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Impact of Lorentz Invariance Violation on CP-Violation and Mass-Ordering Sensitivities at DUNE and ESSnuSB

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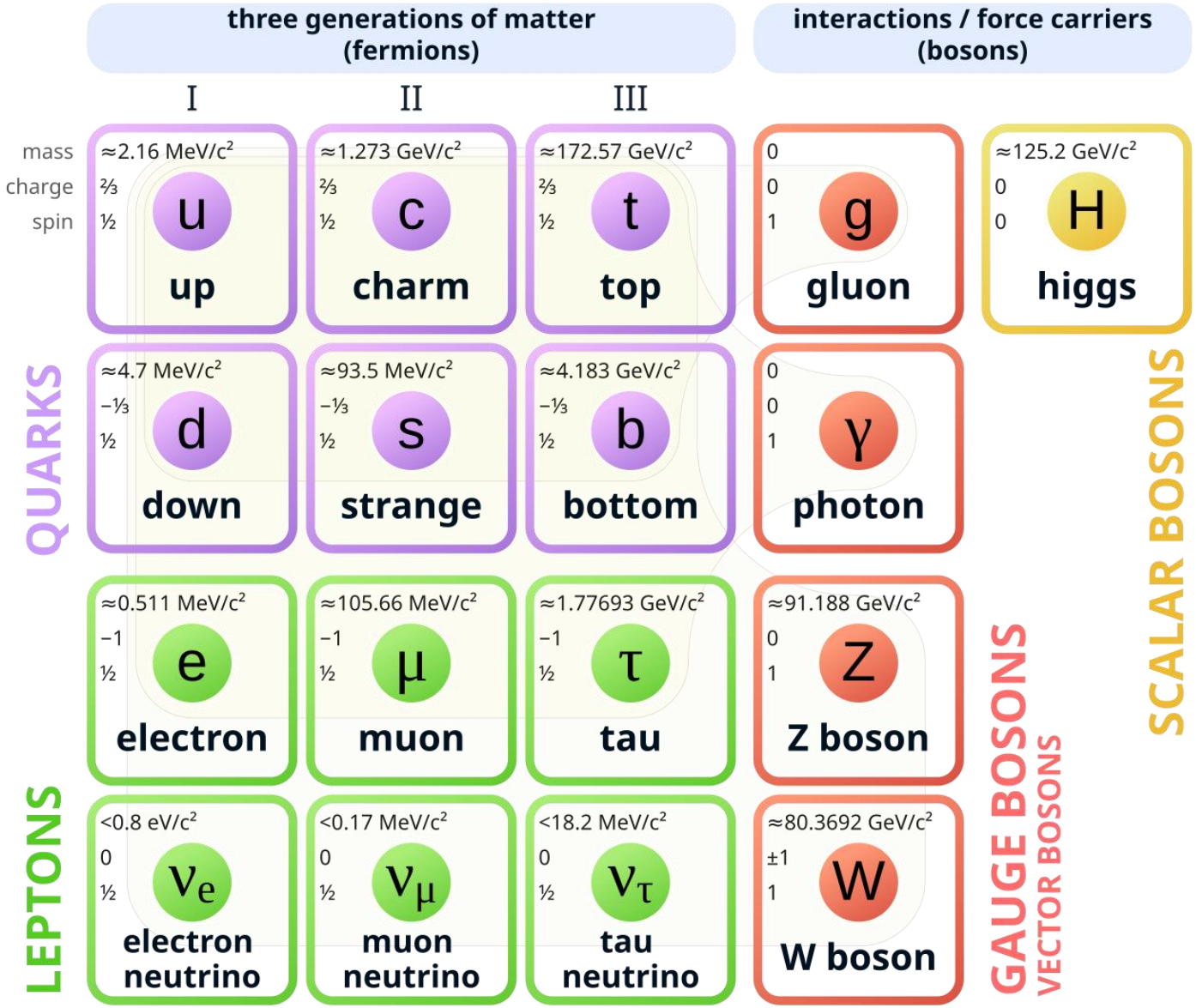
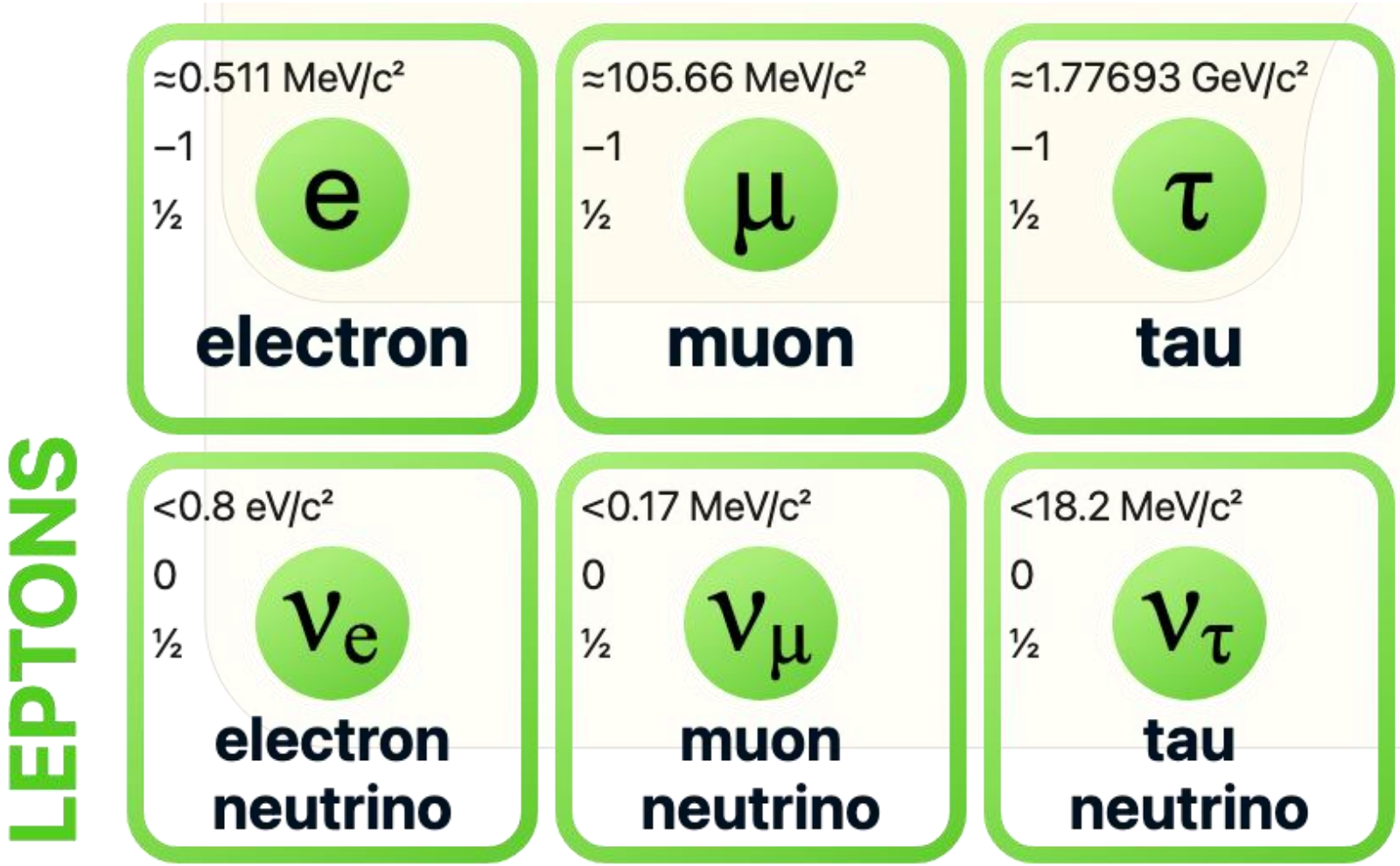
Plan of the Talk

- Neutrino Oscillations and “Unsolved” Problems
- LIV and LIV Hamiltonian
- Long Baseline Neutrino Experiments : DUNE and ESSnuSB
- CP Violation Sensitivity
- Mass Ordering Sensitivity

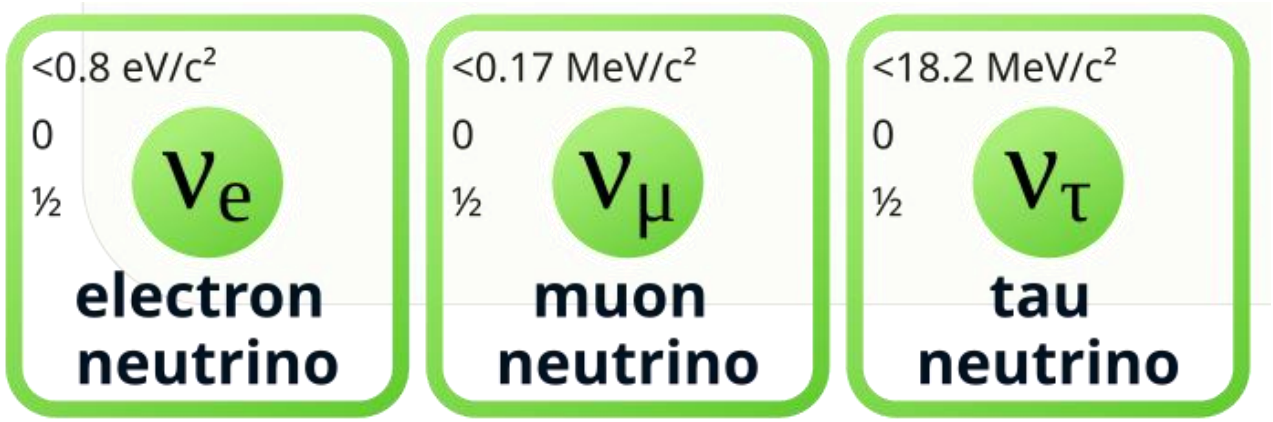
Standard Model of Elementary Particles




LEPTONS
≈0.511 MeV/c²
−1
½
e
electron
≈105.66 MeV/c²
−1
½
μ
muon
≈1.77693 GeV/c²
−1
½
τ
tau
<0.8 eV/c²
0
½
νe
electron neutrino
<0.17 MeV/c²
0
½
νμ
muon neutrino
<18.2 MeV/c²
0
½
ντ
tau neutrino

Neutrinos

- electric charge neutral
- leptons (fermions) spin half
- interacts only via the weak interaction (and gravity?)
- always created in one of the three flavours:



- massless??!!

2×10^{17} solar neutrinos would pass through your body by the time the talk ends!

Very abundant but weakly interacting

Neutrinos

Neutrino participate in weak interactions as flavour eigenstates. A neutrino may be produced (and detected) in any one of the flavour eigenstates.

$$|\nu_e\rangle, |\nu_\mu\rangle, |\nu_\tau\rangle$$

But neutrinos propagate through space with a definite mass, known as mass eigenstates.

$$|\nu_1\rangle, |\nu_2\rangle, |\nu_3\rangle$$

Each flavour state is a quantum superposition of the three mass states and vice-versa. For example:

$$|\nu_\mu\rangle = a_1|\nu_1\rangle + a_2|\nu_2\rangle + a_3|\nu_3\rangle$$

Neutrinos

The evolution of a neutrino state is governed by the time-dependent Schrödinger equation, $$i\frac{d}{dt}|\nu(t)\rangle = H|\nu(t)\rangle.$$

In the basis of mass eigenstates, the Hamiltonian is diagonal, as these are the energy eigenstates:

$$H_{mass} = diag(E_1, E_2, E_3)$$

where $E_i = \sqrt{p^2 + m_i^2}$ is the energy of the mass eigenstate ν_i. Since neutrinos are ultra-relativistic $m_i \ll E_i$, this can be approximated as $E_i \approx p + \frac{m_i^2}{2p}$. The momentum p is nearly identical for all mass components and can be approximated by the total neutrino energy E.

Neutrinos

- Since the flavour eigenstates were superposition of the mass eigenstates, so

$$H_{flavor} = U H_{mass} U^{\dagger}$$

- To find the evolution of a flavor state, we must transform the Hamiltonian into the flavor basis using the PMNS matrix.

$$H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^{\dagger}$$

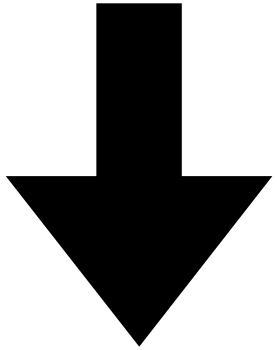
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

where s_{ij} and c_{ij} are used to denote $\sin\theta_{ij}$ and $\cos\theta_{ij}$ respectively.

