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Summary of Parallel Session II – Beyond the Standard Framework

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We give a brief summary of the results presented at the parallel session II - "Beyond the standard framework" of Neutrino Oscillation Workshop 2024. Apart from the determination of neutrino mass ordering and the search for leptonic CP violation, future neutrino oscillation experiments will also be sensitive to new physics beyond the Standard Model. Both experimental and theoretical works on new-physics scenarios that are related to fundamental properties of massive neutrinos are covered in this parallel session.

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1. Introduction

The experimental discovery of neutrino oscillations indicates that neutrinos are actually massive and that lepton flavor mixing exists [1]. The primary goals of the next-generation neutrino oscillation experiments are to determine neutrino mass ordering and to probe leptonic CP violation. Meanwhile neutrino oscillation parameters will be precisely measured, so that any sub-dominant contributions to the neutrino oscillation probabilities from new physics are likely to be restrictively constrained or even clearly identified.

On the theoretical side, the primary goal is to understand the basic properties of massive neutrinos and ultimately sort out the origin of neutrino masses and lepton flavor mixing. However, the model building for nonzero neutrino masses depends crucially on whether neutrinos are Dirac or Majorana particles, signifying the particular importance of observing neutrinoless double-beta decays. Any new ideas towards how to achieve this goal are valuable, especially those testable in the precision era of neutrino experiments.

On the experimental side, a longstanding problem is if the eV-mass sterile neutrino exists or not. In this regard, MicroBooNE and ICARUS in the US and JSNS^2 in Japan are collecting experimental data and some of them released the first analysis of sterile neutrinos. The experimental searches for dark matter and non-standard neutrino interactions in current and future neutrino oscillation experiments are also interesting.

2. Theoretical Results

The origin of neutrino masses definitely calls for new physics beyond the Standard Model (SM). The simplest extension of the SM to accommodate nonzero neutrino masses is to introduce three right-handed neutrinos $\nu_{\rm R}$, which are singlets under the SM gauge group ${\rm SU}(2)_{\rm L} \otimes {\rm U}(1)_{\rm Y}$. The most general gauge-invariant Lagrangian for such a simple extension can be written as

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\nu_{\rm R}} {\rm i} \partial\!\!\!/ \nu_{\rm R} - \left[\overline{\ell_{\rm L}} \tilde{H} Y_\nu \nu_{\rm R} + \frac{1}{2} \overline{\nu^{\rm c}_{\rm R}} M_{\rm R} \nu_{\rm R} + {\rm h.c.} \right] , \quad (1)$$

where $\mathcal{L}_{\rm SM}$ refers to the SM Lagrangian, $\ell_{\rm L}$ and $\tilde{H} \equiv {\rm i}\sigma^2 H^*$ denote respectively the lepton and Higgs doublet. In addition, Y_ν is the Dirac neutrino Yukawa coupling matrix, and $M_{\rm R}$ stands for the Majorana mass matrix of three right-handed neutrinos. After the spontaneous breakdown of the SM gauge symmetry, the Dirac neutrino mass matrix is given by $M_{\rm D} \equiv Y_\nu v$ with $v \approx 174$ GeV being the vacuum expectation value of the Higgs field, and three active neutrinos in the SM acquire their tiny masses through the seesaw mechanism $M_\nu \approx -M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^{\rm T}$ [2], where the seesaw scale is much larger than the electroweak scale, namely, $\mathcal{O}(M_{\rm R}) \gg \mathcal{O}(M_{\rm D})$. Therefore, the smallness of light Majorana neutrino masses can simply be ascribed to the heavy Majorana neutrinos.

On the other hand, heavy Majorana neutrinos can be copiously produced in the early Universe through their Yukawa interaction with lepton and Higgs doublets, when the temperature becomes comparable to heavy Majorana neutrino masses. The out-of-equilibrium and CP-violating decays of heavy Majorana neutrinos generate lepton number asymmetries, which are subsequently converted partially into the baryon number asymmetry via the baryon- and lepton-number violating sphaleron processes. The baryogenesis via leptogenesis [3] and the seesaw mechanism for light neutrino masses render the minimal extension of the SM with three right-handed neutrinos to be a very attractive picture under extensive studies in the past few decades.

