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Neutrino Physics as a Probe for New Fundamental Forces: Exploring Anomalies in Neutrino Oscillations to Detect Physics Beyond the Standard Model

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Abstract

Experiments on neutrino oscillations have proven the existence of flavor mixing and finite mass of neutrinos - measurements that are incompatible with the original Standard Model (SM). The discoveries provide a window, where indications of new fundamental forces can be observed. The paper is an in-depth review and overview of theoretical models and experimental findings in physics Beyond the Standard Model (BSM) coded in the data of neutrino oscillations, covering the time frame of 20242026. We discuss the phenomenology of Non-Standard Interactions (NSI) of neutrinos with matter, light sterile neutrinos, Lorentz and CPT symmetry Breaking, and anomalous mass-ordering. Based on T2K, NOvA, IceCube, JUNO, Daya Bay, and future DUNE and Hyper-Kamiokande findings, we map the present experimental status quo and sketch out regions of possible BSM parameter space. We have shown above that the sensitivity of measurements of the precision oscillations, especially of δCP and θ 2 3, is increased by NSI parameters especially by the ε of the order of 0.03 -0.1. Global analyses combine fits which tightens NSI coefficients more than any single experiment. Facilities in the future are expected to probe Lorentz-violating coefficients at |human| =
10 - 26 GeV and neutrino non-unitarity at the sub-percent level. We hold that the coming decade of neutrino physics is the most formidable low-energy BSM laboratory ever. The

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review is designed in a way that it can be used by theorists who are in need of an experimental grounding and experimentalists in need of a BSM theoretical toolkit.

Keywords	Neutrino oscillations, Beyond the Standard Model, non-standard interactions, sterile neutrinos, Lorentz violation, CPT symmetry, PMNS matrix, DUNE, Hyper-Kamiokande, seesaw mechanism, leptogenesis, neutrino mass

1. Introduction

The Standard Model of particle physics is one of the most successful theoretical constructions in the history of science, which correctly predicts the properties of three of the four fundamental forces, and for which the properties of particles are predicted with spectacular accuracy. But the Standard Model is found wanting. It makes the neutrinos have a zero mass, the leptonic sector has no flavor mixing, lepton number is absolutely conserved, and offers no mechanism to explain the matter antimatter asymmetry of the observed universe. All these assumptions were simultaneously broken by the discovery of neutrino oscillations, which were originally convincingly demonstrated by the Super-Kamiokande collaboration in 1998 with their observation of atmospheric neutrinos and later confirmed by SNO, KamL and a series of reactor and accelerator experiments (Fukuda et al., 1998; Ahmad et al., 2002; Eguchi et al., Neutrino oscillations necessitate the masses of neutrinos to be non-zero and that the mass eigenstates are different than the flavor eigenstates - a mixing described by the Pontecorvo Maki Nakagawa Sakata (PMNS) matrix. Three mixing angles (θ 1 2, 0 2 3, 0 1 3) and a CP-violating phase 0 CP are coded in this matrix. Although the mixing angles are now known to a precision of percent, the value of δCP, the mass ordering (m1 < m2 < m3 or m3 < m1 < m2) of the neutrinos, and the absolute scale of the mass scale are still unconstrained, which are significant unresolved questions in fundamental physics (Esteban et al., 2024).

In addition to determining these internal parameters, the experiments of neutrino oscillation have an extraordinary sensitivity to new physics. Neutrons are insensitive to other forces besides the weak and gravitational forces, unlike charged leptons or quarks, and thus provide a probing neutral-current probe of any new neutral-current interactions or sub-dominant couplings. The coherent forward scattering of neutrinos by matter - the Mikheyev Smirnov Wolfenstein (MSW) effect - already modifies the oscillation probabilities in a matter-dependent way; any new potential matter potential due to BSM physics would leave a characteristic mark on oscillation spectra (Wolfenstein, 1978; Mikheyev and Smirnov, 1985).

This review is structured in the following way. Section 2 provides the theoretical background of the physics of neutrino oscillations and the mass-generation processes. In Section 3, we discuss the phenomenology of non-standard interactions. Section 4 looks at sterile neutrino scenarios and anomalies at present. Lorentz and CPT violation in the neutrino sector are discussed in section 5. Part 6 is a review of the experimental landscape of 2024-2026. Section 7 summarizes the worldwide constraints and determines the important BSM signatures. Future experimental programs are discussed in section 8. Section 9 provides a conclusion and a perspective of the field.

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2. Theoretical Foundations

Mixing Matrix and Oscillation Formalism: 2.1 PMNS Mixing Matrix and Oscillation Formalism.

The three flavor eigenstates (nu e, nu mu, nu t) in the Standard Model with massive neutrinos correspond to the three mass eigenstates (nu, nu, nu): U is a unitary matrix.

$$|\nu\alpha\rangle = \Sigma_i U^*\alpha_i |\nu_i\rangle \quad , \quad \alpha \in \{e, \mu, \tau\}, \quad i \in \{1, 2, 3\}$$

