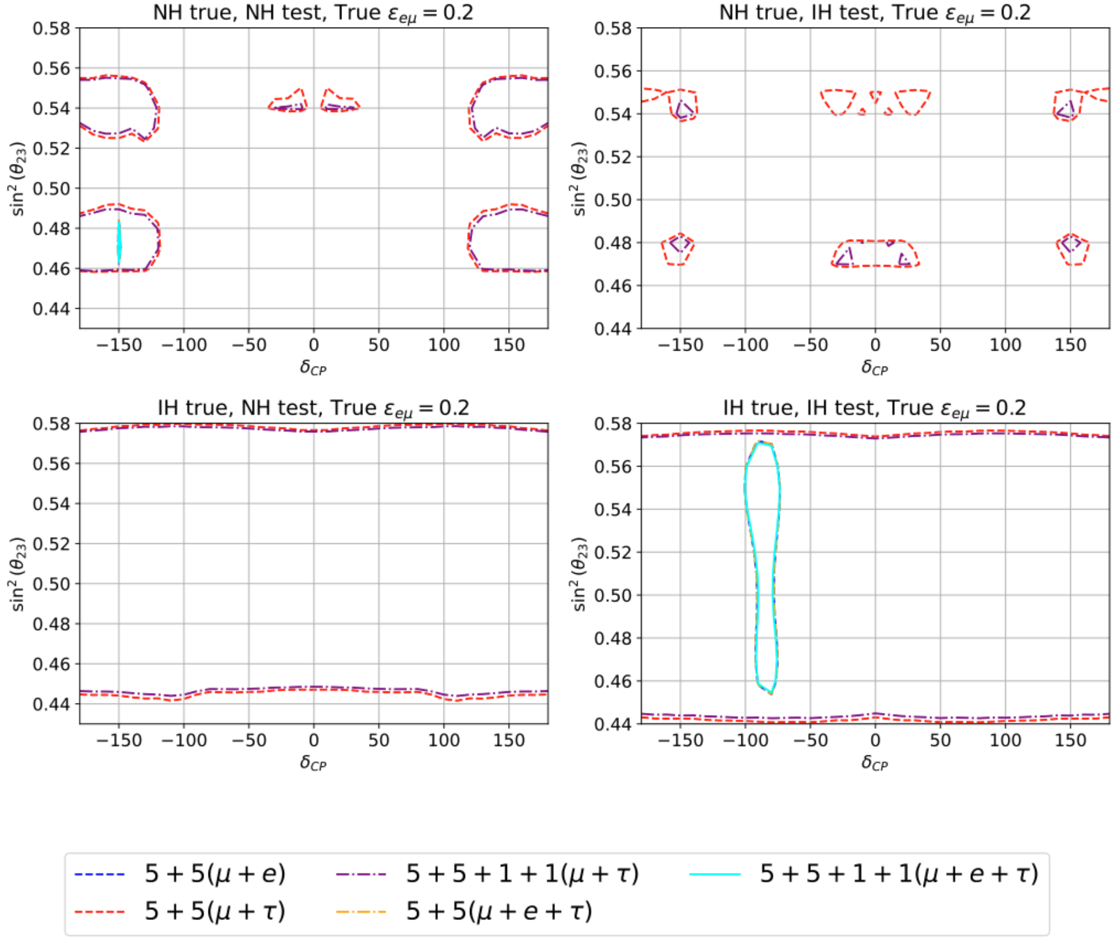
Octant sensitivity