Nowadays theoretical investigations of massive neutrinos focus mainly on their Majorana nature and electromagnetic properties, and on the origin of neutrino masses and lepton flavor mixing. In addition to the type-I seesaw model, many other extensions of the SM to account for tiny neutrino masses are also investigated, in which possible connections of massive neutrinos to dark matter candidates, astrophysics and cosmology can be made.

2.1 Basic Properties of Neutrinos

Now that neutrinos are massive, one fundamental question is whether they are Dirac or Majorana particles [4, 5]. If neutrinos are Majorana particles, the neutrinoless double-beta ($0\nu\beta\beta$) decays of some even-even nuclear isotopes may take place, i.e., $A(Z,N) \to A(Z+2, N-2) + 2e^-$ with both the proton number Z and the neutron number N being even [6]. The positive signal of such a lepton-number-violating (LNV) process will reveal the Majorana nature of massive neutrinos and thus guide us towards the true mechanism of neutrino mass generation [7]. However, neutrinos can be either Dirac or Majorana particles if no $0\nu\beta\beta$ decays are observed. Any other approaches that can be implemented to distinguish between Dirac and Majorana neutrinos will be equally important.

Based on the results in Ref. [8], Akhmedov has further clarified that the quantum statistics cannot help discriminate Dirac neutrinos from Majorana neutrinos in the limit of vanishing neutrino masses [9]. In this limit, the chirality for Majorana neutrinos plays essentially the same role as the lepton number does for Dirac neutrinos [10–13]. Although this is well known as the "Practical Dirac-Majorana Confusion Theorem" in the neutrino community [12], its applicability has recently been challenged in Ref. [14]. It is claimed in the latter reference that Majorana neutrino states from the pair-production processes should be antisymmetrized and the feature of antisymmetrization survives even in the massless limit $m_\nu \to 0$. However, as demonstrated by Akhmedov [8, 9], the impact of antisymmetrization due to the Majorana nature will be suppressed at least as m_ν/E_ν. Therefore, quantum statistics of identical fermions in the case of a pair of Majorana neutrinos does not lead to the exceptions to the Practical Dirac-Majorana Confusion Theorem.

In the simplest extension of the SM with nonzero neutrino masses, one can directly calculate the electromagnetic dipole moments (usually parametrized as the effective magnetic moment μ_ν) of neutrinos, which arise from one-loop corrections and turn out to be highly suppressed due to tiny neutrino masses [15]. The Majorana nature of massive neutrinos ensures that both electric and magnetic dipole moments must be zero, so only the transition effective magnetic moments $\mu^{\rm M}_{\alpha\beta}$ (for $\alpha\beta = e\mu, e\tau, \mu\tau$) may be nonvanishing. In the case of Dirac neutrinos, both intrinsic and transition magnetic moments $\mu^{\rm D}_{\alpha\beta}$ (for $\alpha, \beta = e, \mu, \tau$) could be nonzero. The most stringent bound on the neutrino magnetic moments $\mu_\nu \lesssim 1.5 \times 10^{-12}~\mu_{\rm B}$ at the 95% confidence level has been derived from the impact of extra energy losses on low-mass stars in the red-giant branch of globular clusters [16]. To probe the electromagnetic properties of massive neutrinos, Vignaroli presents the sensitivities of future high-energy colliders to neutrino magnetic moments [17, 18] by considering the LNV processes. The basic idea is to work in the SM effective field theory (SMEFT) and calculate the contributions from two independent effective operators of dimension-seven, i.e., $O^B_{\alpha\beta} \equiv g' \left(\overline{\ell^{\rm c}_{\alpha{\rm L}}}\epsilon H\right) \sigma^{\mu\nu} \left(H^{\rm T}\epsilon\ell_{\beta{\rm L}}\right) B_{\mu\nu}$ and $O^W_{\alpha\beta} = {\rm i}g\varepsilon_{abc} \left(\overline{\ell^{\rm c}_{\alpha{\rm L}}}\epsilon\sigma^a\sigma^{\mu\nu}\ell_{\beta{\rm L}}\right) \left(H^{\rm T}\epsilon\sigma^b H\right) W^c_{\mu\nu}$, which describe new-physics effects in a model-independent way. In the future muon colliders with a center-of-mass energy of 50 TeV and an integrated luminosity of 250 ab^{-1}, one can search for the LNV process $\mu^+\mu^- \to e^-\mu^- W^+ W^+$ with a very low background and reach a very competitive sensitivity $|(\mu_\nu)_{e\mu}| \lesssim 7.5 \times 10^{-13}\ \mu_{\mathrm{B}}$ at the 2σ level.