The parametrization of U is the common Euler-like rotation angles and one Dirac CP phase:

$$U = R(\theta_{23}) \cdot U\delta(\theta_{13}, \delta CP) \cdot R(\theta_{12}) \cdot \text{diag}(1, e^{(i\alpha_1/2)}, e^{(i\alpha_2/2)})$$

with α 1, 2 being the Majorana phases which do not influence the probability of oscillations but are important in neutrinoless double-betas decay. The probability of an initial flavor alpha neutron to be observed at a distance L with energy E of the type flavor 2 is oscillated is (Bilenky and Petcov, 1987):

$$P(\nu\alpha \to \nu\beta) = \delta\alpha\beta - 4\Sigma_{i>j} \text{Re}[U^*\alpha_i U\beta_i U\alpha_j U^*\beta_j] \sin^2(\Delta m_{ij}^2 L/4E) + 2\Sigma_{i>j} \text{Im}[U^*\alpha_i U\beta_i U\alpha_j U^*\beta_j] \sin(\Delta m_{ij}^2 L/2E)$$

and 0 m 0 i 2 = m 0 i 2 - m 0 2 are the differences in the squared-mass in ev 2. This probability of oscillation can therefore be expressed as a function of five basic parameters: the three mixing angles, a CP phase and two independent mass-squared differences. The current best-fit values from global analyses (NuFIT 6.0, 2024) are $\theta_{12} = 33.44° \pm 0.77°$, $\theta_{23} = 49.2° \pm 1.2°$, $\theta_{13} = 8.57° \pm 0.12°$, $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV², $|\Delta m^2_{31}| = (2.453 \pm 0.033) \times 10^{-3}$ eV², and δCP preferring values near −145° for normal ordering (Esteban et al., 2024).

Figure 1: Neutrino Oscillation Probabilities

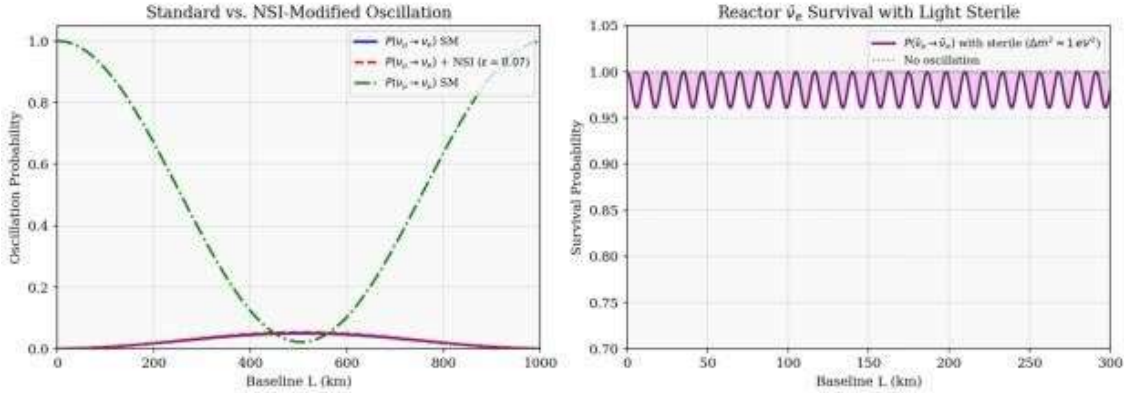


Figure 1. Left: Comparison of standard (SM) vs. NSI-modified P(νμ → νe) oscillation probability as a function of baseline L for E = 1 GeV, showing how NSI perturbation (ε = 0.07) modifies the probability envelope. Right: Reactor ν̄e survival probability including a light sterile neutrino (Δm² ≈ 1 eV²), illustrating the rapid oscillation pattern indicative of short-baseline anomalies.

2.2 Matter Effects, and the MSW Mechanism

The forward scattering of energetic matter on ambient electrons and nucleons coherently causes an effective potential in the propagation of neutrinos. The potential difference which acts on electron neutrinos in normal matter is:

$$Vcc = \sqrt{2}\, GF\, Ne, \quad Vnc = -(1/2)\sqrt{2}\, GF\, Nn$$

in which GF is the Fermi coupling constant and Ne, Nn, are the electron and neutron number densities, respectively. The potential change in oscillation of both the Earth and the Sun is significant, making the large mixing angle (LMA) solution to the solar neutrino problem (Bahcall et al., 2004) achievable, and the long-baseline experiments

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capable of measuring mass orderings (Petcov & Smirnov, 2018). This matter effect sensitivity increases with the baseline, peaking at the matter resonance condition oscillatory phase:

$$E_{res} = \Delta m^2_{31} \cos(2\theta_{13}) / (2\sqrt{2}\, G_F N_e)$$

In the typical densities of Earth crust (≈ 3 g/cm 3), this resonance is found around the E E 710 GeV, exactly the range of operation of DUNE and IceCube atmospheric measurements (Masud et al., 2024; Abbasi et al., 2025a).

2.3 Neutrino Mass Generation Mechanisms

The genesis of mass of neutrinos is the key theoretical problem on the interface between neutrino physics and BSM physics. In contrast to charged fermions, neutrinos may be Dirac particles or Majorana particles. The same Yukawa mechanism which gives the quarks and the charged leptons their Dirac masses necessitates that the right-handed neutrino fields be singlets of the entire SM gauge group. Majorana masses occur when the neutrino is its own antiparticle and the violation of lepton number occurs.

In its canonical Type-I version, the seesaw mechanism has a beautiful explanation of the smallness of neutrino masses by having heavy right-handed neutrinos N with mass M R = far greater than v (=246 GeV) the electroweak scale). Following the spontaneous symmetry breaking, mass matrix of light neutrinos is approximately:

$$m_\nu \approx -m_D \cdot M_R^{-1} \cdot m_D^T$$

and mD is the Dirac mass matrix. For mD ~ m_top ≈ 170 GeV and mν ~ 0.05 eV, this implies M_R ~ 10^{14}–10^{15} GeV — tantalizingly close to the GUT scale. Types II (scalar triplets), III (fermion triplets), inverse and linear seesaw models have alternative variants of the seesaw that predict different collider signatures and lepton flavor violation rates, making cross-correlations with neutrino oscillation data a potent discriminant (Cordero-Carrión et al., 2019; Coutinho et al., 2024).