Neutrino Oscillation

$$i\frac{d}{dt}|\nu(t)\rangle = H|\nu(t)\rangle$$



Oscillation Probability

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t)\rangle|^2 = \left|\langle \nu_\beta | e^{-iHt} | \nu_\alpha \rangle\right|^2$$

Neutrino Oscillation

This leaves us with six mixing parameters to be determined :

1. Three Mixing Angles

- θ_{12} (Solar Mixing Angle):
- θ_{23} (Atmospheric Mixing Angle)
- θ_{13} (Reactor Mixing Angle)

2. One CP-Violating Phase

- δ_{CP} (Dirac CP Phase)

3. Two Mass-Squared Differences

- Δm^2_{21} (Solar Mass Splitting)
- Δm^2_{31} (Atmospheric Mass Splitting)

“Unsolved” Problems in Neutrino Oscillation

The fundamental questions that need to be resolved through measurements from experiments with increased precision in the neutrino sector are:

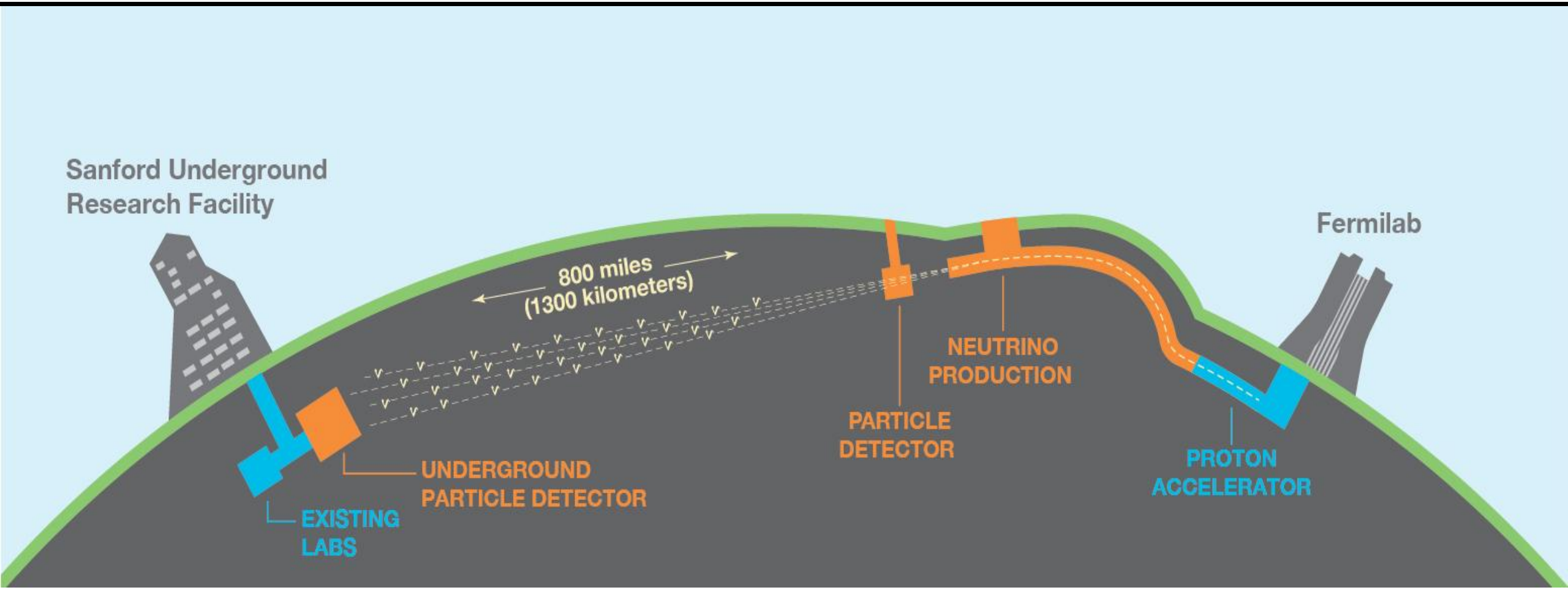
- **The Neutrino Mass Ordering**: The sign of $\Delta m^2_{3\ell}$ is yet to be determined. It is not known whether the mass spectrum follows a “Normal Ordering” ($m_3 > m_2 > m_1$) or an “Inverted Ordering” ($m_2 > m_1 > m_3$), although current data show a preference for Normal Ordering.

- **Leptonic CP Violation:** It is not definitively known whether the phase δ_{CP} is different from $0°$ or $180°$. Resolving this would reveal if the weak interactions of leptons and antileptons are different, and might help us understand the matter-antimatter asymmetry of the universe.

- **The Octant of θ_{23}:** It is also not determined whether the mixing angle θ_{23} is exactly $45°$ (maximal mixing), or is it located in the lower octant ($< 45°$) or upper octant ($> 45°$). This has important implications for neutrino mass models.

Long Baseline Neutrino Experiment

DEEP UNDERGROUND NEUTRINO EXPERIMENT

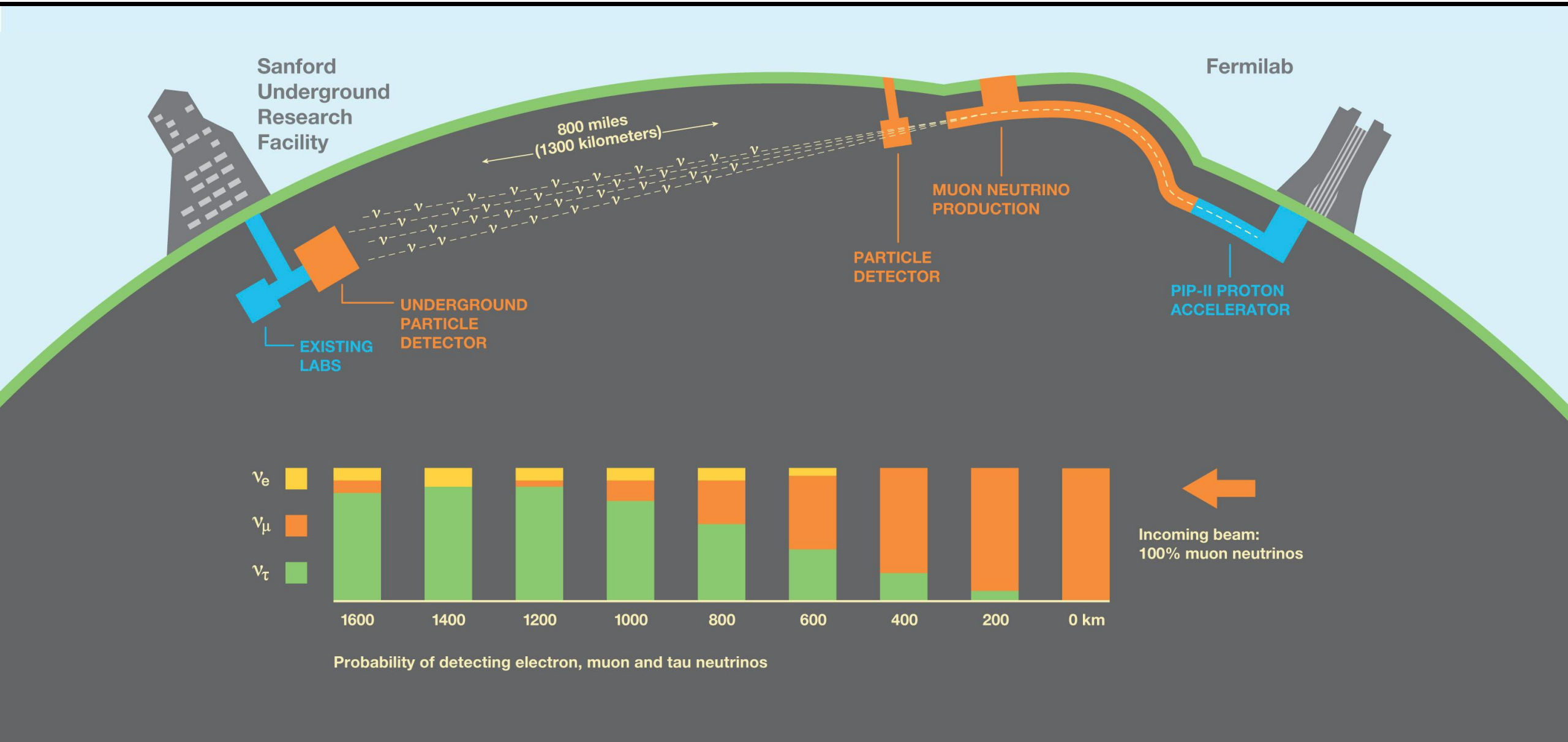


Measure event rates to compare against oscillation probabilities calculated for

$\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$

Long Baseline Neutrino Experiment

DEEP UNDERGROUND NEUTRINO EXPERIMENT



Neutrino Oscillation Parameters

www.nu-fit.org

NuFIT 6.1 (2025)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 1.5$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC23 without SK atmospheric data	$\sin^2\theta_{12}$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \to 0.3295$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \to 0.3295$
	$\theta_{12}/^\circ$	$33.76^{+0.42}_{-0.41}$	$32.54 \to 35.03$	$33.76^{+0.42}_{-0.41}$	$32.54 \to 35.03$
	$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.014}$	$0.432 \to 0.587$	$0.555^{+0.013}_{-0.016}$	$0.437 \to 0.590$
	$\theta_{23}/^\circ$	$43.27^{+1.0}_{-0.82}$	$41.11 \to 50.02$	$48.15^{+0.75}_{-0.92}$	$41.40 \to 50.21$
	$\sin^2\theta_{13}$	$0.02249^{+0.00057}_{-0.00057}$	$0.02070 \to 0.02420$	$0.02261^{+0.00056}_{-0.00056}$	$0.02091 \to 0.02433$
	$\theta_{13}/^\circ$	$8.62^{+0.11}_{-0.11}$	$8.27 \to 8.95$	$8.65^{+0.11}_{-0.11}$	$8.31 \to 8.97$
	$\delta_{\rm CP}/^\circ$	207^{+23}_{-20}	$114 \to 405$	283^{+24}_{-28}	$202 \to 347$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.537^{+0.094}_{-0.10}$	$7.236 \to 7.823$	$7.537^{+0.094}_{-0.10}$	$7.236 \to 7.822$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.521^{+0.026}_{-0.018}$	$+2.454 \to +2.592$	$-2.500^{+0.024}_{-0.023}$	$-2.569 \to -2.430$

Ref.

- NuFit-6.0: Updated global analysis of three-flavor neutrino oscillations
  Ivan Esteban, M.C. Gonzalez-Garcia, Michele Maltoni, Ivan Martinez-Soler, João Paulo Pinheiro, Thomas Schwetz
  (arXiv:2410.05380v2)

Beyond Standard Model Physics

For incorporating BSM Physics, we need to add a term to the standard Hamiltonian that can account for the new physics effects

$$H = U \underbrace{\begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix}}_{\text{vacuum}} U^\dagger + \underbrace{\begin{pmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{\text{matter}} + H_{BSM}$$

This introduces perturbations in the standard oscillation probabilities.

BSM Physics: Lorentz Invariance Violation

What if Lorentz Symmetry does not hold at Planck Scale? What if **L**orentz **I**nvariance is **V**iolated?

$$H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + H_{LIV}$$

BSM Physics: Lorentz Invariance Violation

What if Lorentz Symmetry does not hold at Planck Scale? What if **L**orentz **I**nvariance is **V**iolated?

$$H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + H_{LIV}$$

$$\begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a_{\tau\tau} \end{pmatrix} - \frac{4}{3}E \begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c^*_{e\mu} & c_{\mu\mu} & c_{\mu\tau} \\ c^*_{e\tau} & c^*_{\mu\tau} & c_{\tau\tau} \end{pmatrix}$$

BSM Physics: Lorentz Invariance Violation

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$$H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + H_{LIV}$$

$$\begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a_{\tau\tau} \end{pmatrix} - \frac{4}{3}E \begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c^*_{e\mu} & c_{\mu\mu} & c_{\mu\tau} \\ c^*_{e\tau} & c^*_{\mu\tau} & c_{\tau\tau} \end{pmatrix}$$

CPT-odd

CPT-even

BSM Physics: Lorentz Invariance Violation

What if Lorentz Symmetry does not hold at Planck Scale? What if **L**orentz **I**nvariance is **V**iolated?

$$H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + H_{LIV}$$

$$\begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a_{\tau\tau} \end{pmatrix} - \frac{4}{3}E \begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c^*_{e\mu} & c_{\mu\mu} & c_{\mu\tau} \\ c^*_{e\tau} & c^*_{\mu\tau} & c_{\tau\tau} \end{pmatrix}$$

CPT-odd

CPT-even

BSM Physics: Lorentz Invariance Violation

Neutrinos

$$H_{eff} = H_{vac} + H_{mat} + H_{LIV}$$

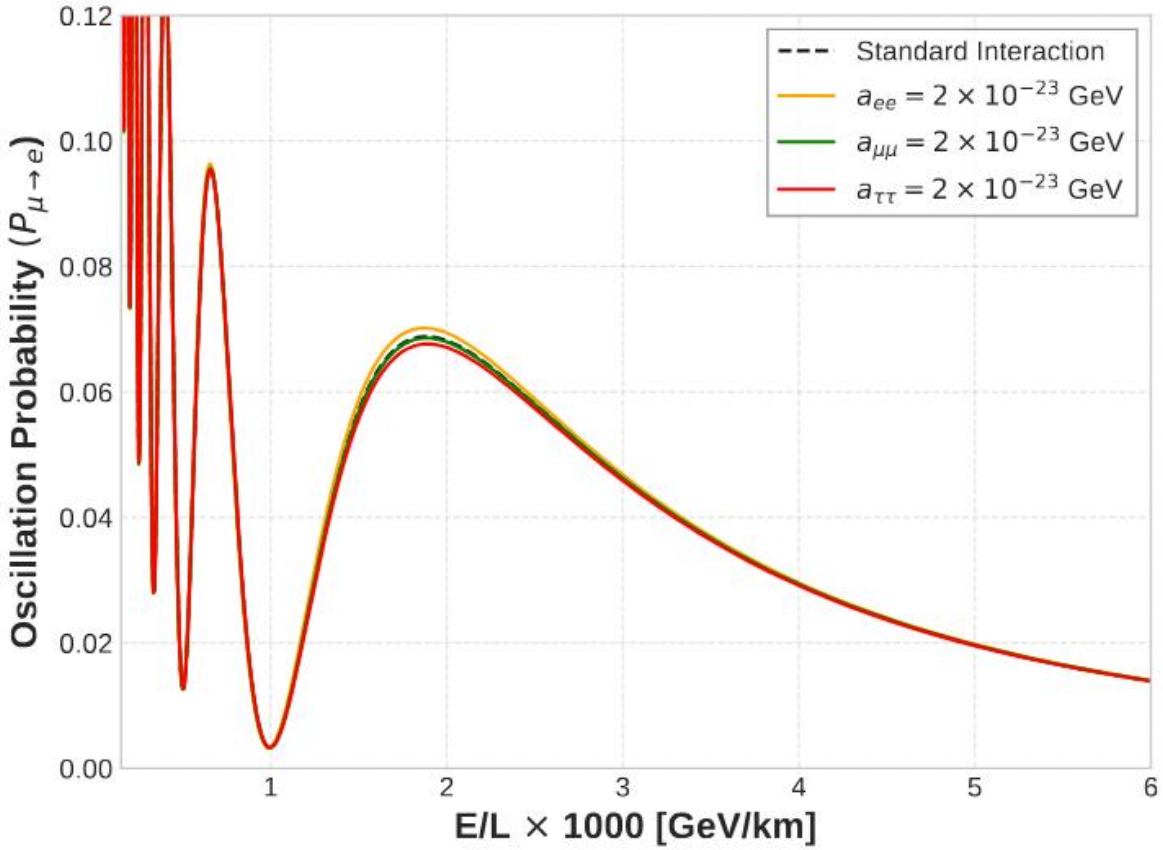
$$H_{eff} = \underbrace{\frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger}_{H_{\rm vac}} + \underbrace{\begin{pmatrix} V_{\rm CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{H_{\rm mat}} + \underbrace{\begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a_{\tau\tau} \end{pmatrix}}_{H_{\rm LIV}}$$