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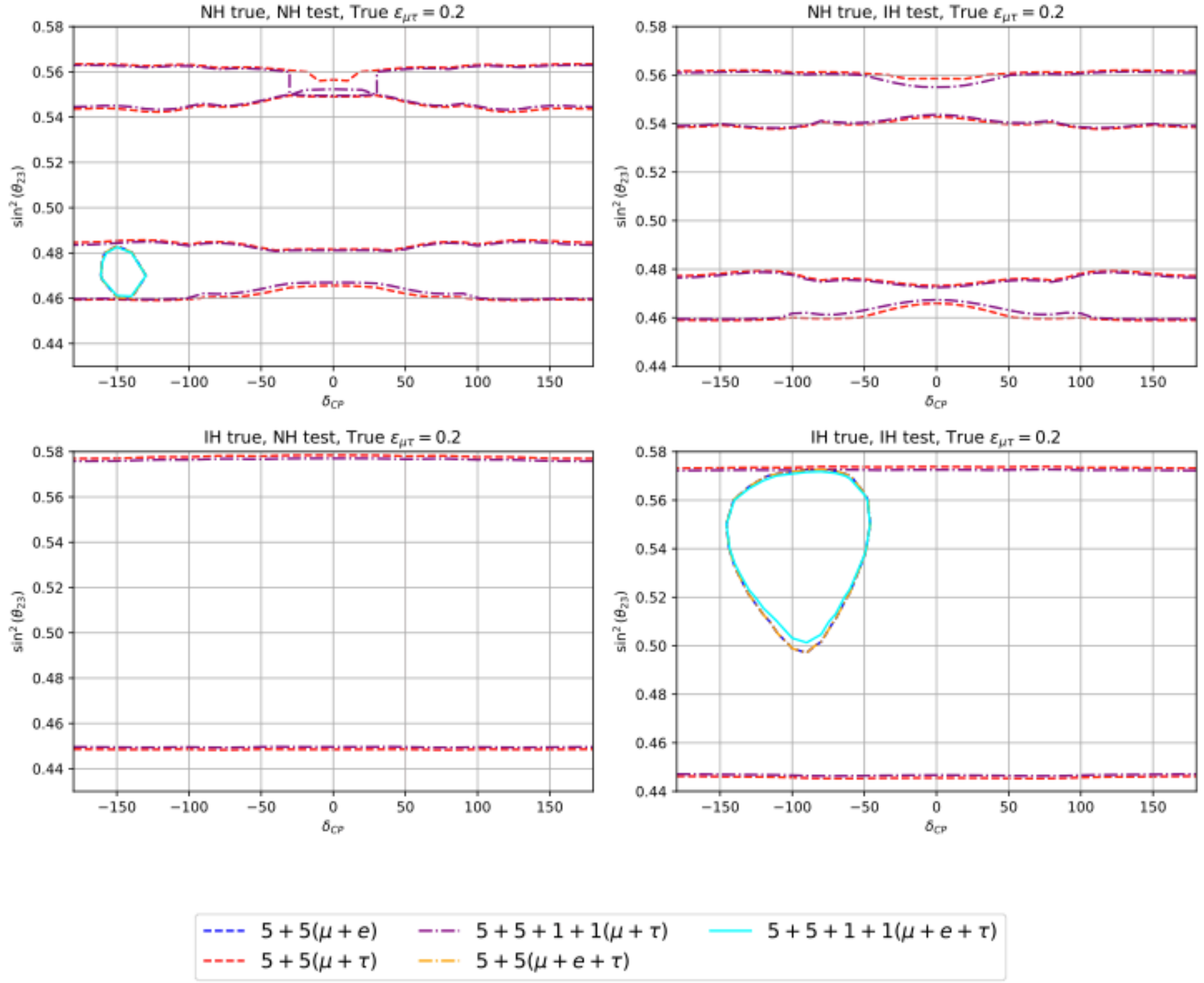