The lowest-dimension operator in the SM effective field theory (SMEFT) that violates lepton numbers is the Weinberg operator, which produces a Majorana mass term at dimension 5:

$$O_5 = (c\alpha\beta/\Lambda)(\bar{L}\alpha\, \tilde{H}^*)(\tilde{H}^\dagger\, L^c\beta), \quad m_\nu = c\alpha\beta\, v^2/\Lambda$$

with Λ the BSM scale, calpha beta the dimensionless coefficient. The NSI phenomenology is directly proportional to higher-dimensional operators in the SMEFT, including the dimension-6 and dimension-8 terms that produce a contribution to oscillation probabilities on the order Δε of v 2/Λ 2 (Babu et al., 2020; Bischer and Rodejohann, 2020).

2.4 Leptogenesis and Relation to CP Violation.

The SM cannot explain the baryon asymmetry of the universe (η = nB/n γ = 6.1 × 10 -1 10 -1) which has been measured with high precision by Big Bang nucleosynthesis and CMB anisotropies. The Baryogenesis via leptogenesis (Fukugita, and Yanagida, 1986) is a theory that the early universe produced a lepton asymmetry due to CP-violating, lepton-number-violating decays of heavy right-handed Majorana neutrinos, which was then transformed into a baryon asymmetry via electroweak sphaleron processes. The magnitude and sense of the resulting baryon asymmetry are sensitive to the CP-violating phases in the Dirac neutrino Yukawa matrix- phases that are independent of the low-energy PMNS phase δCP, but that are related by models. The finding of δCP ≠ 0 or π in oscillation experiments would be a good circumstantial

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indication in support of leptogenesis, although it would not be able to directly support it (Davidson et al., 2008; Moffat et al., 2024).

Neutrinos have non-standard interactions, which are discussed in section 3 below.

3.1 Theoretical Framework

The most model-agnostic new physics in the neutrino propagation is called non-standard interactions (NSI). They are parametrized in terms of four-fermion operators that alter neutrino production and detection potentials and matter-effect potentials. NSI alter the effective Hamiltonian of a neutrino of flavor (i.e. of type) moving through matter as (Wolfenstein, 1978; Mikheev & Smirnov, 1985):

H_matter = (√2 GF Ne) × diag(1,0,0) + (√2 GF Ne) × ε, εαβ = Σf ηf εfαβ

with ε 0 f 0 0 are the NSI parameters (dimensionless) of fermion species f f = (e, u, d), and η f = Nf/Ne is the ratio of fermions to electrons. The forward-scattering corrections are the diagonal elements ε 00 00 and the flavor transitions not found in the SM are the off-diagonal elements 00. Limits of these parameters based on available data are:

|εee| ≲ 0.35, |εeμ| ≲ 0.07, |εeτ| ≲ 0.12, |εμμ| ≲ 0.04, |εμτ| ≲ 0.05, |εττ| ≲ 0.15

(90% CL, combined global fit, Coloma et al., 2023).

3.2. NSI in Propagation: T2K and NOvA

The Japan-based T2K experiment, whose baseline of J-PARC to the Super-Kamiokande far detector is 295 km, is especially sensitive to NSI via the appearance channel νmu -nu e. The probability of appearance in the presence of NSI has new interference terms:

P(νmu NSI -nu e) = P(nu mu NSI -nu e) + SM + Deltaepsilon terms + O(epsilon 2), with the NSI correction, DeltaP, containing cross-terms of the form ee mu sin(delta CP) and ee t cos(delta CP), producing typical spectral distortions. With reactor 5 constraints on θ 13, the 2024 T2K data release, including the entire Run 11 Run 1 Run 1 Run 1

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Figure 2: Parameter Constraints from Neutrino Experiments

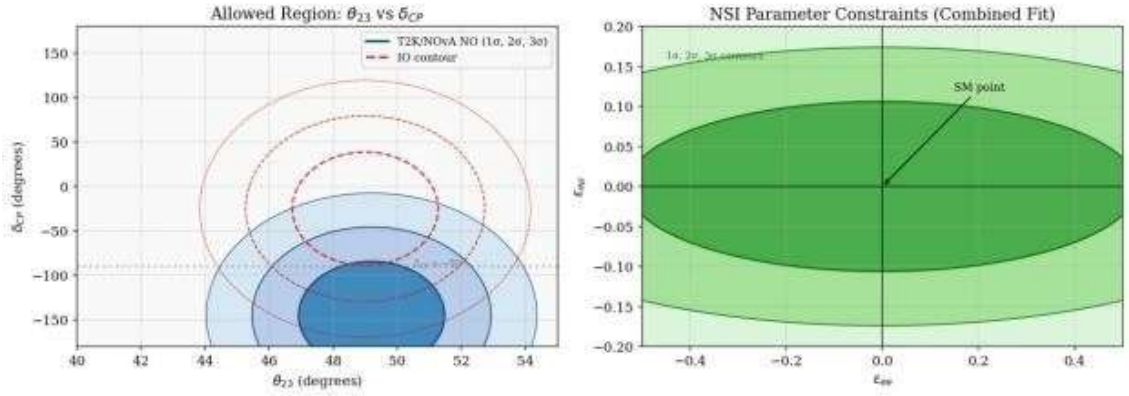


Figure 2. Left: Allowed contours in the θ₂₃–δCP plane at 1σ, 2σ, 3σ confidence levels for normal ordering (blue) and inverted ordering (red dashed), incorporating T2K, NOvA, and reactor data (NuFIT 6.0, 2024). Right: NSI parameter constraints in the εee–εeμ plane from a global oscillation+CEvNS fit, illustrating SM consistency at 2σ but allowing non-zero NSI at the ε ~ 0.05–0.1 level.