2.2 Neutrino Mass Models

As mentioned before, the canonical seesaw model is able to simultaneously account for tiny Majorana neutrino masses and the baryon number asymmetry in the Universe. However, the mass scale of heavy Majorana neutrinos is not subject to the electroweak gauge symmetry breaking and thus can vary in a broad range. Given different masses of heavy Majorana neutrinos and their Yukawa couplings to the SM particles, the phenomenology can be quite distinct.

Granelli introduces an interesting connection between low-energy CP violation and the CP asymmetries from heavy Majorana neutrinos in the scenario of low-scale leptogenesis [19, 20]. First, implementing the Casas-Ibarra parametrization of the Yukawa coupling matrix [21], one can further assume that nontrivial CP-violating phases appear only in the lepton flavor mixing matrix, where the Dirac CP-violating phase is responsible for CP violation in neutrino oscillations while two Majorana CP-violating phases are relevant for $0\nu\beta\beta$ decays. Second, taking heavy Majorana neutrino masses to be in the range of 100 MeV to 100 GeV, one can achieve the successful leptogenesis via heavy neutrino oscillations and their out-of-equilibrium decays [22]. At the same time, such low-mass heavy Majorana neutrinos receive stringent constraints from the collider searches for long-lived heavy neutral leptons. Third, this scenario will be further tested in the lepton-flavor-violating (LFV) processes, such as $\mu \to e\gamma$, $\mu \to 3e$ and μ-e conversions [20].

Within the same theoretical framework, Rosauro-Alcaraz considers that one of three heavy Majorana neutrinos is around the keV-mass scale, serving as a promising candidate for warm dark matter [23, 24]. Meanwhile, two other heavy Majorana neutrinos with nearly degenerate masses can account for the baryon number asymmetry in the Universe via the Akhmedov-Rubakov-Smirnov mechanism [22]. Via the mixing with active neutrinos, the keV-mass neutrinos as dark matter will decay into lighter active neutrinos and photons, the latter of which are observed as X-ray lines from dark-matter-dominated galaxies. Taking into account the constraints from X-ray observations, one should also examine whether such keV-mass sterile neutrinos can be produced in a sufficient way in the early Universe and at the same time be consistent the observed large-scale structures. In Ref. [24], it has been found that the thermal effects at $T \sim 100$ GeV highly suppress the production of ν_{DM} from W and Z decays, but the decays in the channel $\nu_{\mathrm{H}} \to h + \nu_{\mathrm{DM}}$ below $T < 160$ GeV are efficient enough, where ν_{H} and ν_{DM} denote 100 GeV- and keV-mass neutrinos, respectively.