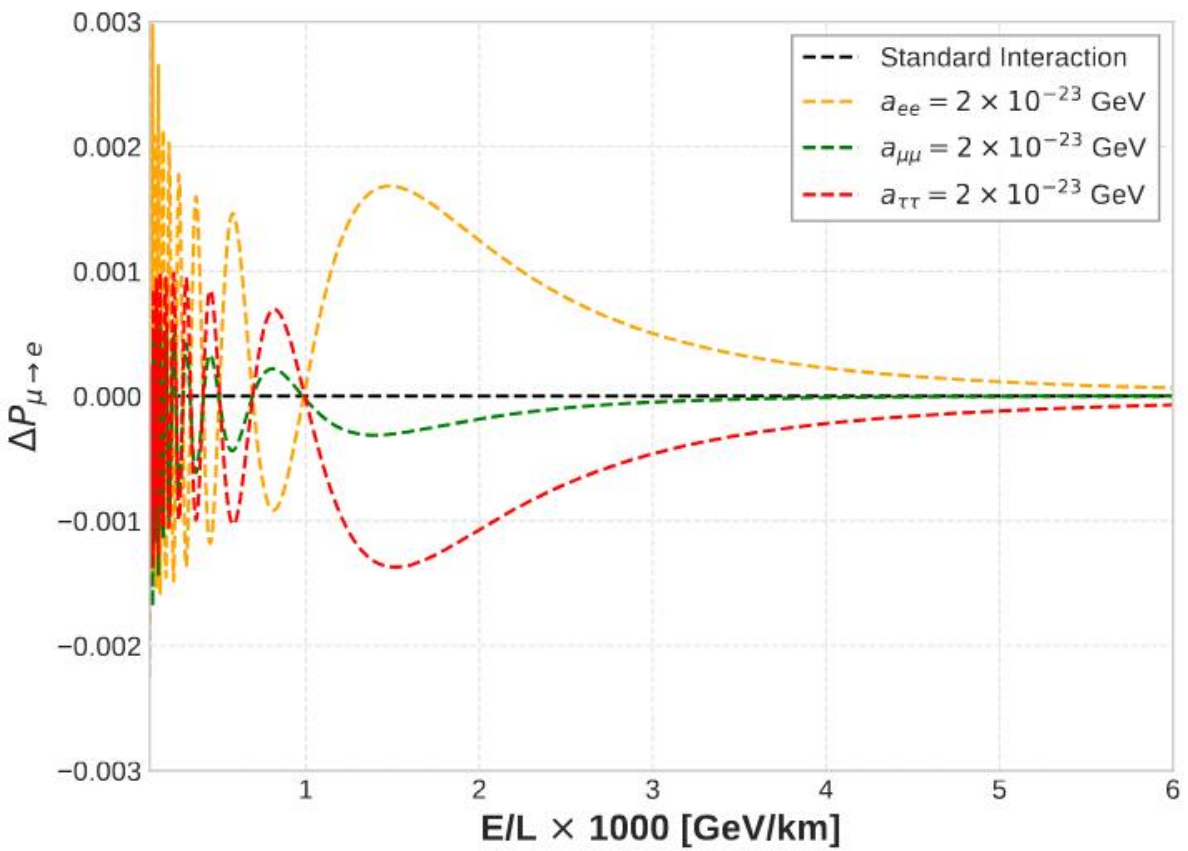
Anti-neutrinos

$$H_{eff}(\overline{\nu}) = H_{vac} - H^*_{mat} - H^*_{LIV}$$

$$H_{LIV}(\overline{\nu}) = -H^*_{LIV} = - \begin{pmatrix} a_{ee} & a^*_{e\mu} & a^*_{e\tau} \\ a_{e\mu} & a_{\mu\mu} & a^*_{\mu\tau} \\ a_{e\tau} & a_{\mu\tau} & a_{\tau\tau} \end{pmatrix}$$

Oscillation Probability in presence of LIV



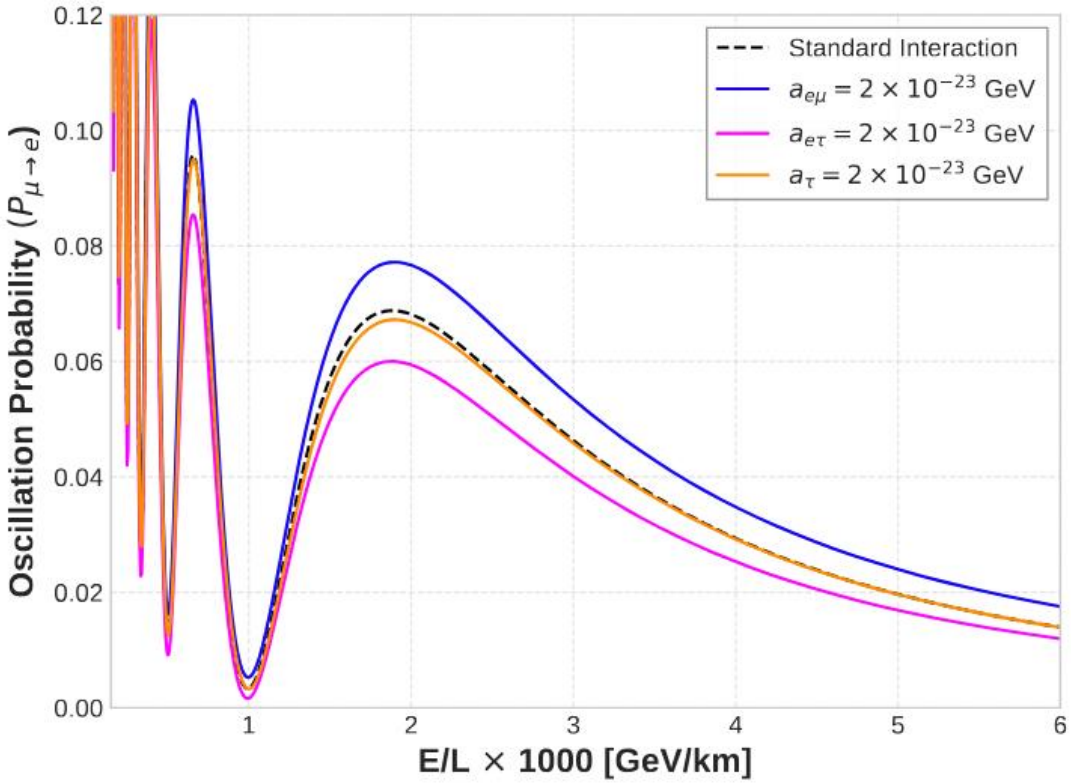


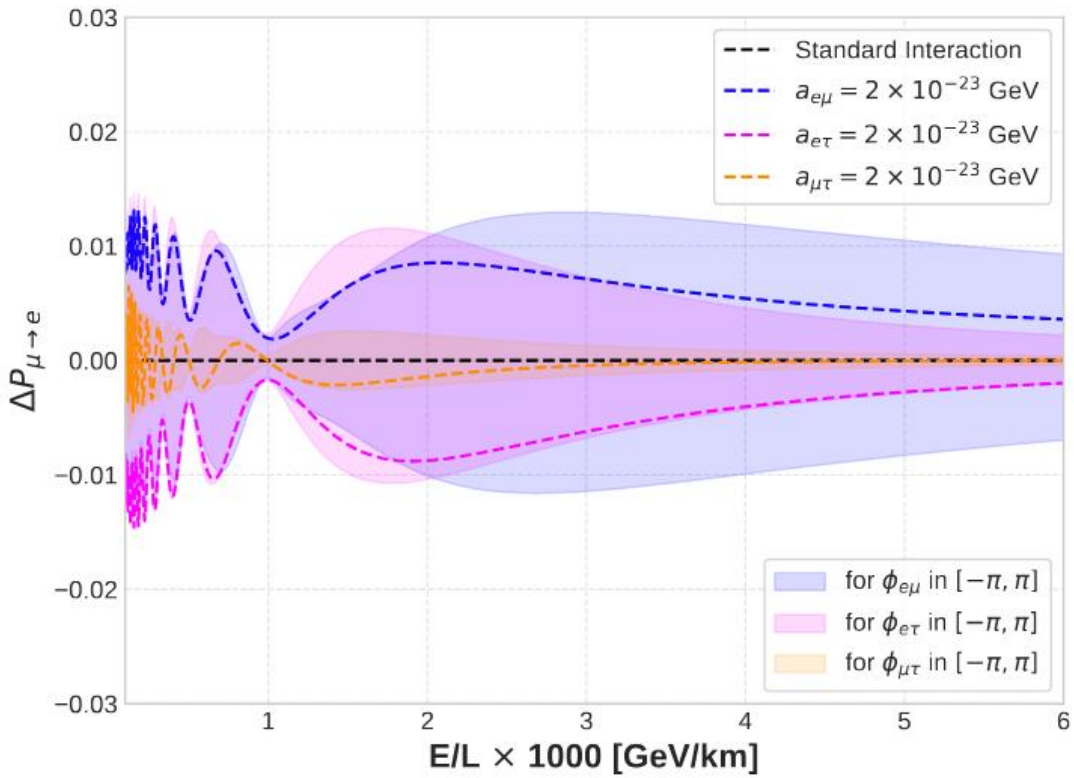
DIAGONAL PARAMETERS

$$\nu_\mu \to \nu_e$$

ArXiv: 2512.06953 , 10.1007/JHEP08(2026)200

Oscillation Probability in presence of LIV





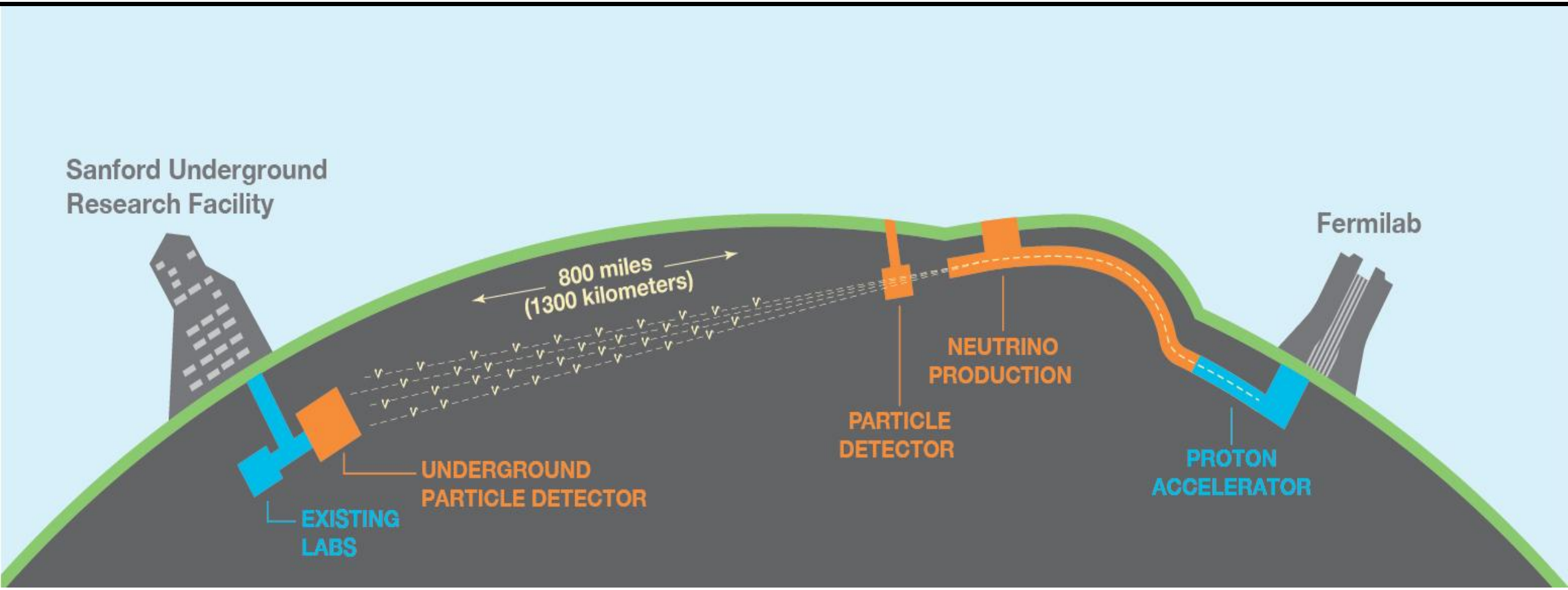
OFF-DIAGONAL PARAMETERS

$$\nu_\mu \to \nu_e$$

ArXiv: 2512.06953 , 10.1007/JHEP08(2026)200

Long Baseline Neutrino Experiment

DEEP UNDERGROUND NEUTRINO EXPERIMENT



Measure event rates to compare against oscillation probabilities calculated for

$\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$

Long Baseline Neutrino Experiment

ESS neutrino Super Beam plus

ESSnuSB, Baseline: 360 & 540 km

L/E = 1200 & 1534 km/GeV

Fiducial mass = 538 kt (WC)