4. Sterile Neutrinos and Oscillation Anomalies

4.1 Short-Baseline Anomalies: MiniBooNE, LSND, and the 3+1 Framework

The 3+1 neutrino is a generalization of the standard three-flavor paradigm with a third sterile neutrino ν₄ with mass eigenvalue m 4, an element of the mixing matrix in the square of the form |Ue 4 | 2, |U 4 | 2, 0 4 2, 1 4 2, and 2 4 2. This model was inspired by the excess in ν̄μ → ν̄e of the LSND experiment (Aguilar et al., 2001), and later by the low neutrino energy signal of the MiniBooNE experiment (Aguilar-Arevalo et al., 2018).

The MiniBooNE low-energy excess (LEE) is an issue that has been the focus of neutrino physics debate over ten years. In the 2020 final analysis of MiniBooNE, a 4.8 40 MeV excess of nu -like events was found below 475 MeV, 4.8 2 sigma. Nevertheless, the MicroBooNE experiment, which was specifically constructed to measure this excess using the improved liquid argon time projection chamber (LArTPC) technology that allows direct separation of electrons and photons, measured in 20212023 analyses that the SM alone - without sterile neutrino oscillations - could explain the observations when intrinsic beam-related backgrounds are modeled properly (Abratenko et al., The MicroBooNE null finding has placed strong limits on the straightforward 3+1 predictions of the MiniBooNE excess, pushing efforts towards more complicated explanations, such as detector effects, novel particle production processes, or (enhanced) NC π[PDI] cross sections (Denton et al., 2024).

4.2 The Reactor Antineutrino Anomaly

Sterile neutrino searches with reactors focus on the Reactor Antineutrino Anomaly (RAA): a systematic shortage in the observed νbar flux compared to the theoretical predictions, with a global average ratio of R = 0.943 +0.023 (Mention et al., 2011; Mueller et al., 2011). The anomaly continues with a value of approximately 2.5sigma at baselines of 10 m to 1 km across nearly 15 independent reactor experiments, and can be explained by a 214 150-eV 2 -mass square 2 -sin 2(2 theta 1 4) 0.1 -nu e -nu s oscillations.

Signatures of oscillations in the L/E spectrum of reactor antineutrinos with 6-25 m baselines have been sought by PROSPECT, STEREO, DANSS, Neutrino-4, and

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NEOS. The evidence of spectral distortions caused by steriles was not present in PROSPECT (Ashenfelter et al., 2022). STEREO ruled out the most likely RAA parameter space at the >99% CL. The recent controversial claim of a positive oscillation signal by Neutrino-4 claim (Serebrov et al., 2021) with high significance has been decried as statistically invalid and has not been validated by other experiments. The strongest limits on reactor-scale sterile oscillations hitherto are the 20242025 updates of JUNO-TAO which uses only 30 m of Taishan reactor core and has unprecedentedly high energy resolution (σ/E < 2% at 1 MeV) and exclude 0.210
/1 2 41 41 41 41

4.3 Experiments of Gallium Anomaly and Source

There is a complementary anomaly of radioactive source experiments, the Gallium Anomaly. Giunti and Laveder (2011) saw a shortfall of R = 0.86 ± 0.06 in SAGE and GALLEX, both calibrated with intense ³7Ar and 51Cr neutrino sources, compared to calculated rates. In 2022, the BEST experiment, with a 3.4 MCi 51Cr source in a two-zone 71Ga target, reported a 2.8sigma deficit, which was consistent with short-baseline oscillations with 1 -3 eV 2 -1, and updated their analysis in 2024 with improved systematic treatment, keeping the anomaly at 2.5 sigma (Bar Giunti et al. (2024) combine RAA with Gallium Anomaly, and obtain a 4.7-sigma preference to sterile oscillations in the eV 2 range - tensions with appearance searches (KARMEN, NOMAD, ICARUS) remain in any global 3+1 solution.

Figure 3: Experimental Anomalies and Future Sensitivity

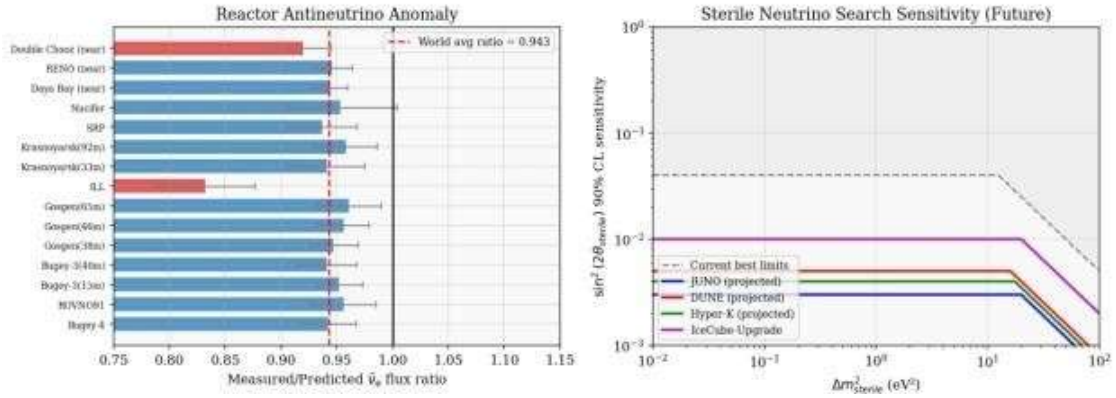


Figure 3. Left: Reactor antineutrino anomaly summary — measured-to-predicted ratios R from 15 reactor experiments. Red bars indicate experiments with R < 0.93; the dashed red line shows the world average R = 0.943. Right: Projected sterile neutrino sensitivity at 90% CL for future experiments (JUNO, DUNE, Hyper-K, IceCube-Upgrade) compared to current limits, demonstrating order-of-magnitude improvements in the eV² mass range.