Instead of heavy right-handed neutrinos, a Higgs triplet with hypercharge $Y = 1$ is introduced in the type-II seesaw model [25–27] and couples with two lepton doublets, leading to tiny Majorana neutrino masses after the spontaneous symmetry breaking. Li presents the calculation of the cross section for neutrino trident processes $\nu_\mu + N \to \nu_\mu + N' + \mu^+ + \mu^-$, taking account of experimental constraints from neutrino oscillations, $0\nu\beta\beta$ decays, the rare LFV decays of charged leptons and electroweak precision data [28]. In the type-II seesaw model, the singly-charged scalar boson will contribute to the neutrino trident processes. Given current experimental constraints, the deviation of the cross section from the SM one is around the 0.1% level, which is very challenging for future experimental tests [29].

2.3 Lepton Flavor Mixing

Although the seesaw models are able to naturally explain the smallness of light neutrino masses, the lepton flavor mixing pattern cannot be determined by the seesaw mechanism itself [1]. Recently the finite modular symmetry has been proposed to further constrain the flavor structure of neutrino mass models [30] such that theoretical predictions for the mixing angles and neutrino mass-squared differences can be consistent with the observations from neutrino oscillation experiments. See, e.g., Refs. [31, 32], for recent comprehensive reviews on this topic.

Penedo gives a brief but clear review on the finite modular groups and recent progress in their applications to neutrino physics [33]. Two interesting points related to model building with finite modular symmetries are summarized. First, it has been demonstrated in Ref. [34] that the generalized CP symmetry can be combined with finite modular symmetries to construct neutrino mass models, where the consistency conditions for these two types of symmetry transformations on the modulus parameter τ and matter fields are satisfied and the complex modulus τ serves as the only source of CP violation. Second, it is possible to explain fermion mass hierarchy in the framework of modular symmetries [35]. The basic idea arises from the observation that some Yukawa couplings vanish as a symmetric point $\tau_{\rm sym}$ of the modulus parameter is reached. Therefore, the small deviation $\epsilon \equiv |\tau - \tau_{\rm sym}| > 0$ from the symmetric point results in nonzero Yukawa couplings proportional to some powers of ϵ, for which the power index depends on the modular weights. As an immediate consequence, the fermion mass hierarchy can be derived from the resultant Yukawa coupling matrices.

Hagedorn presents the results from Ref. [36] about the application of discrete flavor symmetries $\Delta(3n^2)$ and $\Delta(6n^2)$ combined with CP symmetry to the inverse seesaw model [37]. Such a model further extends the type-I seesaw model by three extra gauge-singlet fermions $S_{\rm R}$, which are coupled to three right-handed neutrinos via a complex singlet scalar and assigned a Majorana mass matrix μ_S. After the spontaneous gauge symmetry breaking, there appears a Dirac mass term M_{NS} for two different sets of gauge-singlet fermions $\{N_{\rm R}, S_{\rm R}\}$. Since the Majorana mass term violates the lepton number by two units, it is naturally small in the sense that the lepton number will be conserved if μ_S vanishes. In the inverse seesaw model, the light neutrinos acquire tiny masses according to $M_\nu \approx M_{\rm D}(M_{NS}^{-1})^{\rm T}\mu_S M_{NS}^{-1} M_{\rm D}^{\rm T}$, where $O(\mu_S) \sim$ keV and $O(M_{NS}) \sim$ TeV. For proper settings of the model parameters, the rare LFV decays of charged leptons and μ-e conversions can be sizable and testable in future experiments, while both the neutrino mass spectrum and the flavor mixing pattern are compatible with experimental observations [38].

3. Experimental Results

In the following a summary of the experimental results will be described in the framework of sterile neutrino and dark matter search. Then an overview of the new-physics potential of the experiments which are in the construction phase or in the design phase will be presented.