Runtime : 5 years ν + 5 years $\bar{\nu}$

DUNE, Baseline: 1300 km

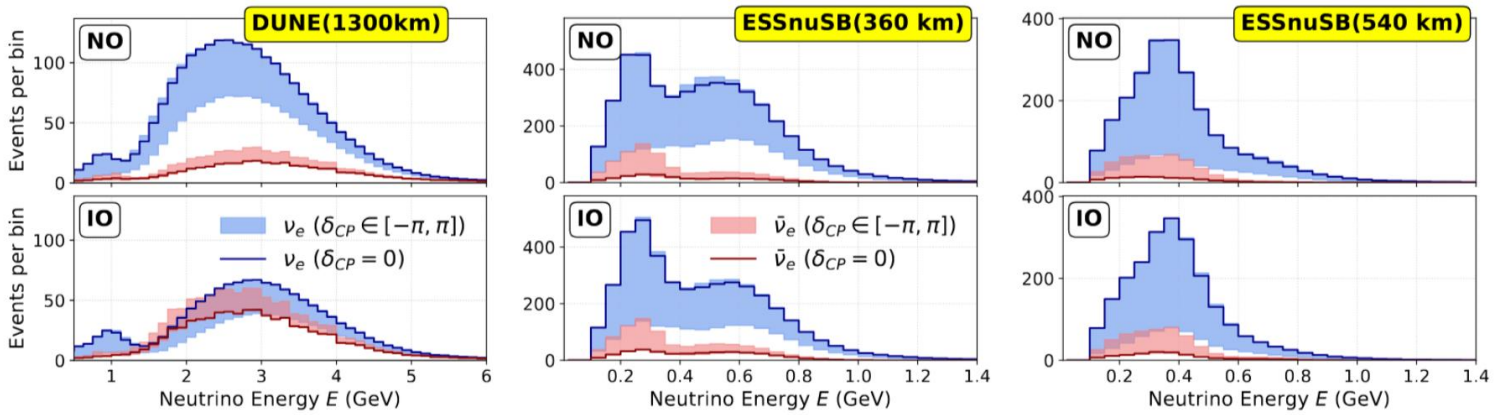
L/E = 1543 km/GeV

Fiducial mass = 40 kt (LArTPC)

Runtime : 6.5 years ν + 6.5 years $\bar{\nu}$

DEEP UNDERGROUND NEUTRINO EXPERIMENT

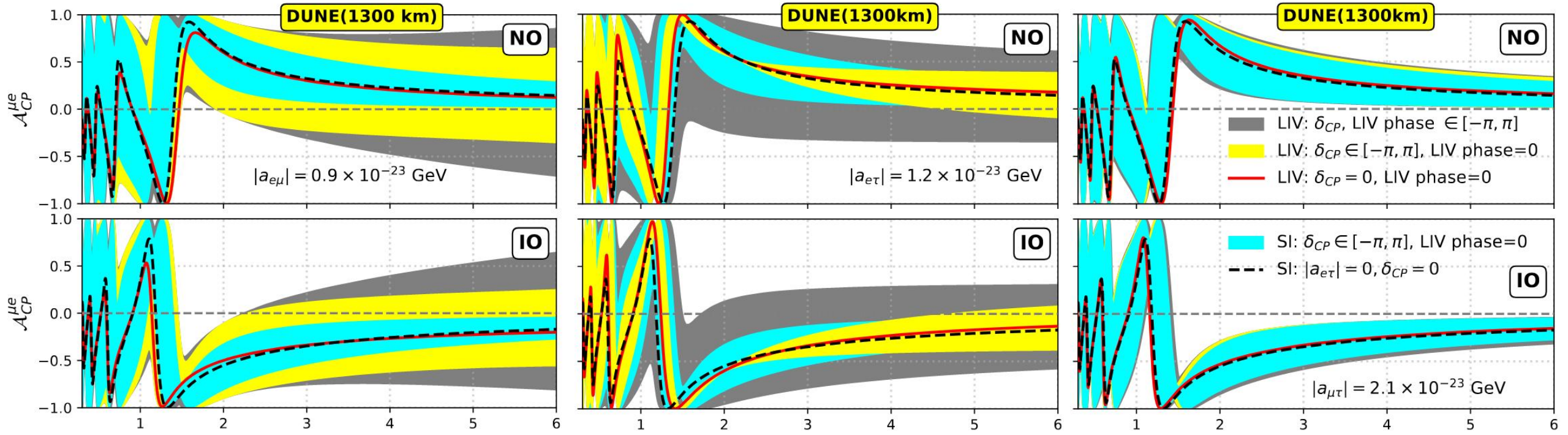
- DUNE has longer baseline (1300 km) compared to the two candidate baselines of ESSnuSB (540 km and 360 km) - DUNE experiences more matter effects

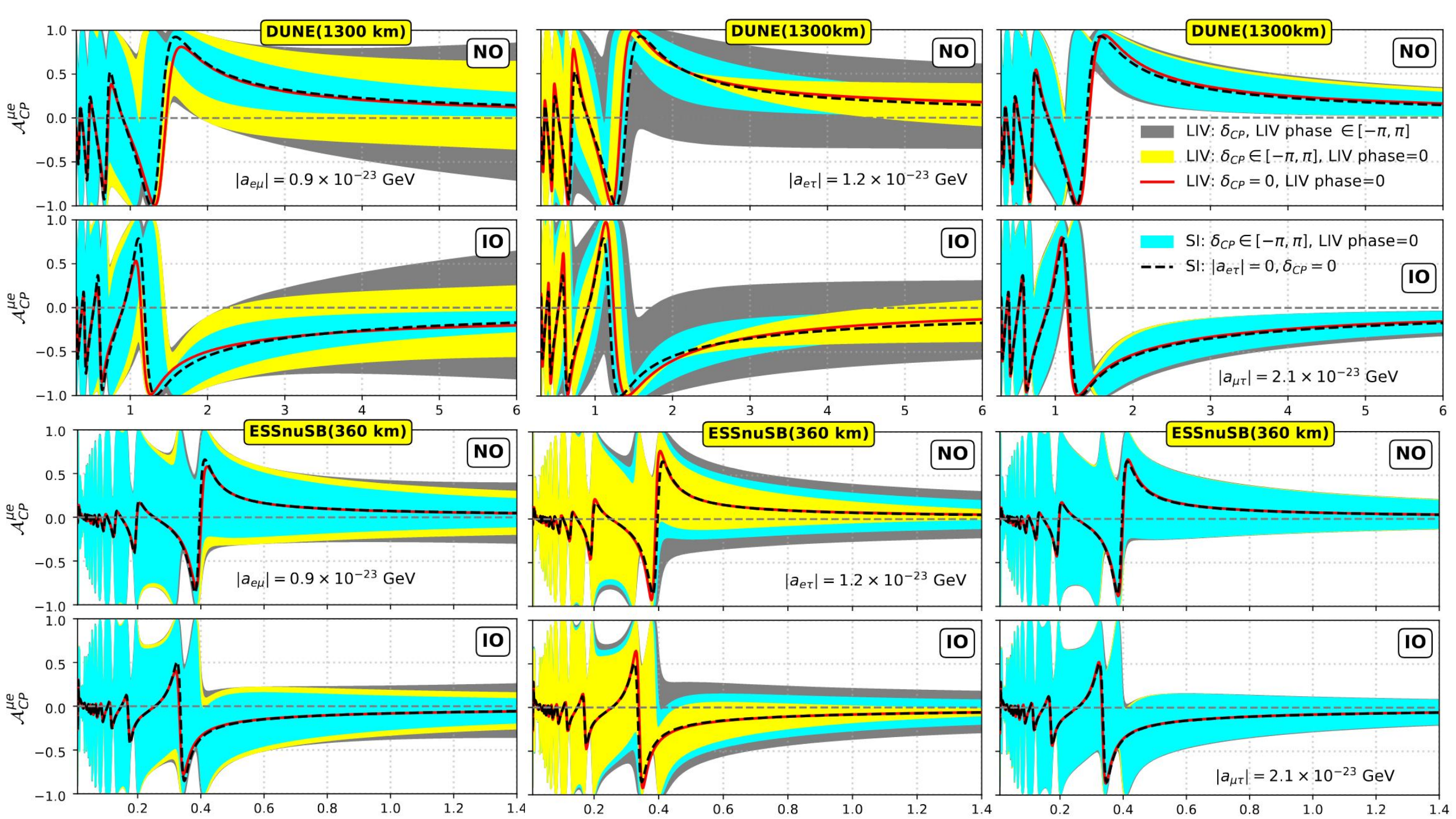


- DUNE sees the first oscillation maximum while ESSnuSB 540km baseline sees second oscillation maximum, 360 km sees the second oscillation maximum as well as a little bit of the first oscillation maximum

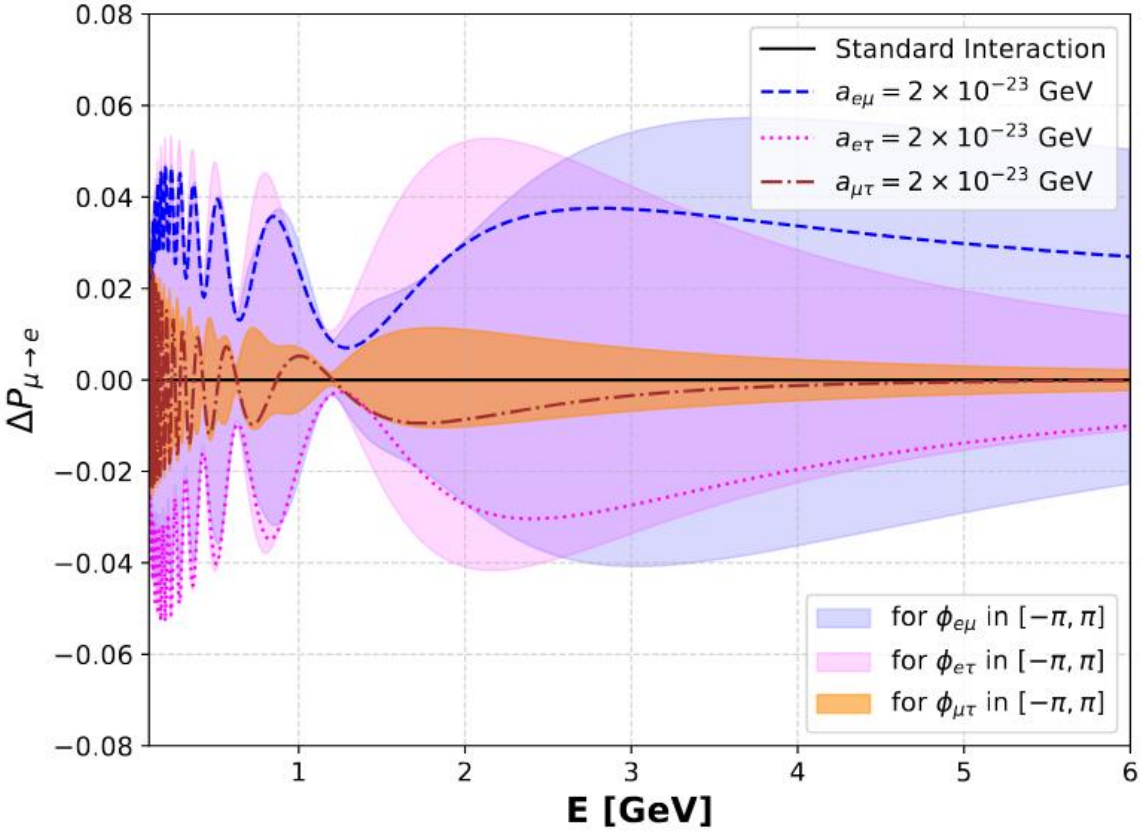
Oscillation Probability in presence of LIV

$$\mathcal{A}_{CP}(E) \equiv \frac{P_{\mu e}(E) - \bar{P}_{\mu e}(E)}{P_{\mu e}(E) + \bar{P}_{\mu e}(E)}$$



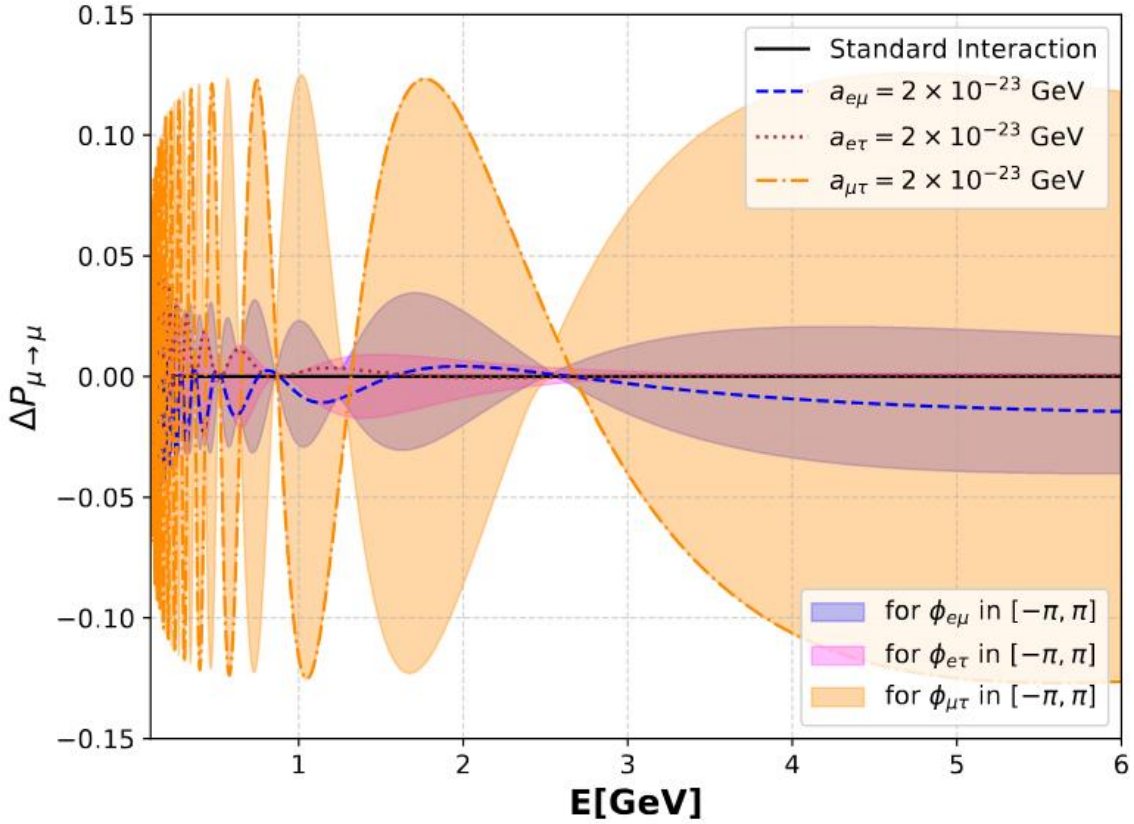

DUNE(1300 km)
NO
IO
$|a_{e\mu}| = 0.9 \times 10^{-23}$ GeV
DUNE(1300km)
$|a_{e\tau}| = 1.2 \times 10^{-23}$ GeV
$|a_{\mu\tau}| = 2.1 \times 10^{-23}$ GeV
LIV: δ_{CP}, LIV phase $\in [-\pi, \pi]$
LIV: $\delta_{CP} \in [-\pi, \pi]$, LIV phase=0
LIV: $\delta_{CP} = 0$, LIV phase=0
SI: $\delta_{CP} \in [-\pi, \pi]$, LIV phase=0
SI: $|a_{e\tau}| = 0, \delta_{CP} = 0$
ESSnuSB(360 km)
$\mathcal{A}_{CP}^{\mu e}$