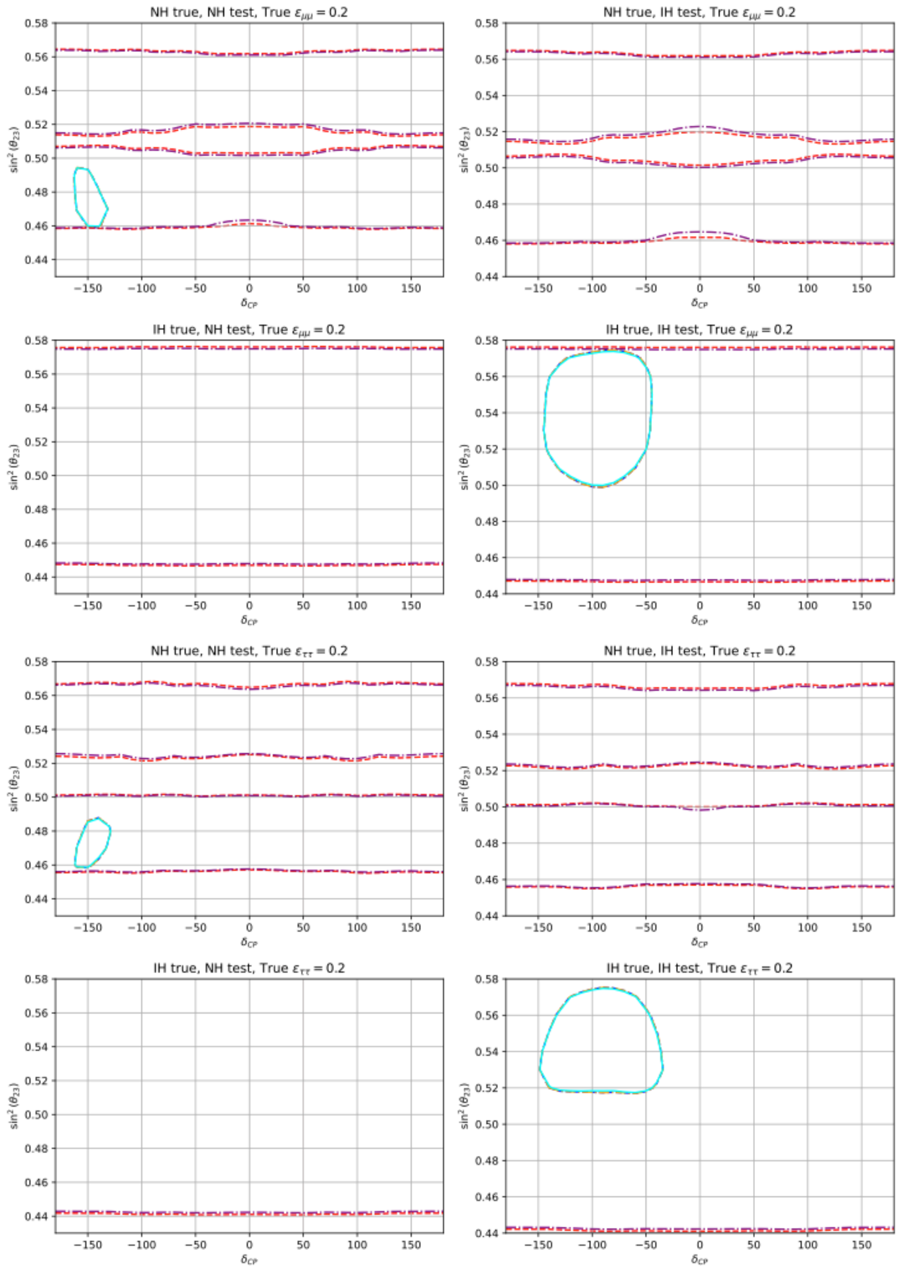
Octant sensitivity