3.1 eV sterile neutrino search

Sterile neutrino in the eV mass range have been hypothesized after different observations called anomalies, which are not explained by the standard neutrino oscillation model. One of these

anomalies was reported by LSND and MiniBooNE, as an excess of electron-neutrino-like events in muon neutrino beam. In order to confute or to prove the sterile neutrino existence the Short Baseline Neutrino Program was installed at Fermilab National Laboratory in USA. It is made by three detectors, based on liquid Argon time projection chamber technology and placed at different distances from the proton target along the Booster Neutrino Beam. ICARUS, the Far Detector, is placed at 600 m from the proton target and it is currently taking data, the Near Detector SBND (at 110 m from the target) has just completed the commissioning phase, while MicroBooNE placed at 470 m from the target has concluded 5 years of data taking in 2020. The three detectors will be able to characterize the neutrino beam and to clearly identify any deviations on the standard neutrino oscillation at short-baseline distance. First analysis performed by MicroBooNE have shown no evidence for an excess of electron neutrinos [3] and no evidence for photon excess if searched from delta decay ($\Delta \rightarrow N + \gamma$) in neutral current interactions [41]. However inclusive single-photon analysis are on going by considering the full 5-year MicroBooNE dataset. At the same time no evidence for a sterile neutrino was found by MicroBooNE data [42], but an higher sensitivity will be achieved by combining data from the three detectors. Christian Farnese in his talk [52] presented the status of the analysis of the first ICARUS dataset for the sterile neutrino search in the muon neutrino disappearance channel and for sub-GeV dark matter search in the off-axis NuMI neutrino beam. In addition the contribute of the systematics effects in the oscillation analysis were discussed in the talk of E. Worcester [53].
In the same scenario, the JSNS^2 experiment at J-PARC facility was conceived with the goal of reproducing and confirming LSND excess by using the same neutrino source (muon decay at rest), the same target (Hydrogen), and the same detection principle (inverse beta decay process). As shown by C. Shin [55] the detector started long physics runs in 2021 and it was able to measure the electron-neutrino flux by using $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$ reaction and to detect mono-energetic neutrino events from kaon decay at rest. In the second phase it will be upgraded with a new far detector almost identical to the previous that will allow to completely cover the LSND allowed region.

3.2 Dark matter search

Many analysis have been already performed by MicroBooNE aimed at exploring new physics beyond standard model and at discovering experimental evidences of dark matter. An overview of the different analysis performed by MicroBooNE have been presented by M. Ross-Lonergan [39] both in the minimal portal scenario and in a more general scenario. MicroBooNE searched for long lived heavy neutral leptons produced from NUMI beam absorber which site just below the MicroBooNE detector, but no signal was observed in all the decay modes. Most stringent limits were set for the two channels $N \rightarrow \nu + e^+ + e^-$ and $N \rightarrow \nu\pi^0$[43]. In addition a world leading exclusion limits was set from MicroBooNE for Dark Trident production [44], a light dark matter which might be detected when it scatters of Argon leaving a visible e^+e^- pair.

Moreover keV sterile neutrino search investigated by the KATRIN experiment was presented by A. Nava [56]. The primary goal of KATRIN is a direct measure of the neutrino mass by observing the shape of energy spectrum of the beta decay of tritium. However the existence of keV neutrinos would lead to a global distortion plus a kink in the beta spectrum where the kink's position and its amplitude are related to sterile neutrino parameters. KATRIN searched for keV sterile neutrinos in integral mode in the 0.01-1.6 keV mass range and no signal was observed. In order to improve this results and to reduce systematics currently dominated by source activity fluctuations from 2026 KATRIN will switch into a differential mode after the commissioning of the TRISTAN detector. This will allow an improvement on the energy resolution 10 times better and this will open the possibility to search for keV sterile neutrinos with a mixing down to $\sin^2\theta < 10^{-6}$.