Oscillation Probability in presence of LIV



$\nu_\mu \to \nu_e$

APPEARANCE



$\nu_\mu \to \nu_\mu$

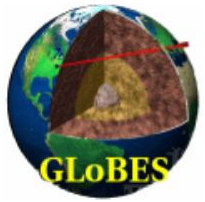
DISAPPEARANCE

ArXiv: 2512.06953 , 10.1007/JHEP08(2026)200

Motivation

- Presence of LIV can severely entangle with standard oscillation probabilities, introducing non-standard phase effects and amplitude modifications.
- These LIV effects can closely mimic variations in standard parameters. This continuous parameter degeneracy leads to incorrect physical interpretations, such as determining a false octant or obscuring the true mass ordering or changing the experiment's ability to accurately determine Dirac CP phase.
- How robust is the experiment's ability to determine the standard oscillation parameters? How much does unaccounted LIV affect the robustness?
- Can our long-baseline experiment discover non-standard LIV phase?

Simulation Software



GLoBES
General Long Baseline Experiment Simulator

GLoBES is maintained by
Patrick Huber, **Joachim Kopp**, **Manfred Lindner**, and **Walter Winter**

Ref.

- Simulation of long-baseline neutrino oscillation experiments with GLoBES
  P. Huber, M. Lindner, W. Winter
  (arXiv:hep-ph/0407333)

- New features in the simulation of neutrino oscillation experiments with GLoBES 3.0
  Patrick Huber, Joachim Kopp, Manfred Lindner, Mark Rolinec, Walter Winter
  (arXiv:hep-ph/0701187v2)

Simulation Parameters

Experiment details	Channels	Normalization uncertainty	
		Signal	Background
ESSnuSB, Baseline: 360 & 540 km			
L/E = 1200 & 1534 km/GeV	$\nu_e(\bar{\nu}_e)$ appearance	5% (5%)	5% (5%)
Fiducial mass = 538 kt (WC)	$\nu_\mu(\bar{\nu}_\mu)$ disappearance	5% (5%)	5% (5%)
Runtime : 5 years ν + 5 years $\bar{\nu}$			
DUNE, Baseline: 1300 km			
L/E = 1543 km/GeV	$\nu_e(\bar{\nu}_e)$ appearance	2% (2%)	5% (5%)
Fiducial mass = 40 kt (LArTPC)	$\nu_\mu(\bar{\nu}_\mu)$ disappearance	5% (5%)	5% (5%)
Runtime : 6.5 years ν + 6.5 years $\bar{\nu}$			

Table 1: Experimental configurations and detector uncertainties for the simulated ESS-nuSB and DUNE setups used in our GLoBES simulation.

Simulation Parameters

Parameter	Reference / benchmark value	Marginalization or scan range
Standard oscillation parameters		
θ_{12}	33.76° (NO, IO)	1σ allowed interval
θ_{13}	8.62°(NO), 8.65°(IO)	1σ allowed interval
θ_{23}	43.29°(NO), 47.90°(IO)	3σ allowed interval
δ_{CP}	-90° (max.); $0, \pm 180^\circ$ (cons.)	$[-180^\circ, 180^\circ]$
Δm^2_{21}	7.537×10^{-5} eV^2 (NO,IO)	1σ allowed interval
Δm^2_{31}	$[2.511(\text{NO}), -2.483(\text{NO}))] \times 10^{-3}$ eV^2	1σ allowed interval
Off-diagonal CPT-odd LIV parameters		
$\lvert a_{e\mu} \rvert$	0.9×10^{-23} GeV	1σ allowed interval
$\phi_{e\mu}$	$0, \pm 180^\circ$ for CP-conserved	$[-\pi, \pi]$
$\lvert a_{e\tau} \rvert$	1.2×10^{-23} GeV	1σ allowed interval
$\phi_{e\tau}$	$0, \pm 180^\circ$ for CP-conserved	$[-\pi, \pi]$
$\lvert a_{\mu\tau} \rvert$	2.1×10^{-23} GeV	1σ allowed interval
$\phi_{\mu\tau}$	$0, \pm 180^\circ$ for CP-conserved	$[-\pi, \pi]$

Table 2: Standard oscillation inputs and off-diagonal LIV benchmarks used in the analysis. The Standard-Interaction reference has $a_{\alpha\beta} = 0$; the non-zero LIV values listed here are used for the benchmark LIV hypotheses.

Simulation Parameters

For the LIV sector, only one off-diagonal coefficient is switched on at a time. The Standard-Interaction reference corresponds to $a_{\alpha\beta} = 0$. When an LIV signal is injected, we use the benchmark magnitudes

$$|a_{e\mu}| = 0.9 \times 10^{-23}\ \text{GeV}, \qquad |a_{e\tau}| = 1.2 \times 10^{-23}\ \text{GeV}, \qquad |a_{\mu\tau}| = 2.1 \times 10^{-23}\ \text{GeV}.$$

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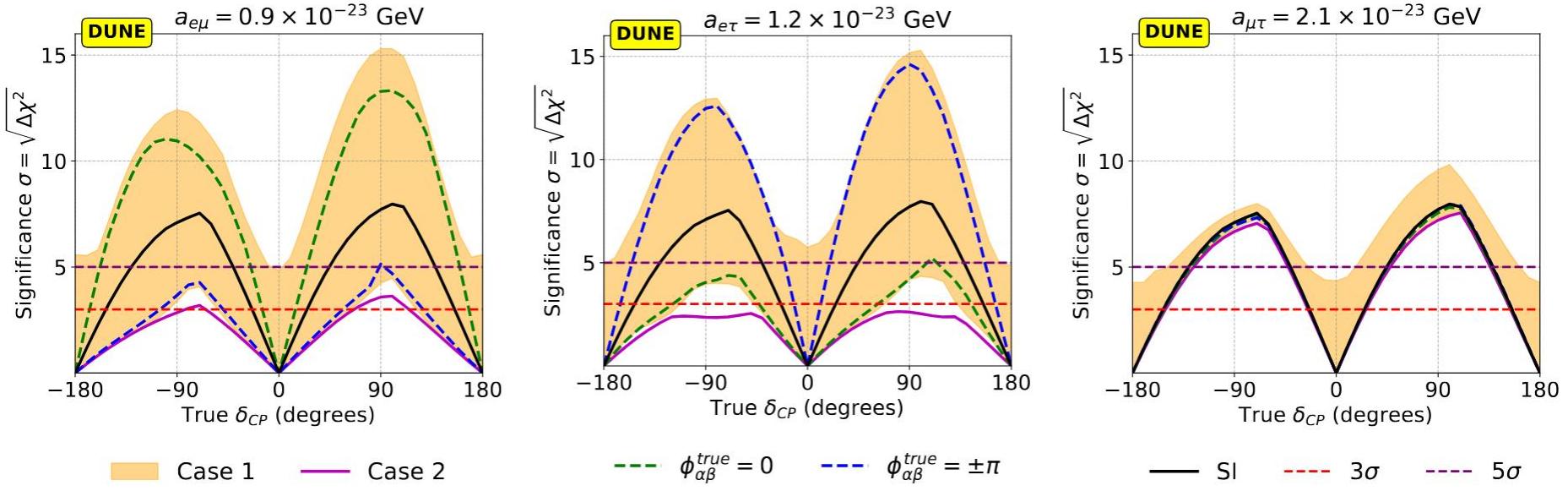
10.1007/JHEP08(2026)200

The LIV phases are allowed to span their complete physical interval $\phi_{\alpha\beta} \in [-\pi, \pi]$.

Off-diagonal CPT-odd LIV parameters		
$\lvert a_{e\mu}\rvert$	0.9×10^{-23} GeV	1σ allowed interval
$\phi_{e\mu}$	$0, \pm 180°$ for CP-conserved	$[-\pi, \pi]$
$\lvert a_{e\tau}\rvert$	1.2×10^{-23} GeV	1σ allowed interval
$\phi_{e\tau}$	$0, \pm 180°$ for CP-conserved	$[-\pi, \pi]$
$\lvert a_{\mu\tau}\rvert$	2.1×10^{-23} GeV	1σ allowed interval
$\phi_{\mu\tau}$	$0, \pm 180°$ for CP-conserved	$[-\pi, \pi]$

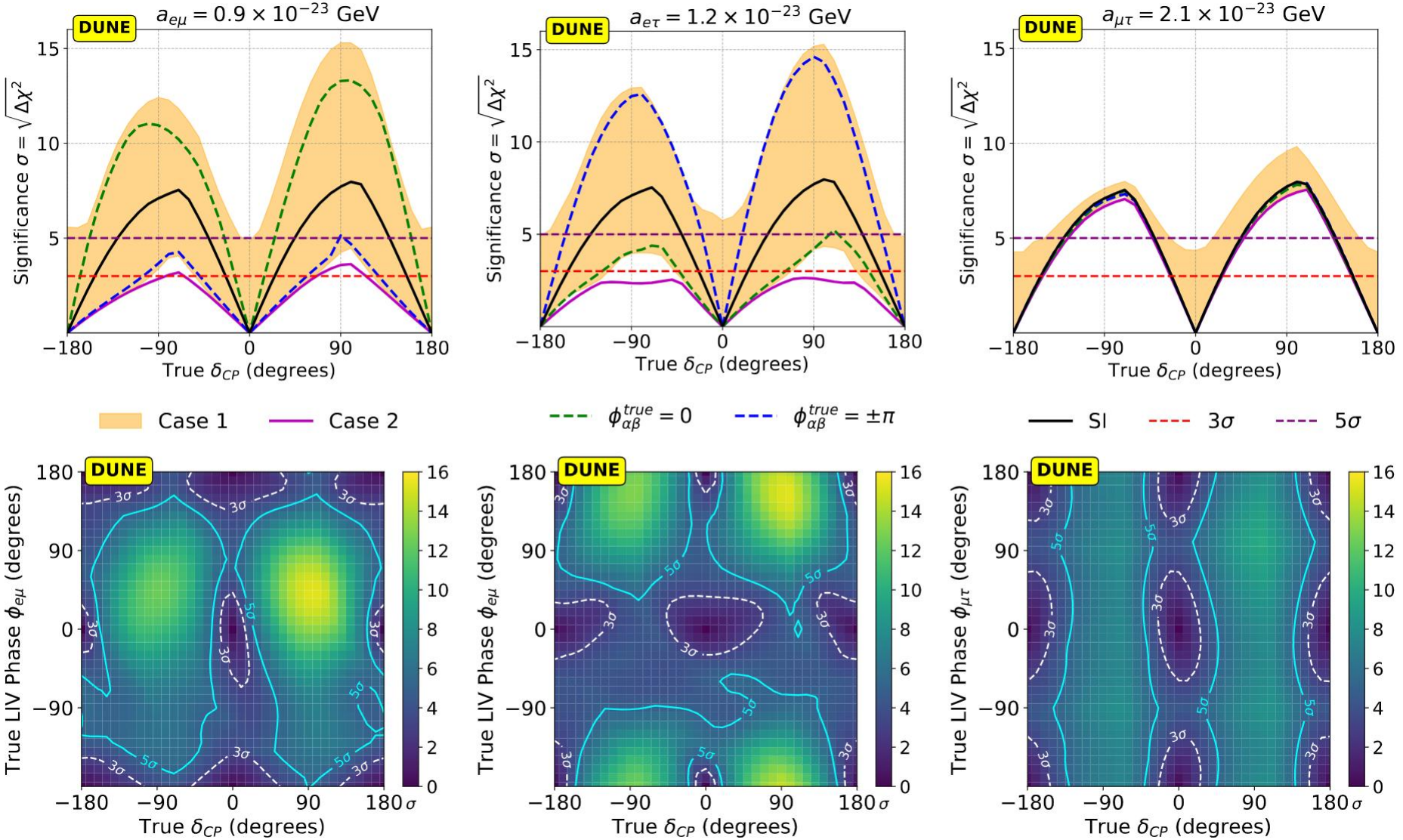
Results (CP Sensitivity)