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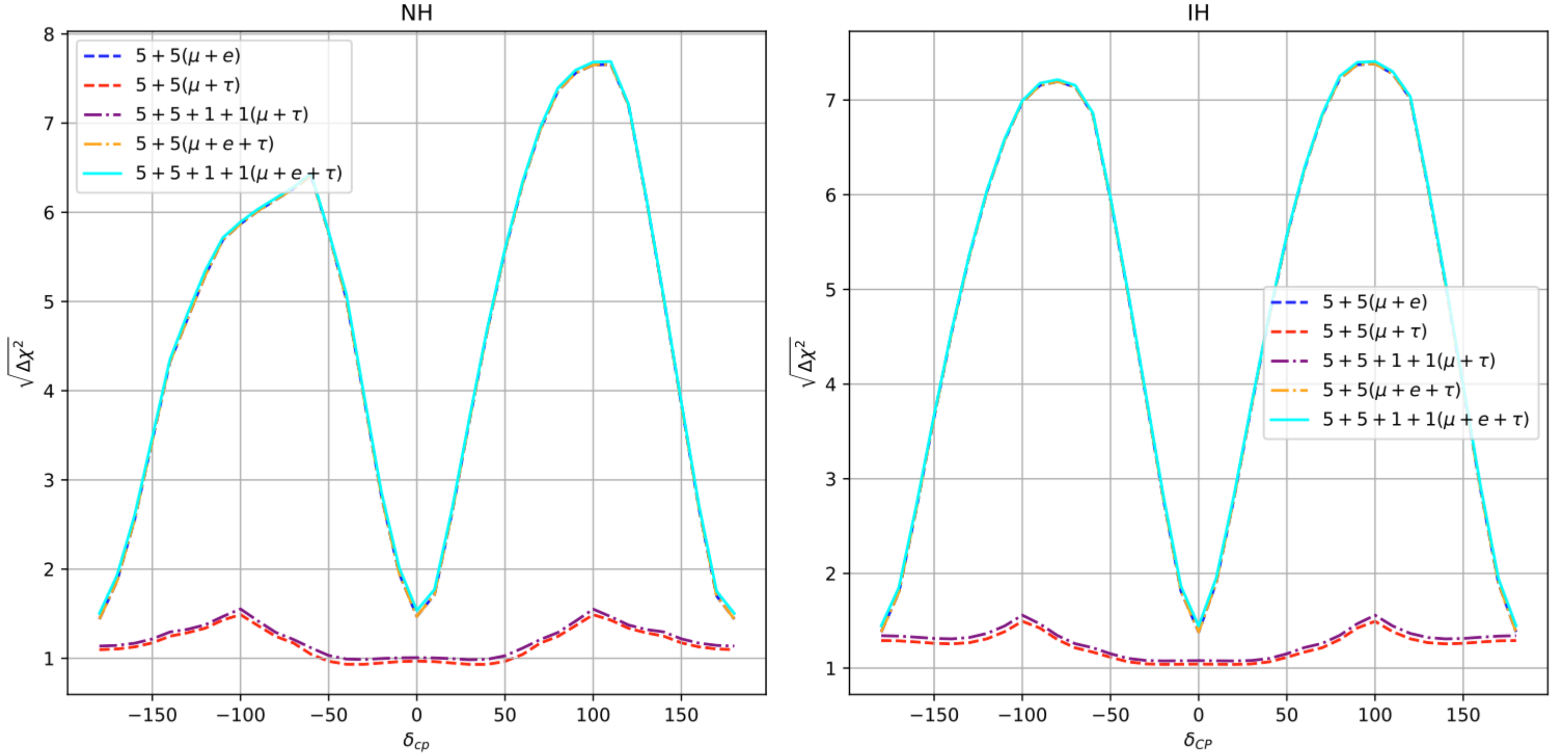
CP sensitivity