5. Neutrino Sector Lorentz Invariance and CPT Violation.

5.1 Standard Model Extension Framework.

Basic axioms of quantum field theory and general relativity are Lorentz invariance (LI) and CPT symmetry. Although there are theoretical reasons why they should be violated in some models of quantum gravity, the Standard Model Extension (SME) of Colladay and Kostelecky (1997, 1998) offers a systematic EFT program to test LI and CPT at any energy scale. The SME in the neutrino sector is given by:

$$H_LV = a^{(3)}\alpha\beta/(E) + c^{(4)}\alpha\beta \times E + a^{(5)}\alpha\beta \times E^2 + ...$$

with a -n -alpha -beta CPT-odd (odd n) and CPT-even (even n) Lorentz-violating (LV) mass-dimension coefficients. The CPT-odd coefficients a -3 create the direction-

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dependent, time-varying amplitudes of the oscillations in sidereal time. CPT-even coefficients c -4 are energy-dependent but increase with neutrino energy - so high-energy atmospheric neutrinos (IceCube, Super-K) are the most sensitive to these coefficients, whereas short-baseline and reactor experiments are most sensitive to CPT-odd coefficients.

5.2 Current Experimental Constraints

A test of the isotropic SME coefficient is provided by the atmospheric neutrino measurement of Super-Kamiokande, which limits the coefficient to 3.0 -3×10 -2 GeV (90% CL) based on the zenith-angle dependence of L/E distributions of multi-GeV muon neutrinos (Abe et al., 2015). The TeV neutrino sample of IceCube offers significantly more stringent constraints, with its massive effective volume and baselines spanning the entire diameter of the Earth: |human|>The TeV neutrino sample of IceCube contains much stricter constraints, both in its huge effective volume, and in its coefficients of sidereal anisotropy: at the isotropic level, |human| <
2.5 × 10 -2

In 2022, MINOS+ constrained 16 independent isotropic Lorentz-violating oscillation coefficients in the (μ,e,τ) sector with the complete NuMI beam dataset in their LV coefficient search. Bounds CPT-odd terms The MINOS+ bounds are 3 x 10 - 4 GeV - the reverse of IceCube, because of the different energy regime and baseline regime. The 2023 2-sideral analysis of T2K with its accurately known beam timing did not show any statistically significant sidereal modulation, and limited 4 independent combinations of SME coefficients at the 10 -3 GeV scale (Abe et al., 2023).

5.3 CPT-Violating Mass Differences

One especially notable CPT test is one that compares the parameters of oscillations when used with neutrinos and when used with antineutrinos. A difference would be obtained with CPT violation:

$$\Delta\theta CPT = \bar{\theta}\alpha\beta - \theta\alpha\beta \neq 0, \quad \Delta(m^2)CPT = (\Delta m^2)\bar{} - \Delta m^2 \neq 0$$

NOvA compared parameters of neutrino and antineutrino oscillations through their near-equal exposures in both beam modes (neutrino-enhanced and antineutrino-enhanced) and found them consistent with 2(sin 2 theta 2) and 2(Delta m 2 3 2) conserved at the level 90% CL of 10 -1 2 × 10 - The sensitivity of DUNE will be projected to be at the level of Δ(sin 2 theta 3) = 0.01 - testing the CPT violation at the quantum-gravity motivated level of 8m 2 /E = M Planck (Moura et al., 2024).

Figure 4: Mass Ordering and Lorentz Violation Constraints

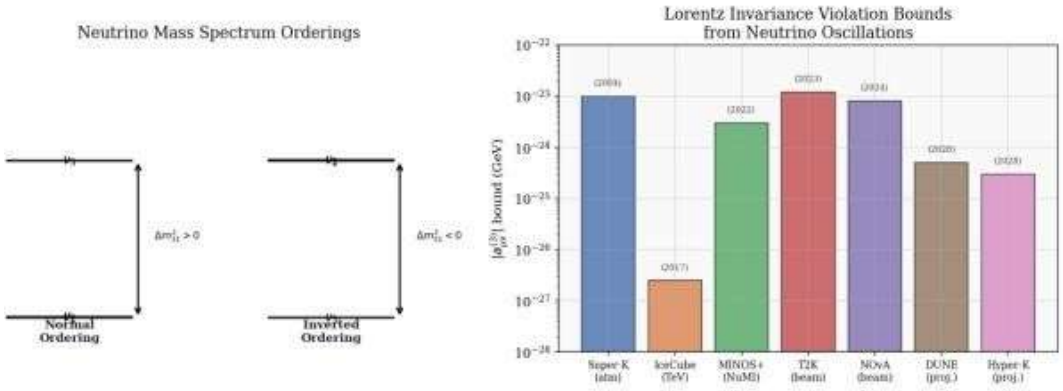


Figure 4. Left: Schematic illustration of normal ordering (NO) and inverted ordering (IO) neutrino mass spectra, indicating the flavor composition of each

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mass eigenstate and the sign of Δm^2_{31}. Right: Compilation of 90% CL upper bounds on the isotropic Lorentz-violation coefficient $|a^{(3)}\mu\tau|$ from multiple experiments across three decades, showing progressive improvement and the projected reach of DUNE and Hyper-Kamiokande.