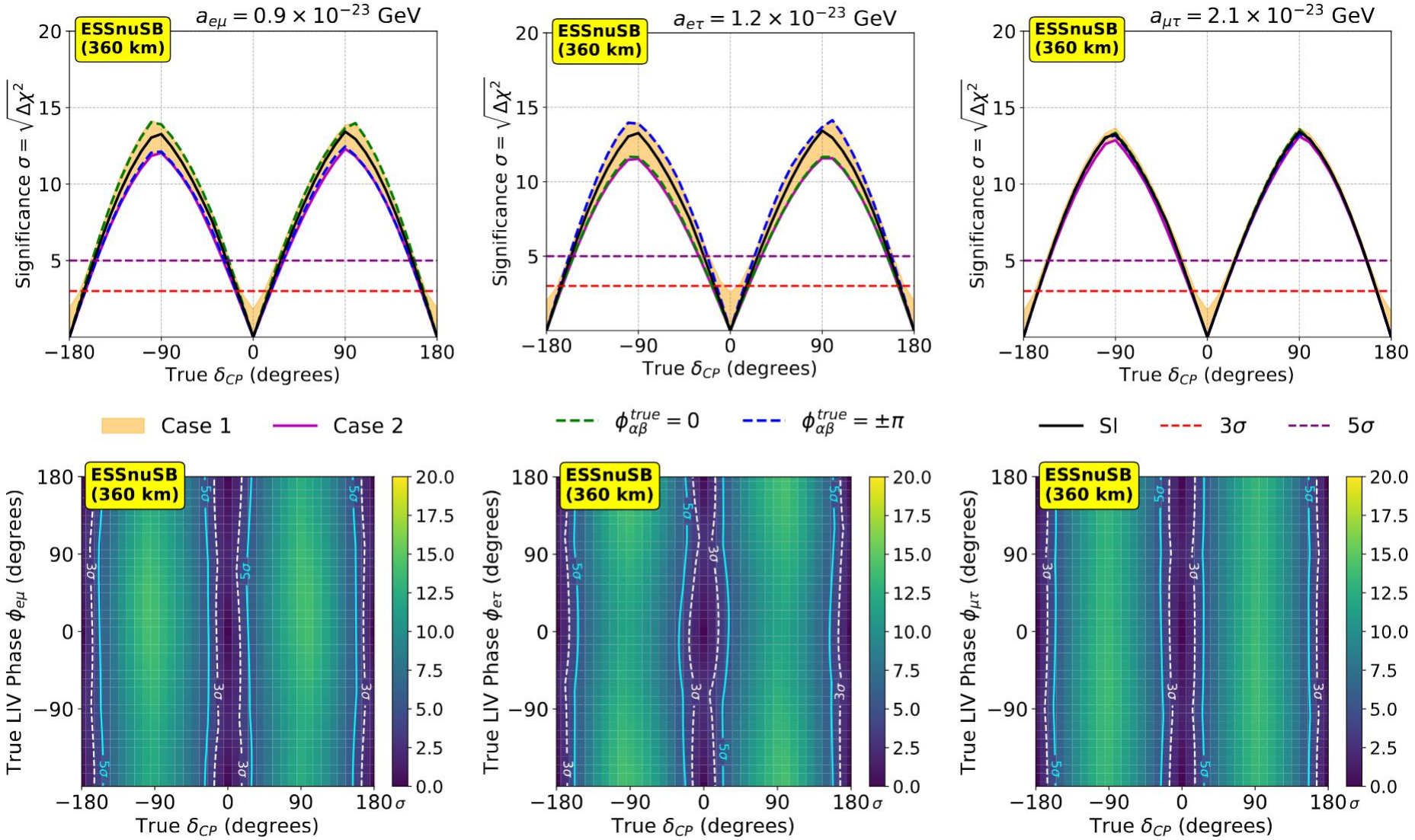
- **Case 1:** CP violation irrespective of its origin, i.e., the overarching capability of an experiment to discover any form of leptonic CP violation, regardless of whether it originates from the standard Dirac phase (δ_{CP}) or the new physics LIV phase ($\phi_{\alpha\beta}$).

- **Case 2:** Standard CP Violation under Unconstrained LIV where the true and the test LIV phase ($\phi_{\alpha\beta}$) are allowed to vary in $\phi_{\alpha\beta} \in [-\pi, \pi]$. The test LIV magnitude ($a_{\alpha\beta}$) is also varied in its 1σ allowed range

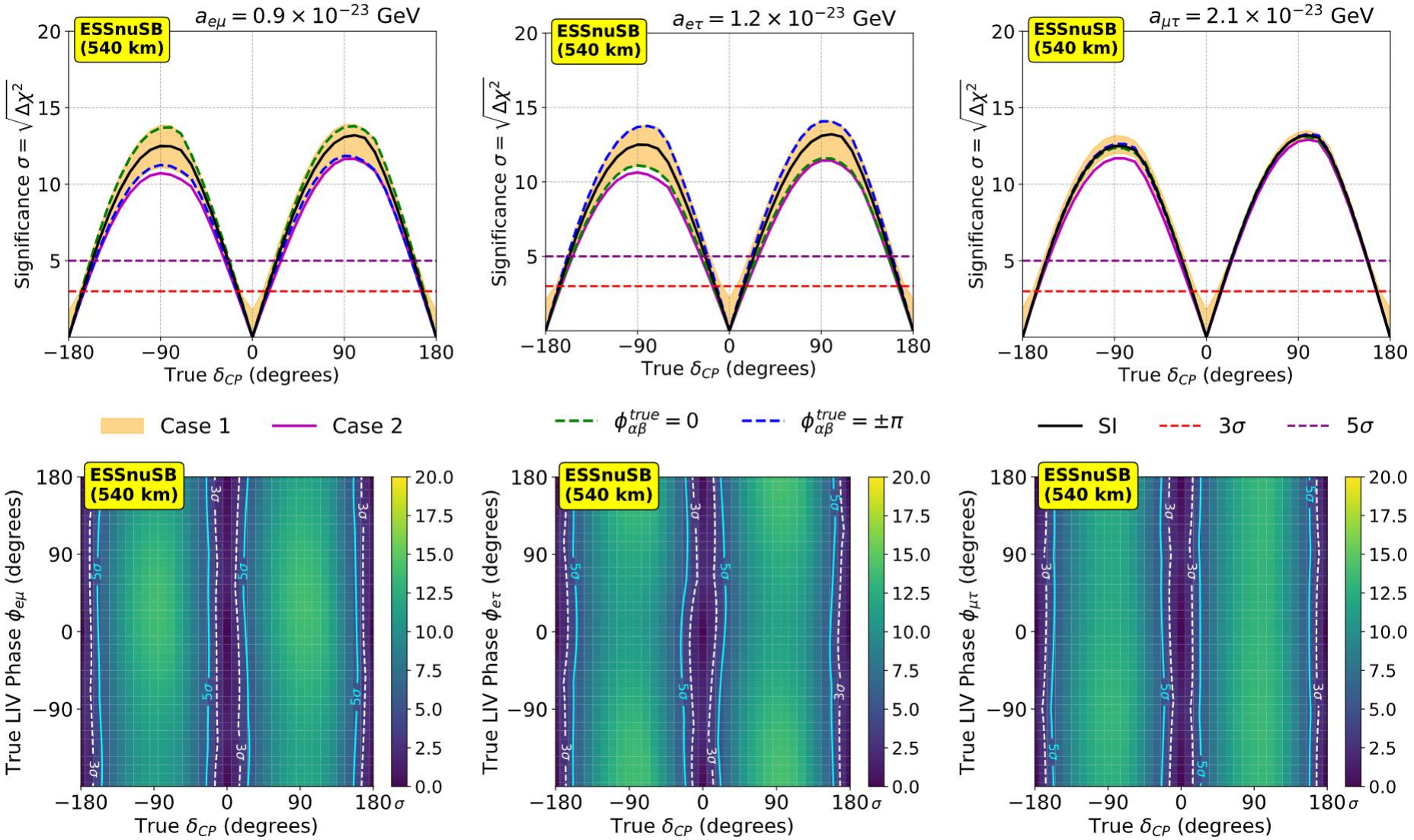
Results (CP Sensitivity)



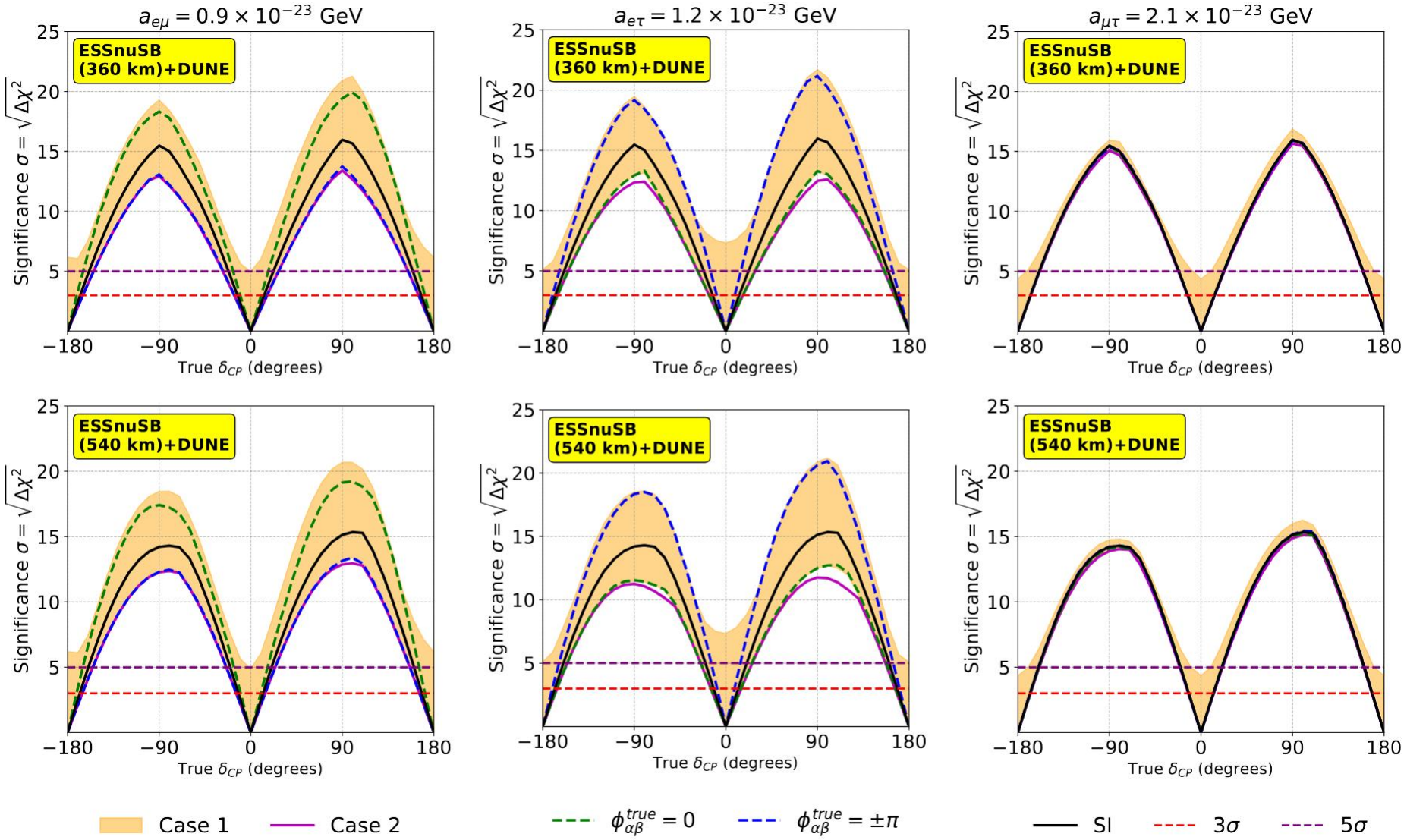
Results (CP Sensitivity)



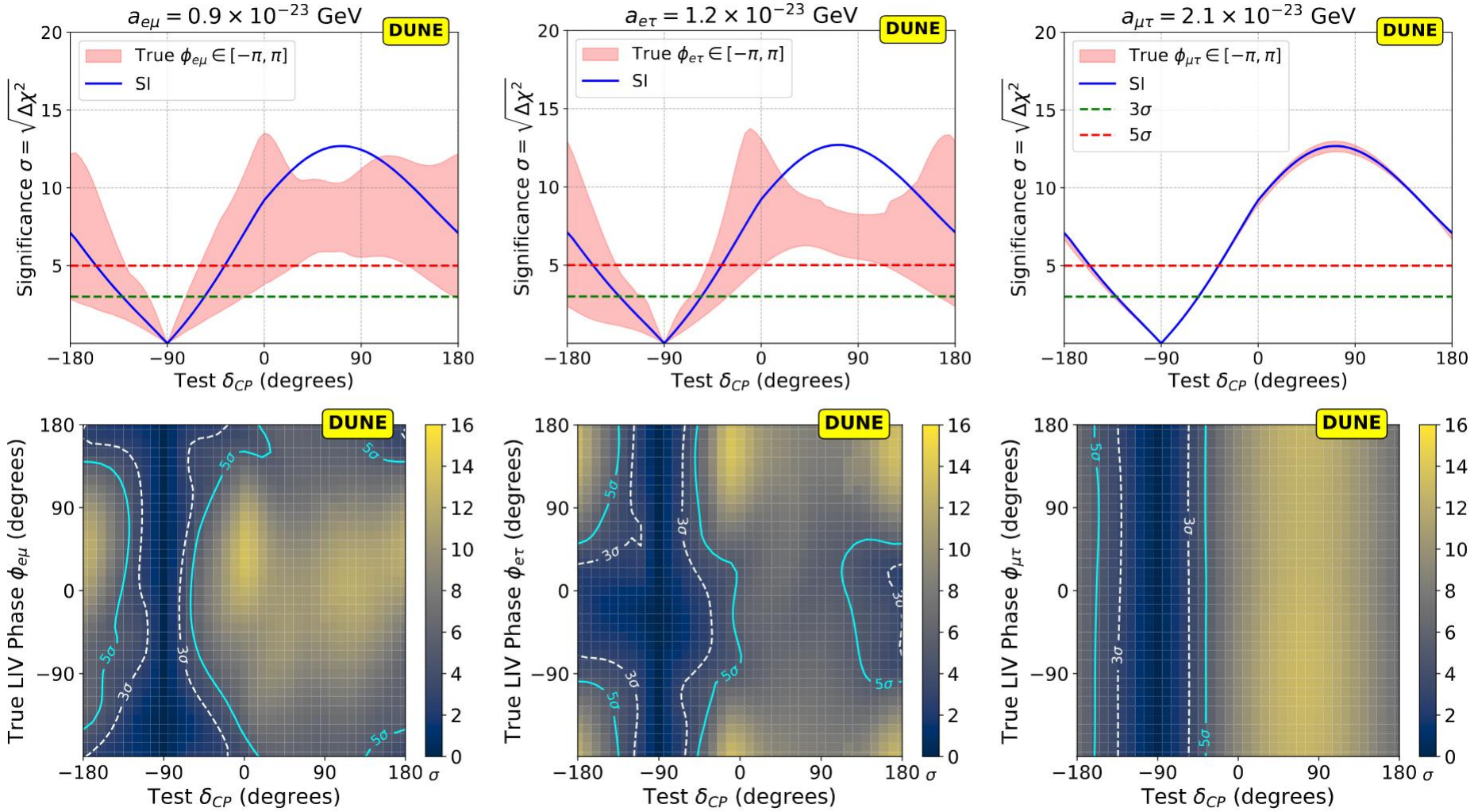
Results (CP Sensitivity)