Finally the rich program of IceCube Neutrino Observatory for dark matter search was shown by L. Fisher [48]. IceCube is a cubic kilometer Ice-Cherenkov neutrino detector placed at geographic South Pole and it is able to detect high energy (100 100 GeV) neutrino events. IceCube was designed to detect atmospheric neutrinos and diffuse astrophysical neutrinos at energies above 10^5 GeV and to perform dark matter search produced in different mechanism. In particular it might detect dark signal produced by dark matter annihilation (in the Galactic center/halo, in dwarf spheroidals, in galaxy clusters,..) or from dark matter decay (from Galactic Halo, extragalactic, galaxy clusters) or from dark matter scattering on nucleon (in the Sun o in the Earth) or on neutrinos (in Milky Way halo, or from astrophysical sources). IceCube placed world leading limits on various dark matter interaction scenarios (annihilation, decay ...). Results about dark matter annihilation in the Sun due to dark matter-nucleon scattering were shown in term of upper limit of dark matter-nucleon elastic cross-section based on 3 years of atmospheric 5-100 GeV sample [49], while preliminary results were shown for decaying dark matter from galaxies and galaxy cluster with masses between 10 TeV and 1 EeV and assuming a decay into Standard Model particle pair. In addition a search for heavy neutral lepton was performed by using 10 years of atmospheric 5-100 GeV sample and no significant signal was found.

3.3 Non standard neutrino interactions

Generic neutrino beyond standard model physics can be tested in the form of non-standard interactions (NSI). IceCube have performed several analysis for testing Non-Standard Interaction by using two samples based on 3 years of atmospheric neutrino data in the energy range of 5-100 GeV and 500-10^5 GeV and no evidence was found [50].

On the other side in the talk of A. Palazzo [57] it was discussed about the tension at $\sim 2.5\sigma$ level between T2K and NOvA results on neutrino oscillation parameter measurements and on the various mechanism, as sterile neutrino, non unitarity, ultra light dark matter, which were considered for resolving this tension. As it was demonstrated in [51] none of those hypothesis was satisfactory till non standard interactions were considered. In this case a non-zero value of $\epsilon_{e\mu} \sim 0.1$ can be achieved and the tension can be reduced at about 1.8 σ. In this framework a preference for neutrino mass normal ordering is restored. However assuming a non zero value for $\epsilon_{e\mu}$, further confirmation are expected in the next few years from T2K, NOvA, ANTARES and Icecube experiment and in the case the NSI indication persists, DUNE and HyperK will definitely confirm/disconfirm it.

Neutrino physics is the ideal environment where conducting the search for new "exotic" physics, since the oscillation phenomenon is not yet completely included in the Standard Model of particles and this can require the necessity to investigate new theoretical models. This new physics effect is usually described by supposing the existence of tiny neutrino masses, that can cause the oscillations. Lorentz symmetry is one such fundamental symmetry in nature, but if Lorentz invariance violation (LIV) occurs, oscillations could be due to other mechanisms. In particulat alternative theories based on LIV are able to generate neutrino masses and, consequently, flavour oscillations. The effect of LIV is treated as a perturbation to the standard neutrino Hamiltonian considering the Standard

Model Extension (SME) framework. The neutrino sector of the SME provides a description of how Lorentz and CPT violation would affect neutrino propagation, interactions, and oscillations. First limits on LIV were already shown by Icecube. They searched for Lorentz Violating Neutrino Oscillations in a atmospheric 500-10^5 GeV sample and no evidence was found. This analysis tested dimension 4/5/6 scenarios placing world-leading constraints.

3.4 Future experiments

Neutrino oscillations offer great potential for probing new-physics effects beyond the Standard Model. For this reason new generation neutrino experiments are currently under design and construction with the goal of improving the precision measurement of the oscillation parameters as well as searches of new-physics effects as for example the Lorentz Invariance Violation or neutrino decoherence which can directly modify the neutrino oscillation probability.