- Varied the CP Violating phase
- Marginalized $\sin^2\theta_{23}$ and $|\Delta_{31}|$ in their respective 3 sigma range
- Test CP values 0, 180, -180.
- Good CP sensitivity at the plotted ranges.



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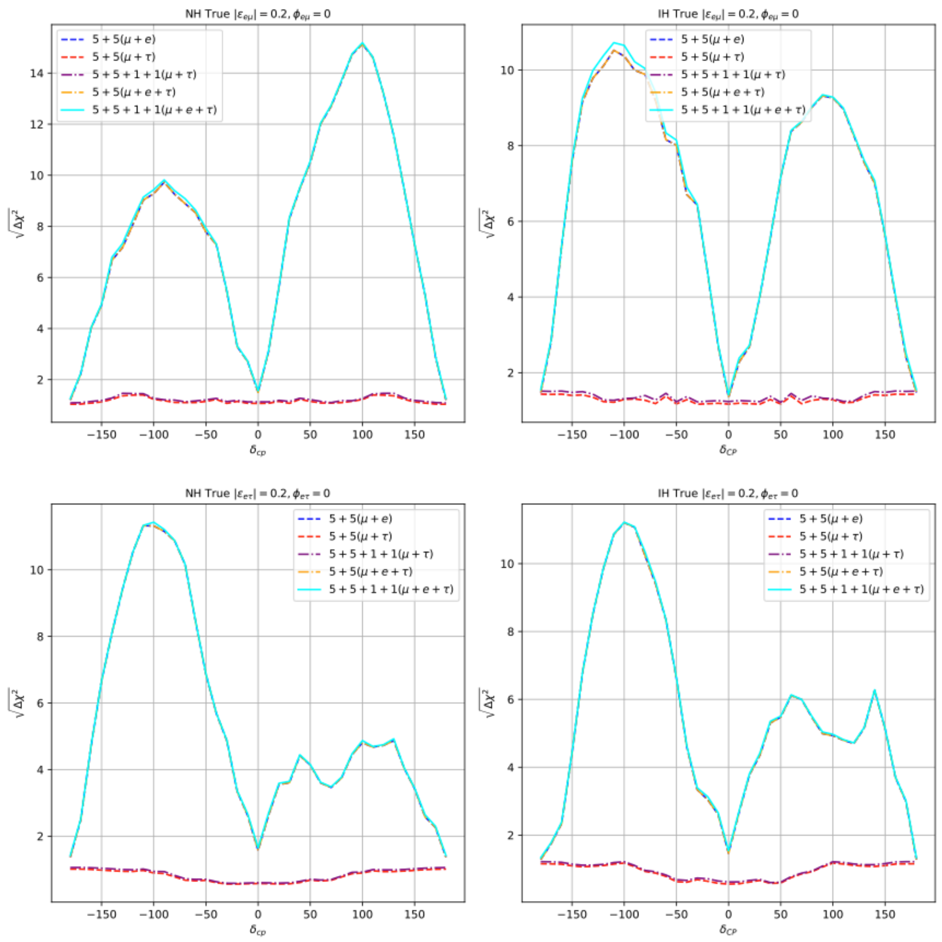
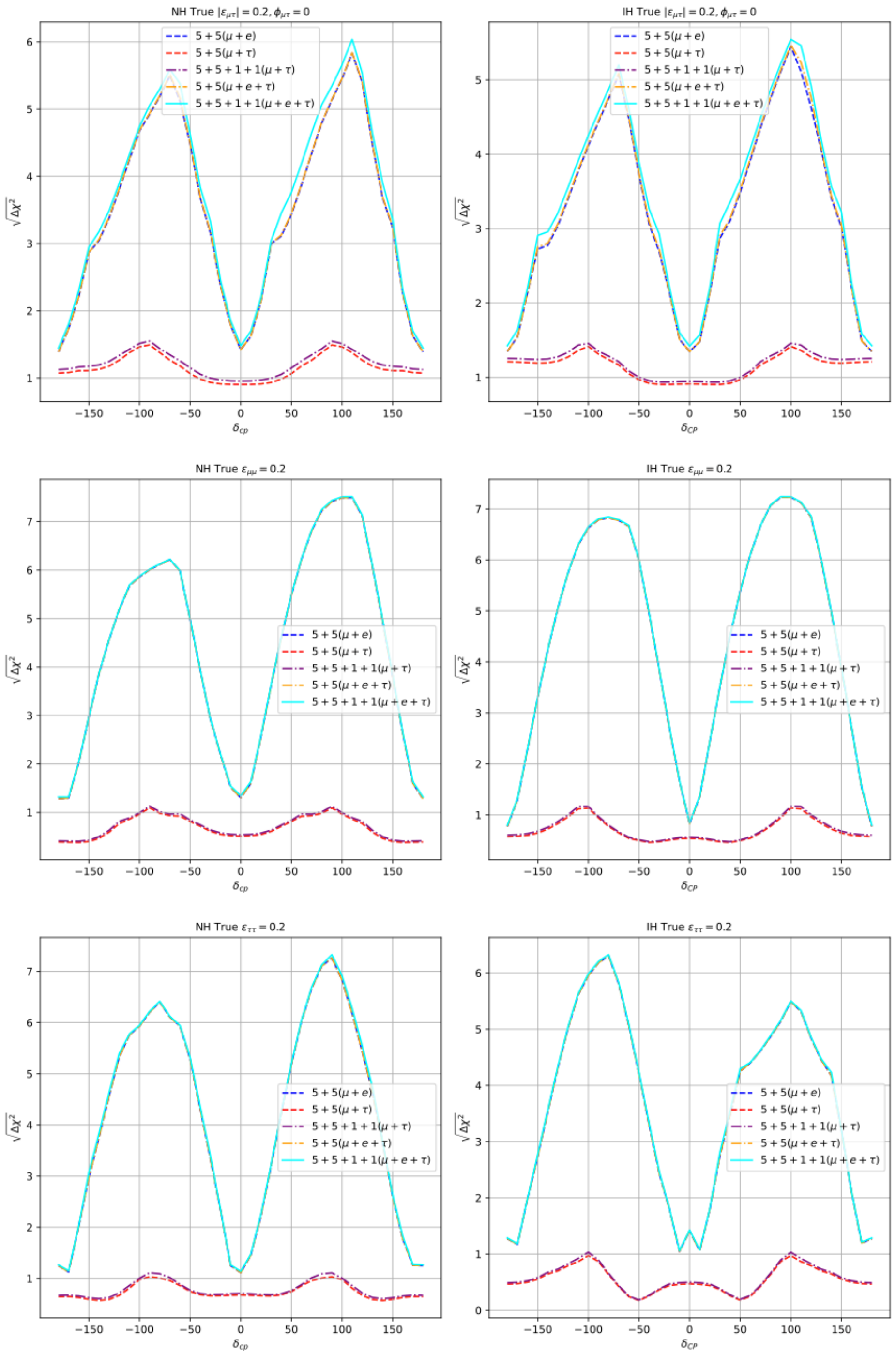
CP sensitivity