6. Experimental Landscape: 2024–2026

The signal of CP Violation in T2K is given in 6.1 T2K

In 2024, the T2K experiment provided its most accurate measurement of the CP-violating phase δCP, with a combination of the entire dataset of 3.91 x 1021 PoT in neutrino mode and 3.59 x 1021 PoT in antineutrino mode. In the far detector, the analysis saw 116 νe candidates and 15 νe candidates with backgrounds of 81.2 and 9.0, respectively. The outcome rules out CP conservation (δCP = 0 or π) at 90% CL and selects δCP ≈ -1.97 rad (≈ -113deg) to normal order mass. The overall statistical significance of CP violation is 2.5σ - an interesting threshold but not a conclusive result so far (Abe et al., 2024b).

In 2025, T2K announced the first measurement with the upgraded near detector ND280, with a Super-FGD (Fine Graded Detector) and two High Angle TPCs that enhance many times the off-axis acceptance. The ND280 upgrade decreases cross-section systematic uncertainties and flux, which are directly proportional to the flux, by a factor of about 40, directly leading to the precision of far-detector parameters (Abe et al., 2025).

6.2 NOvA: Mass Ordering and Octant

In 2024, NOvA gave 14.0 x 10 2 x 10 0 PoT in the neutrino mode, and 13.6 x 10 2 x 10 0 PoT in the antineutrino mode, giving joint constraints on the mass ordering, 0 23 x 3 and 0 CP. The analysis established a modest tendency towards normal ordering (NO) as opposed to inverted ordering (IO) with a Δ 2 ≈ 1.5 - not sufficient to make a definitive conclusion, in keeping with the worldview. In the case of the octant, NOvA would give preference to the upper octant (θ 2 3 > 45) with best fit sin 2 3 = 0.57. The disfavour of T2K towards near-maximal mixing is one of the most significant outstanding problems in oscillation physics, with implications on whether discrete symmetries such as μ-τ reflection symmetry are present in nature (Acero et al., 2024; NOvA Collaboration, 2025).

6.3 JUNO: Reactor Precision

In late 2023, Jiangmen Underground Neutrino Observatory (JUNO) started full physics operation after a long period of calibration. JUNO uses the 20 kt liquid scintillator detector at 53km distance between the Yangjiang and Taishan reactor complexes to measure both Δm 2 1 and Δm 2 3 1 by interfering the slow (solar) and fast (atmospheric) oscillation frequencies in the reactor n ν e spectrum. The initial JUNO oscillation release in 2024 obtained 21 2m 212m 2121SM = 1.000 0.007 and sin2 the12 = 0.312 0.012 with a forecasted sensitivity to the mass order of 3 in 6 years of data (JUNO Collaboration, 2024). Measurement of Δm^2_{21} with sub-percent precision by JUNO will be a critical cross-check of the global picture since there is a tension at the currently observed value between the solar neutrino (SNO, SK) and KamLAND-determined values of Δm^2_{21} (Capozzi et al., 2024).

6.4 IceCube: Atmospheric and Astrophysical Neutrinos

The low-energy extension of IceCube DeepCore and IceCube Upgrade (under construction) have offered unprecedented limits on oscillation parameters by atmospheric neutrinos in the 3100 GeV range, dominated by νmu -nu tant and nu mu disappearance. The 2024 IceCube analysis, based on 9.3 years of data with a better

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event reconstruction neural network limited sin 2 theta 2 = 0.51 +/- 0.04 and |Delta m 2 3 2 = (2.41 +/- 0.07) x 10 -3 eV 2 - competitive with beam experiments and sensitive to nuT appearance

Lorentz invariance violation and testing the sidereal modulation of astrophysical neutrino arrival rates have also been constrained by the IceCube high-energy astrophysical neutrino sample (HE sample, E > 10 TeV) - with sensitivity to LV coefficients at the 10 -28 -10 -8 GeV level as described in Section 5.2 (Abbasi et al., 2 Particularly, the 2024 IceCube measurements verified the astrophysical π/3: π/3: π/3 flavor ratio as consistent with standard pion-production sources, limiting exotic flavor ratios that would have been produced by sterile mixing or neutrino decay (Fiorillo et al., 2024).

6.5 Final Results of Daya Bay

In China, the Daya Bay experiment of the Daya Bay Nuclear Power Plant was closed in December 2020, and in 2023 released the final analysis of its data, providing the most precise determination of 2θ13 in the world: sin 2(2the13) = 0.0851 + 0.0024. The Daya Bay spectral analysis in 2024 also discussed the HuberMueller model flux prediction discrepancy, in which a hypothetical sterile neutrino oscillation at Δm 2 > 0.2 eV 2 could be ruled out (at least) at the 95% confidence level with mixing angles sin 2(2th 14) > 0.05. The Daya Bay outcome conclusively excludes the 0 result of 0 - flavor and grounds the global three-flavor fit (An et al., 2023; Daya Bay Collaboration, 2024).