KM3NEt experiment described by N. Lessing [47] is a new generation neutrino telescope under construction in the deepest seas of the Mediterranean. It is composed by two Cherenkov detectors with different designs: ORCA, a compact and dense detector optimized for the high-statistic measurement of atmospheric neutrino physics in the 1- 100 GeV energy range, and ARCA, a set of two telescopes instrumenting a cubic kilometer to catch fluxes of extraterrestrial neutrinos from 100 GeV to 10 PeV. Both ARCA and ORCA can search for BSM by observing any deviations from standard neutrino oscillations. For example neutrino eV-scale sterile neutrino produces matter enhanced resonance at TeV energies or decoherence effect can be detected since the effect accumulates along the path and atmospheric neutrinos in KM3NeT have long baselines. If neutrino mass eigenstates lose their coherent superposition due to interactions with the environment oscillation amplitude will result to be suppressed. This effect accumulates along the path and this is atmospheric neutrinos in KM3NeT have long baselines. In particular ARCA can search for BSM effects at high energies (TeV to few PeV) where standard oscillations for atmospheric neutrinos are suppressed and it will investigate neutrino decoherence effect proportional to E, E^2, while ORCA is sensitive to atmospheric neutrino oscillations in the GeV range where BSM effects can modify the standard oscillation pattern and it will observe decoherence effect proportional to E^{-2}, E^{-1} In addition ORCA can perform search of neutrino decay and non-unitary mixing.

DUNE described by the talk of N. Ilic [46] is currently in the design phase and it is a future long-baseline neutrino beam experiment that will measure with high precision the neutrino mixing parameters using a high power (1.2 MW) wide band spectrum muon neutrino/anti-neutrino beam, a Near detector situated at Fermilab and a Far detector located at a distance of 1300 km away at Sanford Underground Research Facility (SURF), South Dakota, USA. The FD is a fiducial 40 kton liquid argon time projection chamber (LArTPC) located underground to eliminate background sources. The primary objectives of the experiment are to precisely establish the neutrino mixing parameters, investigate matter-antimatter asymmetry via Charge-Parity (CP) symmetry violation and identify the true neutrino mass hierarchy. This experiment will provide unmatched precision in establishing neutrino mixing parameters. It will be able to set stringent constraints on Lorentz and CPT violation with the neutrino sector thus testing fundamental principles. In addition it is expected an improvements on the limits on some source/detector NSI by a factor of 2-5, a direct probe of PMNS non-unitarity and finally it will be be uniquely sensitive to dark matter portals in uncovered mass ranges.

PoS(NOW2024)044

ESSnuSB described by M. Ghosh [54] is designed to be a next-to-next generation long-baseline neutrino oscillation experiment to precisely measure the CP violation phase δ_{CP} at the second oscillation maximum by employing the powerful 5MW ESS accelerator as a proton driver for neutrino beam production. It is expected to start taking data after HyperK and DUNE, starting the precision era of leptonic CPV measurement if the existence of CPV is confirmed, while in the opposite case it will allow to search for CPV in the part of parameter space inaccessible to its two predecessor experiments. In addition it is a good experiment to study quantum decoherence, since expected limits will be better than current results from MINOS [58] and comparable to the expected sensitivity of DUNE [59].

Finally JUNO is a large multi-purpose liquid scintillator detector designed for achieving excellent energy resolution ($\sim 3\%$ at 1 MeV) and low threshold (0.2 MeV) with the primary goal of measuring neutrino mass hierarchy. At the same time JUNO will be one of the future experiments for nucleon decay search. As it was described by W.Guo in his talk [45], JUNO is sensitive to the proton decay channel $p \to K^+\bar{\nu}$ since it can detect K^+ in different decay modes and with high efficiency and background rejection. The expected sensitivity at 90% confidence level for proton decay is $\tau/B(p \to \bar{\nu} + \bar{K}^+) > 0.96 \cdot 10^{34}$ years.
In addition also neutron invisible decays from one or two bound neutrons in ^{12}C will be searched with an expected sensitivity of $\tau/B(n \to inv) > 5.0 \cdot 10^{31}$ years and $\tau/B(nnp \to inv) > 1.4 \cdot 10^{32}$ years at 90% confidence level. Such sensitivities are expected after about 2 years of data taking and they are an order of magnitude better than the current best limits.

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