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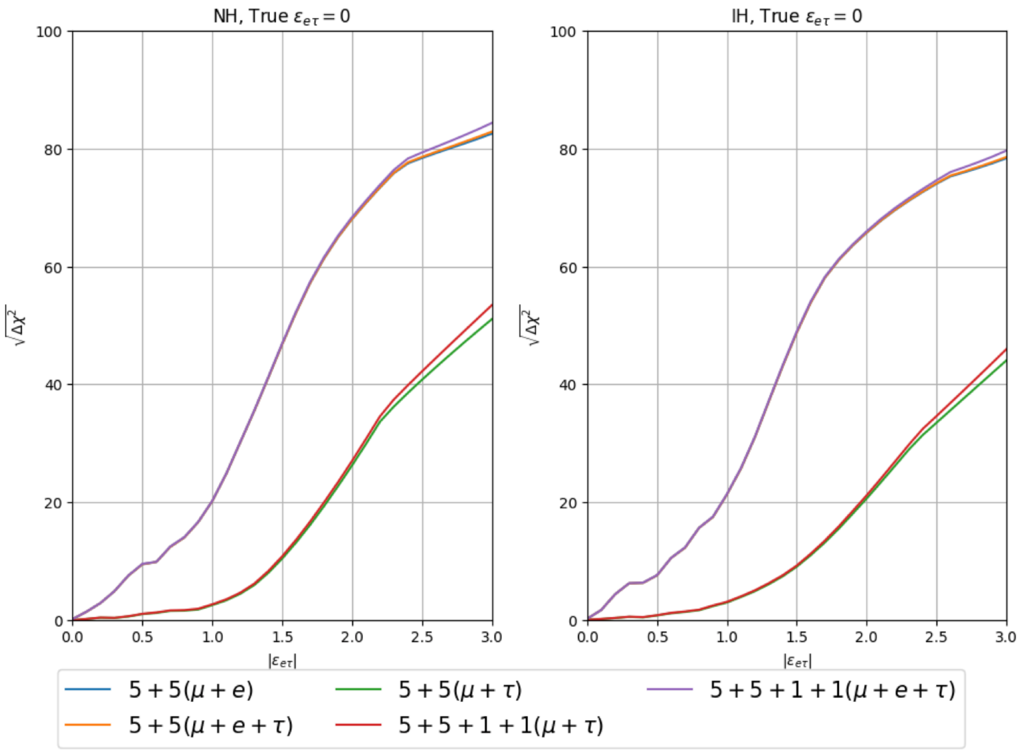
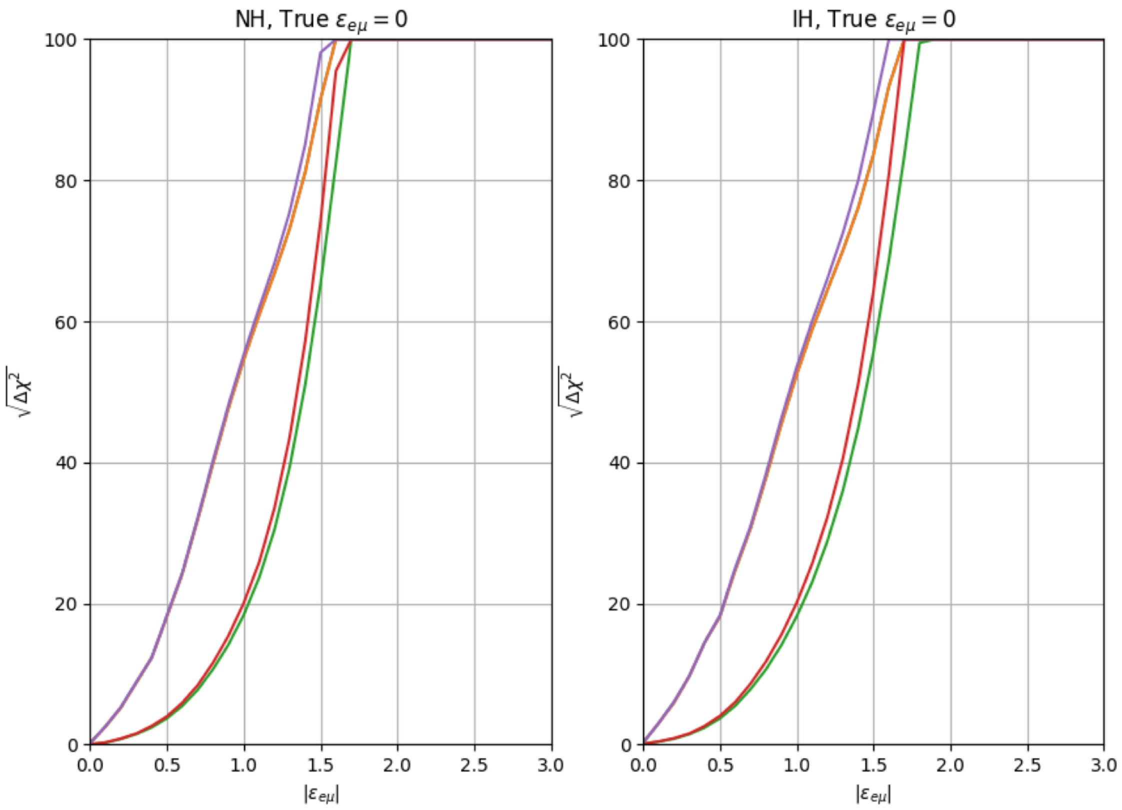
NSI Sensitivity

In truth SI case, ability of DUNE to rule out NSI existence (Terms from subleading contribution)





How NSI affects neutrino oscillation in matter

$$\mathscr{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fC}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_C f)$$

The NSI interaction Lagrangian operator

- α, β denotes neutrino flavours (electron, muon, tau)
- f denotes fermion type in matter (e, u, d)
- C is L or R handed projection operator.
- Very general parameterization of a neutrino flavour changing interaction, at a dimension 6 four particle vertex.
- UV completion come from models such as new heavy states or LFV through light mediators.

$$H = H_{\mathrm{vac}} + H_{\mathrm{mat}} + H_{\mathrm{NSI}},$$

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

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

Effective term from NSI in the Hamiltonian

- Assume: $N_n \approx N_p = N_e$, can use electron density as the scale (electric neutrality)
- NSI enters as an addition effective matter potential term
- Six degrees of freedom from 3 diagonal and 3 off-diagonal terms
- Off-diagonal term introduces flavour-changing neutral-current effects in propagation through matter.

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