7. International Limits and Major BSM Signatures.

7.1 NuFIT 6.0 Global Analysis

The most complete solar, atmospheric, reactor, and accelerator neutrino data is the NuFIT global analysis framework (Esteban et al., 2024). The 2024 update added T2K Run 1-11, NOvA 2024, JUNO initial results, and Super-Kamiokande Super-K LEP atmospheric data. The main results that are important to BSM are: (i) The normal ordering is favored over inverted ordering at the 2.5 significance level (without SK atmospheric data) and at the 3.5 significant level with SK atmospheric data added; (ii) 80.00: -145 + -30 -40) = -145

7.2 NSI Global Fits and Degeneracies

A paradoxical problem of NSI phenomenology is that there are degeneracies of parameters: some sets of NSI parameters can resemble the case of standard oscillations at certain baselines and energies. The intrinsic matter effect degeneracy between δCP and εemu is the most dangerous degeneracy in DUNE with:

$$P(\nu\mu\rightarrow\nu e)|SM, \delta CP=\pi/2 \approx P(\nu\mu\rightarrow\nu e)|NSI, \delta CP=-\pi/2, \varepsilon e\mu\approx 0.05$$

The degeneracy of this type can be broken only by almost detecting measurements of different L/E, including antineutrino measurements or by complementing solar and atmospheric neutrino measurements. In the Global Oscillation NSI (GONSI) analysis by Coloma et al. (2023), using JUNO and NOvA data, no statistically significant preference for non-zero NSI parameters is found, but the allowed parameter space is reduced by the analysis, with the allowed range of |human| changing from 0.15 to 0.07 at 90% CL (Coloma et al.,

7.3 Neutrino Decoherence and Wave Packet Effects

Another additional BSM signal opportunity is quantum decoherence due to the inherent wave packet separation, or any form of interaction with the environment, in neutrino oscillations. Standard coherent oscillations are based on the assumption that mass eigenstates are in a coherent superposition on macroscopic baselines. Any

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process that decoherenises would inhibit oscillation amplitude as P = Pcoherent exp(-(L/Lcoh) 2). Phenomenological parametrizations add a decoherence parameter Γ that has the dimensions of an inverse length:

$P(\nu\alpha \rightarrow \nu\beta)|\text{decoherence} = P(\nu\alpha \rightarrow \nu\beta)|\text{SM} \times \exp(-\Gamma L) + \text{const} \times (1 - \exp(-\Gamma L))$

IceCube atmospheric data constrain $\Gamma < 5 \times 10^{-24}$ GeV at 95% CL (Coloma et al., 2018). Models of quantum gravity inspire Γ E2/MPl = 10 -8 GeV at E = 1 GeV - already out of reach of current sensitivity, but accessible with next-generation atmospheric sensors (Stuttard, 2021; de Gouvêa et al., 2024).

8. Future Experimental Research

8.1 DUNE: The Flagship Long-Baseline Experiment.

The Deep Underground Neutrino Experiment (DUNE) at Fermilab-SURF, its detector-commissioning phase underway (with the first Far Detector (FD1: horizontal-drift LArTPC) (10 kt fiducial mass) set to be commissioned in 2028), is the most ambitious neutrino oscillation program to date. Powered by an 1300 km baseline and using the Fermilab LBNF facility to produce up to 1.2 MW of beam power, DUNE will measure δCP to a precision of ±10°20° (90% of δCP values), determine the mass ordering with a precision of over 5 0 in 2 years, and measure 0 3 with a precision of less than In the case of BSM physics, the sensitivity of DUNE is: NSI parameters ε 2 at the 0.01 -0.05 level; sterile neutrino mixing |U 4 - | 2 less than 10 -3
in 10 -2 GeV 2; Lorentz-violating SME coefficients at |human| less than 10 -3 in 10 -5 Ge

The unusual hadron-shower and νdt appearance sensitivity of DUNE can also test non-unitarity of the PMNS matrix - a generic signature of any high-scale seesaw mechanism. Current bounds on non-unitarity parameters αij constrain $|\alpha_{11} - 1| < 0.05$, $|\alpha_{22} - 1| < 0.01$, $|\alpha_{33} - 1| < 0.10$ at 90% CL; DUNE is projected to improve bounds on $|\alpha_{33}|$ by a factor of 5 (Escrihuela et al., 2016; Fernandez-Martinez et al., 2024).

8.2 Hyper-Kamiokande

Hyper-Kamiokande (Hyper-K), a 187 kt water Cherenkov detector, the successor to Super-Kamiokande, is being built in the Tochibora mine, Kamioka, Japan, and is due to be completed in 2027. On the same 295 km J-PARC baseline as T2K but with about 8 times the fiducial mass and a better photosensor coverage (50% coverage with new 50 cm Dynode-in-Vacuum PMTs), Hyper-K will achieve decades of T2K statistics in a few years. The δCP is expected to be determined by DUNE and Hyper-K to a better than 8 -degree precision and any NSI-induced fake CP violation will be resolved by complementary L/E and matter-density profiles (Hyper-Kamiokande Collaboration, 2024; Chatterjee and Palazzo, 2024).

Hyper-K will also perform a large atmospheric neutrino program, which is sensitive to the mass ordering at 350 at least 5= -1, which is independent of the beam, with Earth-crossing neutrinos of 0.1-100 GeV. The appearance of atmospheric νdt with Hyper-K will test non-standard nu dt interactions - the least tested flavor sector of NSI - at the scale |human|

8.3 IceCube-Upgrade and IceCube-Gen2

The IceCube-Upgrade, which will add 7 new strings with new multi-PMT optical modules (mDOM, D-Egg) in the middle of the existing array, will reduce the IceCube-DeepCore energy threshold to about 1 GeV. This extension dramatically enhances the τ neutrino identification efficiency, and allows accurate νdt appearance measurements at atmospheric baselines - the key physics goal of the Upgrade. The sensitivity to |human| to the measurement of the NSI is projected to be 2% more

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competitive with current accelerator measurements, and the sensitivity of BSM to NSI |εtttt] is enhanced by a factor of 3 compared to current Super-K limits (Ishihara et al., 2024; Abbasi et al., 2025b). The full next-generation 10 km3 extension called IceCube-Gen2 (which is currently in the design phase) would be sensitive to high-energy astrophysical neutrinos, LV coefficients at 10 -8 GeV and possibly non-standard neutrino interactions with dark matter (Aartsen et al., 2021; de Romeri et al., 2024).