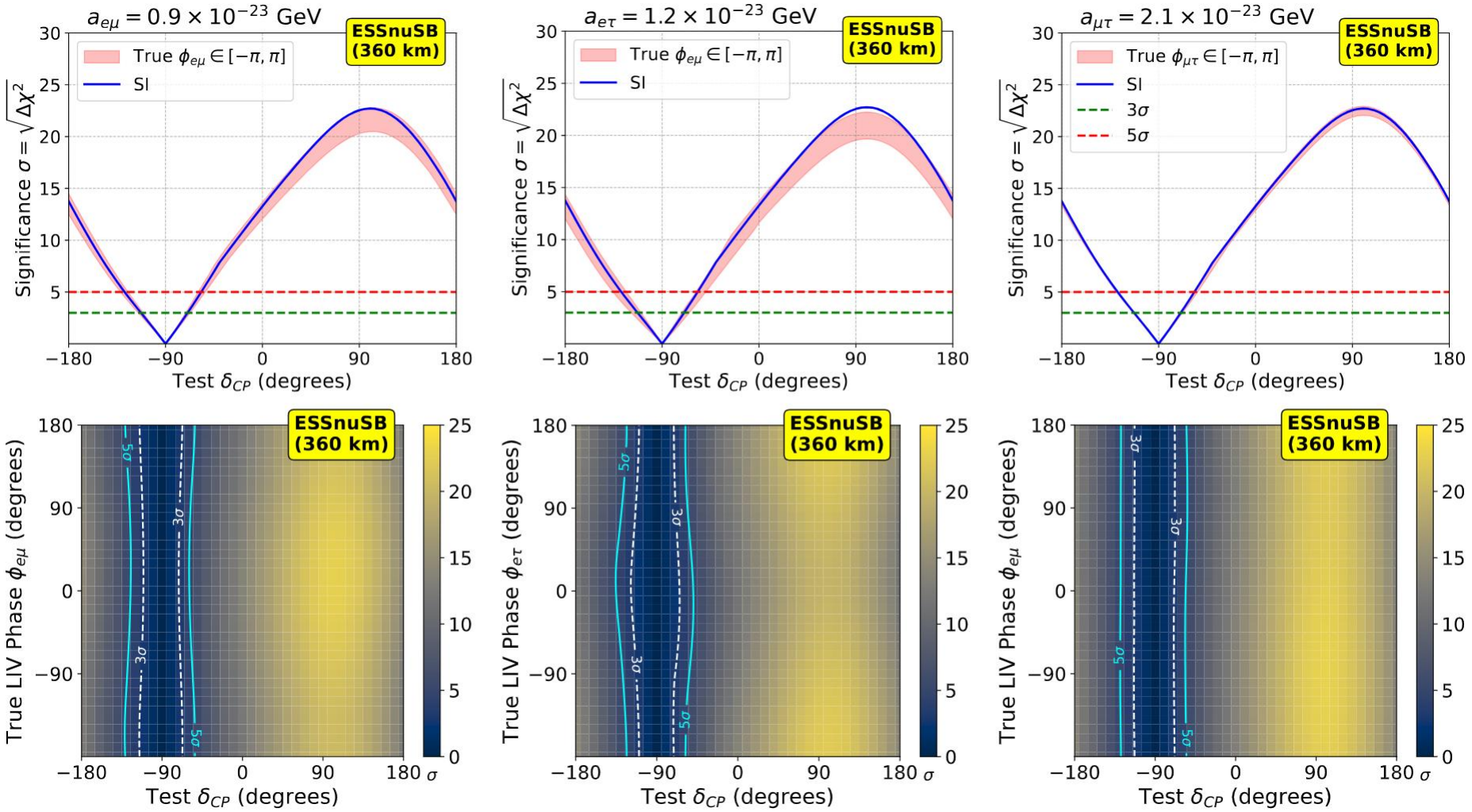
Results (CP Sensitivity)



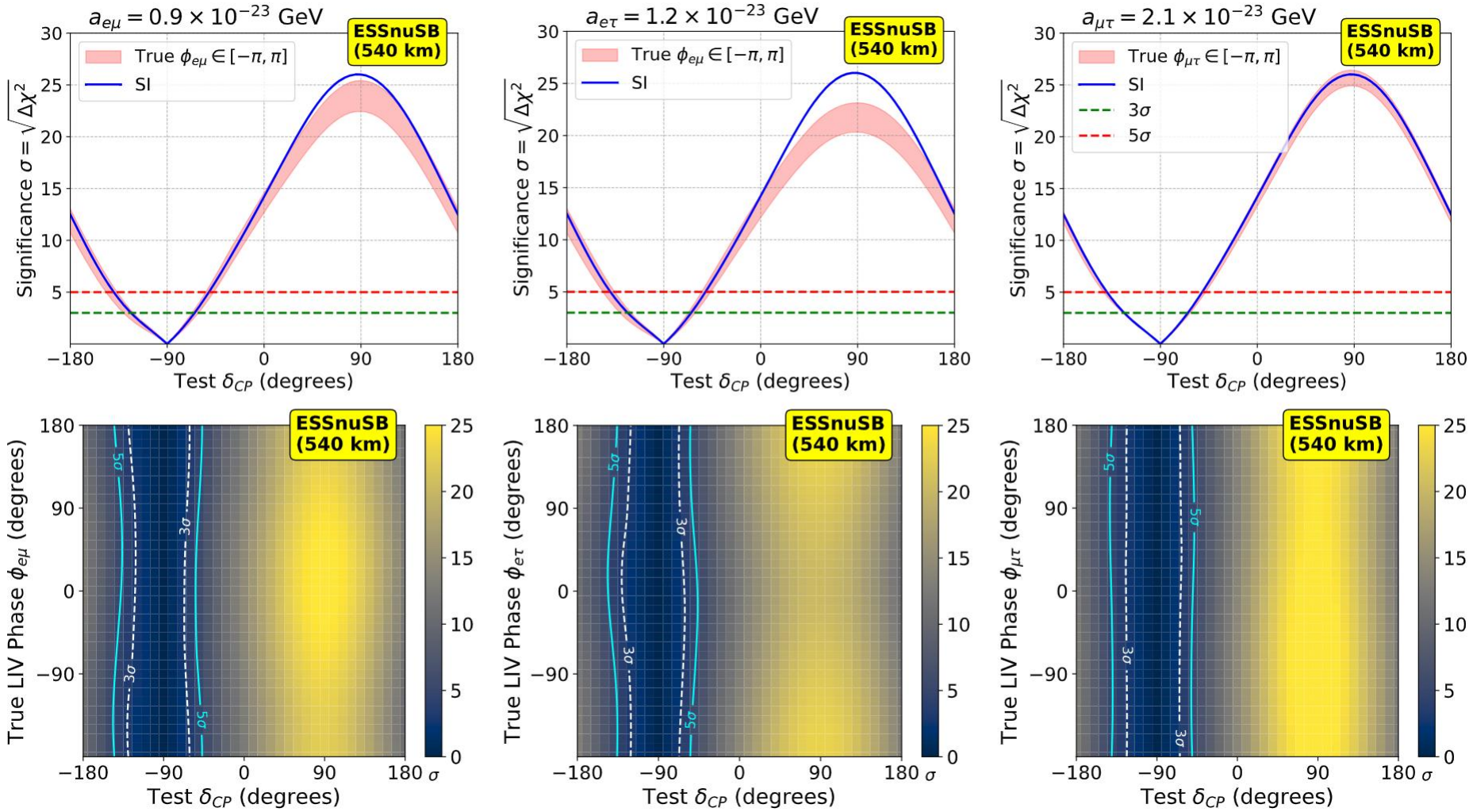
Results (CP Precision)



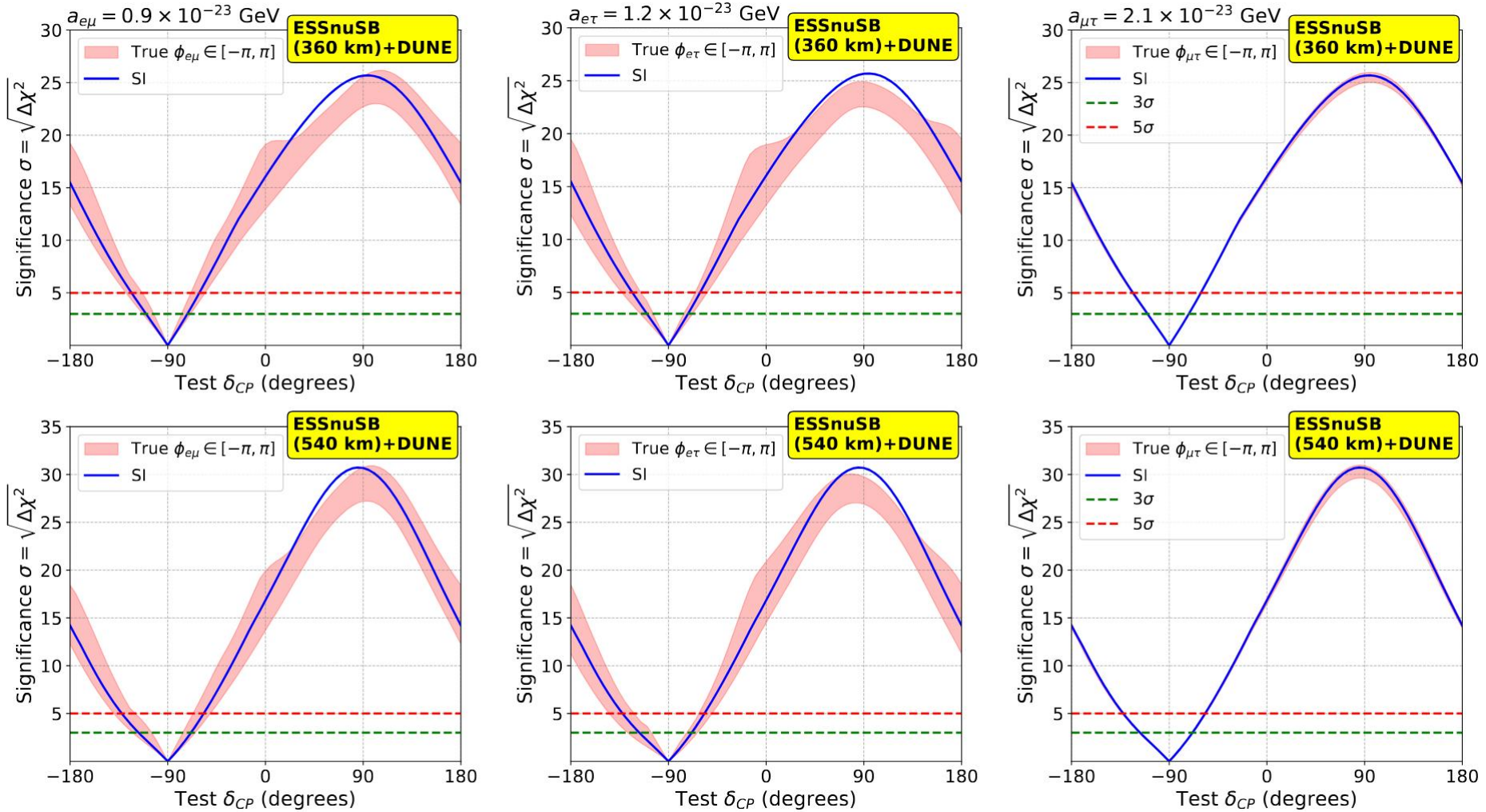
Results (CP Precision)



Results (CP Precision)

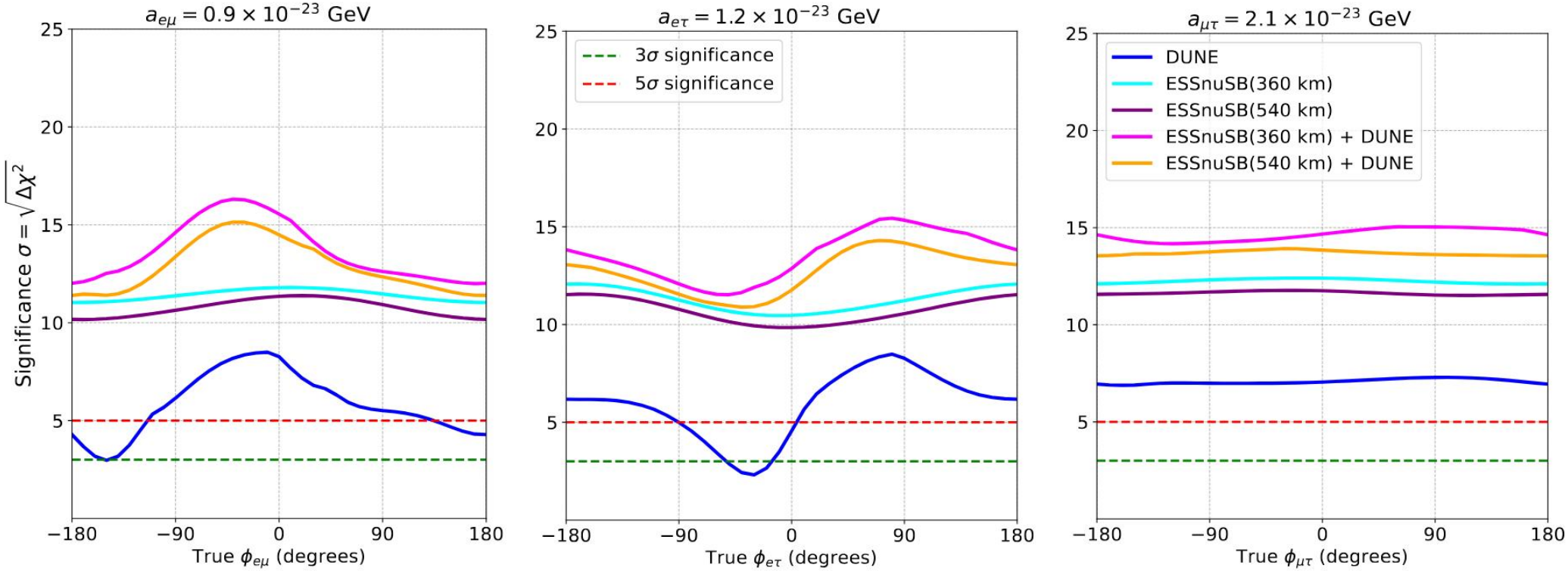


Results (CP Precision)



Results (Risk of False CP Discovery)

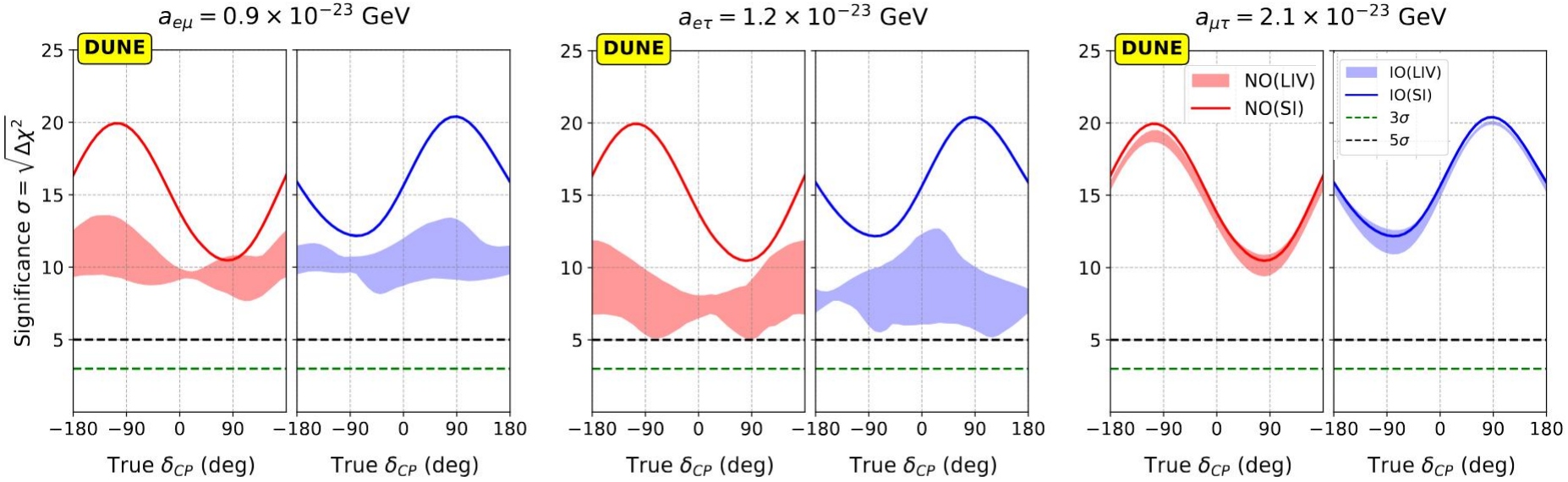
This case strictly tests for severe parameter degeneracies and the critical risk of "CP misidentification." If Nature strictly conserves standard CP ($\delta_{CP}^{\text{true}} \in \{0, \pm\pi\}$), could an unknown true LIV phase ($\phi_{\alpha\beta}$) combine with it to perfectly mimic the signal of a maximally violating standard phase ($\delta_{CP}^{\text{test}} = -90°$)?



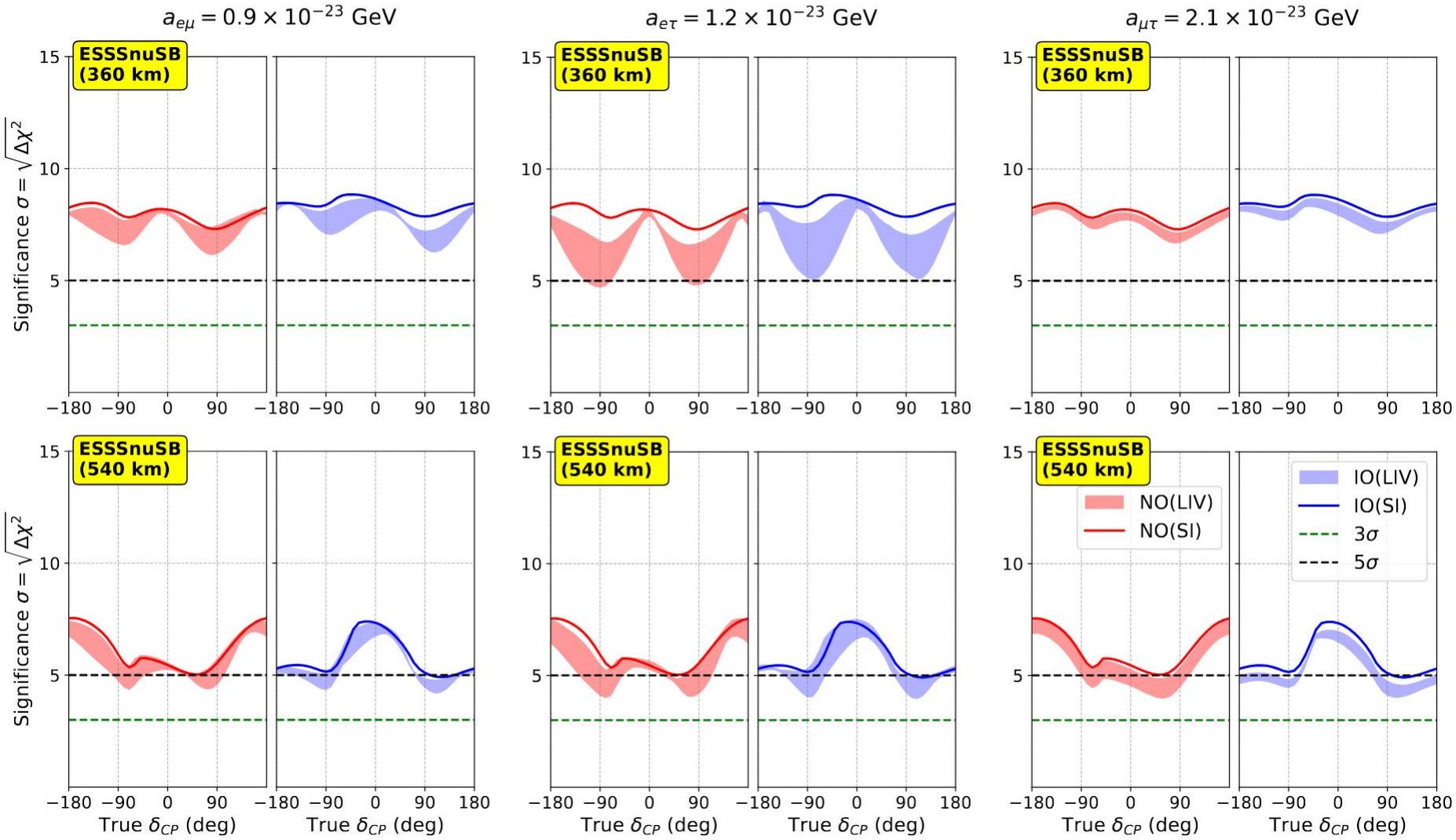
Results (Mass Ordering Sensitivity)

In long-baseline neutrino oscillation experiments, the mass ordering sensitivity is defined as the statistical significance with which the hypothesis of the incorrect neutrino mass ordering can be rejected for a given true mass ordering (NO or IO). We define the mass hierarchy sensitivity as,

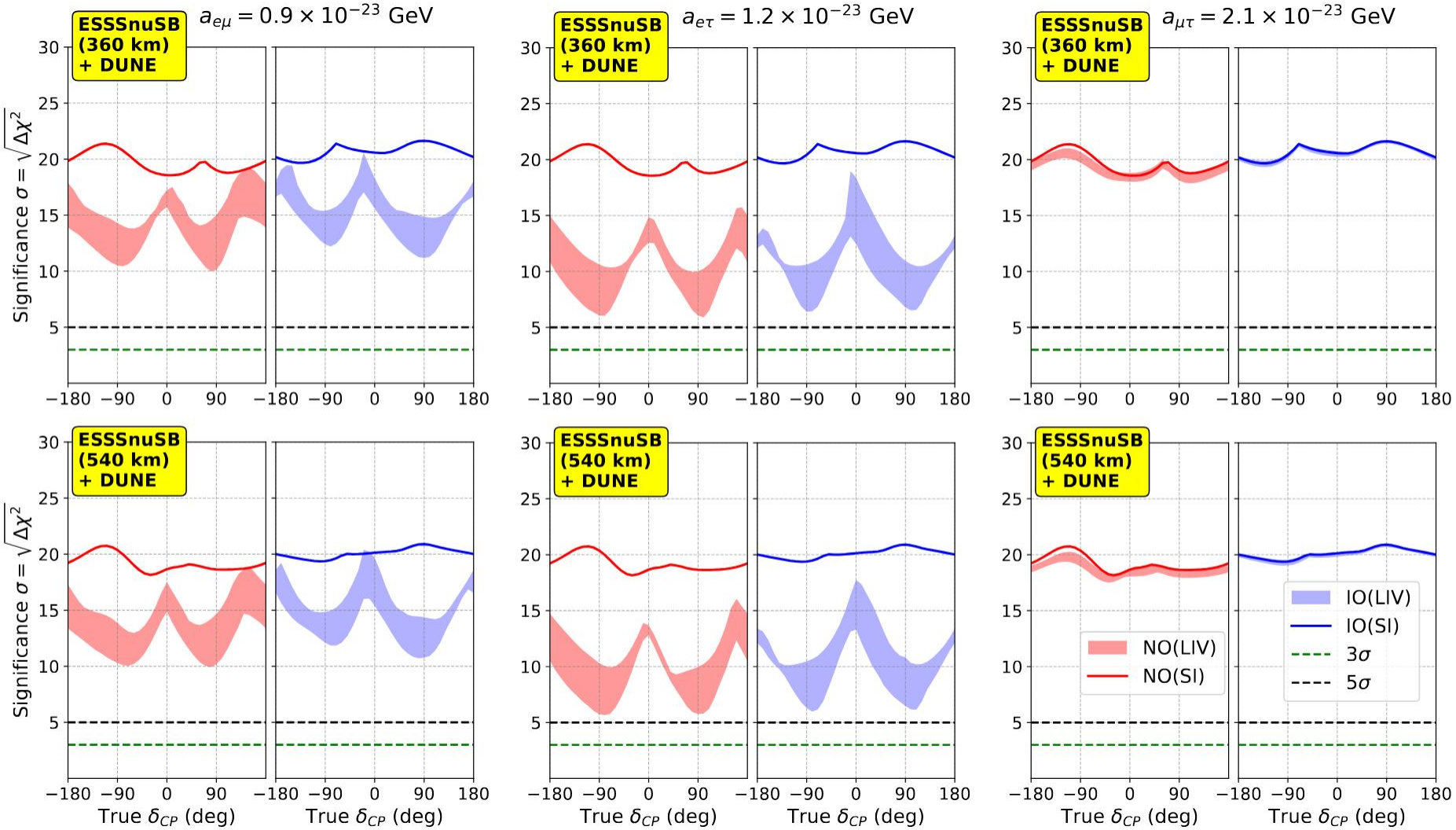
$$\Delta\chi^2\mathrm{MO}(\delta_{\mathrm{CP}}^{\mathrm{true}}) = \begin{cases} \min\left[\chi^2\left(\mathrm{NO}^{\mathrm{true}}(\delta_{\mathrm{CP}}^{\mathrm{true}}), \mathrm{IO}^{\mathrm{test}}\right)\right] & \text{if true ordering is NO,} \\ \min\left[\chi^2\left(\mathrm{IO}^{\mathrm{true}}(\delta_{\mathrm{CP}}^{\mathrm{true}}), \mathrm{NO}^{\mathrm{test}}\right)\right] & \text{if true ordering is IO.} \end{cases}$$



Results (Mass Ordering Sensitivity)



Results (Mass Ordering Sensitivity)



Summary

- CP Violation Sensitivity : ESSnuSB (both 360 and 540 km) better than DUNE (1300 km)
- CP Violation Sensitivity : ESSnuSB 360 km and 540 km baseline performance similar.
- CP Violation Sensitivity : DUNE snergised with ESSnuSB - DUNE’s limitations removed.
- CP Precision Sensitivity : Same as above
- Risk of False CP Discovery : More in DUNE, much lesser in ESSnuSB
- Mass Ordering Sensitivity : DUNE superior to ESSnuSB
- Mass Ordering Sensitivity : ESSnuSB (360km) slightly better than ESSnuSB (540km)

Thanks