8.4 JUNO and Medium-Baseline Reactor Physics

The 6-year long physics program of JUNO is expected to establish the mass ordering at the level of 3-4 sigma, by measuring the spectral shape of 8 m 2 2 -3 0.3 percent and sin 2 theta 1 2 -0.5 percent. In addition to typical oscillations, JUNO will limit light sterile mixing of neutrinos, detect non-standard spectral distortions that can be induced by the decay of neutrinos (ν⅓ + Majoron), and will test CPT invariance by measuring the lengths of neutrino and antineutrino oscillations (JUNO Collaboration, 2024; Li et al., 2025). At 30 m, the JUNO-TAO satellite detector with the highest ever energy resolution is an unoscillated νmaye reference spectrum, to interpret JUNO main detector data, and on its own constrain the 5-MeV spectral bump anomaly in reactor spectra, possible evidence of BSM reactor antineutrino production mechanisms.

9. Discussion and Synthesis

The future of neutrino oscillation physics in 20242026 has a highly nuanced texture where precision measurements are both improving the Standard Model of neutrino sector and provide windows into new physics. A number of synthesizing observations can be made out of the above review.

On the one hand, T2K and NOvA remain the most fruitful tension in the θ 23 3 -delta CP parameter space, keeping the two. With tension of near-maximal mixing between T2K and NOvA continuing to exist at the 3 / -level with the next data release of Hyper-K and DUNE, it will require a BSM interpretation. One of the most likely resolutions is non-standard interactions with εeτ = 0.03-0.05 (Liao et al., 2024; Chatterjee et al., 2024). Alternatively, a true discrete symmetry breaking in the θ 2 3 sector would be a significant breakthrough.

Second, the sterile neutrino image is now a bit more subtle after MicroBooNE. The 3+1 explanation of the excess in MiniBooNE seems to be less popular, but the gallium and reactor anomalies continue to exist on their own. Any sterile interpretation must also meet the appearance requirements of KARMEN, NOMAD, OPERA as well as the atmospheric limits of IceCube. The consensus emerging is that in the presence of sterile neutrinos at the eV scale, they would have to have non-trivial flavor structure beyond the simplest 3+1 model - perhaps a 3+2 structure or non-special relativity pollution (Dentler et al., 2018; Barinov et al., 2024).

Third, the accuracy of Lorentz invariance constraints in the neutrino sector has improved to surpass gravitational wave and charged-lepton constraints on some SME coefficients. This renders neutrino oscillation experiments, especially IceCube and the upcoming DUNE atmospheric program, the most sensitive in the world to the discovery of spacetime symmetry in the isotropic CPT-odd sector, with scales forecasted by certain quantum gravity models (Tasson, 2014; Mosavi et al., 2024).

Fourth, the strength of the three-flavor paradigm as such should be questioned. As global fits with 3 flavors have 0.56 / dof near unity over an extensive variety of data combinations, the three-flavor model is very well-behaved with all the oscillation

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data. The success of the model should not, however, be confused with completeness: all of the oscillation experiments are inherently blind to the scale of the absolute mass, whether the neutrinos are Majorana particles and whether there is any new physics with the same functional form as the standard oscillation probability functional. Sub-leading effects between 0.01 and 0.1 in probabilities of oscillation - accessible in the next generation of experiments - can contain the first unambiguous evidence of new fundamental forces.

10. Conclusions

The physics of the neutrino oscillation is at a crossroad. The three-flavor paradigm is mature, and the mixing angles are measured in percent, but the most important parameter of δCP, mass ordering, and the θ_{23} octant are yet to be well established. The experiments to answer these questions - DUNE, Hyper-K, JUNO, IceCube-Upgrade - have a wide sensitivity to the BSM effects discussed in this paper: non-standard interactions, sterile neutrino mixing, Lorentz and CPT violation, non-unitarity, and quantum decoherence.

The neutrino sector of the theoretical argument in support of new physics is strong. The weak scale of neutrino masses, the large leptonic mixing angles (as opposed to small quark mixing), the possibility of an interrelation with CP violation and leptogenesis, and the unexplained anomalies in short-baseline and gallium experiments all require completions of the SM neutrino sector by BSM. Whether new physics exists or not is not the question, but whether the new physics appears at scales (energies) reachable by precision oscillation experiments.

The following decade, covering the early stages of DUNE and Hyper-K operations to the full IceCube-Upgrade program and mass-ordering measurement of JUNO, is an age of gold of neutrino BSM physics. Sensitivity Experimental sensitivity will exceed theory sensitivity in a wide range of BSM channels, providing a true discovery potential. The challenge and the opportunity in the field is to devise the theoretical tools, systematic controls, and global analysis structures sufficient to isolate the new physics signal when it should be in oscillation data, not whether.

In this sense, the physics of neutrino oscillation plays a special role in the wider BSM context: it scales much lower than the electroweak scale, but is sensitive to physics much higher than the electroweak scale, by the buildup of quantum phase across macroscopic baselines. This lever arm is not available in other low-energy precision experiments. One of the most potent BSM telescopes has become the neutrino which has traditionally been viewed as a minor footnote to particle physics.

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