New physics at nuSTORM

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In this work we investigate the usefulness of nuSTORM as a probe of two new-physics scenarios that are sterile neutrinos and nonunitarity of the neutrino mixing matrix. For the sterile neutrino we show the importance of the neutral current events when combined with the charged current events to constrain the effective mixing angle, $\theta_{\mu\mu}$, and the sterile mixing angles θ_{14} and θ_{24} . We also study the role nuSTORM will play in the study of neutrino oscillation physics if the three generation neutrino mixing matrix is nonunitary. In this context we elucidate the role of nuSTORM, considering both charged current and neutral current events, in constraining the various nonunitarity parameters such as α_{11} , $|\alpha_{21}|$, and α_{22} .

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I. INTRODUCTION

Neutrino oscillation experiments have conclusively established the paradigm of the three-flavor neutrino oscillations and oscillation parameters are being determined with increasing precision. The three parameters that are yet to be determined are the mass hierarchy, the octant of the atmospheric mixing angle, θ_{23} , and the leptonic CP phase, δ_{CP} . There are some indications of the value of these parameters from the current data. Future planned/proposed high statistics experiments are expected to clinch these issues. With the determination of the three-neutrino mixing parameters already on the horizon, efforts have been made to explore new physics beyond the Standard Model in these experiments. New physics scenarios that have garnered considerable interest in the community include light sterile neutrinos, nonunitarity of the neutrino mixing matrix, nonstandard interactions of the neutrinos, etc.

The existence of light sterile neutrinos was postulated to explain the LSND results [1,2]. LSND reported signals of $\nu_\mu - \nu_e$ oscillations with a mass-squared difference of the order of eV^2 . This was supported by MiniBooNE [3,4] and also by the gallium and reactor anomalies [5–7]. In order to accommodate the eV^2 oscillation scale the simplest

possibility is to add a sterile neutrino to the Standard Model. There are two possible ways this can be done: (i) The $2 + 2$ scenario in which the oscillation to the sterile neutrino constitutes the dominant solution either to solar or to atmospheric neutrino anomaly and disfavored from current data [8]. (ii) The $3 + 1$ or $1 + 3$ picture in which the sterile neutrino is separated by an eV^2 mass difference from the three active states [9]. The $3 + 1$ ($1 + 3$) corresponds to the three active states to be lighter (heavier). Cosmological constraints on the sum of neutrino masses pose a serious challenge in accommodating an eV scale sterile neutrino scenario. To address these, secret neutrino interactions [10] or lower reheating temperatures [11–13] are proposed. The $1 + 3$ picture is more disfavored from cosmology since there are three heavier states. The $3 + 1$ picture can provide an acceptable fit to the data [14,15] albeit the tension between disappearance and appearance data. This tension is driven mainly by ν_μ disappearance data and the LSND appearance data [16,17] while the contribution from the MiniBooNE appearance is subleading. The disappearance data which contribute to tension are from CDHS [18] and more recent experiments such as IceCube [19], MINOS/MINOS+ [20], SK [21], DeepCore [22], MiniBooNE, and NO ν A [23].

There are several new experiments planned to test the sterile neutrino hypothesis [24–31]. It was realized recently that beam-based long-baseline experiments can also probe the parameter space of the sterile neutrino models and several studies have been carried out in this direction considering the current as well as proposed experiments. Future experiments such as DUNE [32] or T2HK [33] are high statistics experiments, and therefore the systematics are expected to play a crucial role, one of the major sources

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of systematic uncertainty are the neutrino-nucleus interaction cross sections. Neutrinos from Stored Muons (nuSTORM) [29,30] is a facility proposed for the measurement of neutrino-nucleus cross sections with percent-level precision. The high precision can be achieved because the stored-muon beam will allow the determination of neutrino flux with high accuracy. It has been shown that nuSTORM has the excellent capability to search for the existence of light sterile neutrinos of the type postulated to explain the LSND and MiniBooNE results [1–4].

Beyond the Standard Model (BSM) physics descriptions have become essential in describing the nonzero neutrino mass after the discovery of neutrino oscillations. Nonzero neutrino masses can be generated by the “seesaw” mechanism through an effective lepton number violating a dimension-five operator of the form $LL\phi\phi$ which can be derived from physics beyond the Standard Model [34,35]. Such BSM physics can also lead to nonunitarity of the neutrino mixing matrix [36–44]. The unitarity of the Pontecorvo Maki Nakagawa Sakata (PMNS) matrix can be tested in accelerator-based neutrino oscillation experiments. Several studies have been performed to understand the implications of nonunitarity in present and future long baseline experiments [45–48]. In this context nuSTORM also holds promise for the study of the nonunitarity of the PMNS matrix and the constraint of the parameters that generate nonunitarity in the PMNS sector.

The neutrino beam in nuSTORM originates from the muon decay process: $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ with 50% ν_e and 50% $\bar{\nu}_\mu$, which can give e^- and μ^+ at the detectors in the absence of oscillation or any other new physics. If, however, there are flavor-changing processes, then one can get wrong sign leptons which can constitute smoking-gun signals of new physics. A detector with charge identification capability is therefore ideal.

The sterile neutrino analysis performed in [49] considered a magnetized iron-calorimeter detector with a superior efficiency to identify the charge of the muons. This gives the detector the ability to record the μ^- events originating from $P_{\nu_e \nu_\mu}$ oscillations along with the μ^+ coming from the $P_{\bar{\nu}_\mu \bar{\nu}_\mu}$ channel. In this analysis only the charged current events were considered. However, there are also a large number of neutral current (NC) events. In a three-flavor-mixing paradigm, given the flavor universality of the neutral current interactions and $P_{\mu e} + P_{\mu\mu} + P_{\mu\tau} = 1$, NC events are not sensitive to the oscillation parameters. However, in the presence of new physics this may not be the case. For instance, for oscillations of muon neutrinos to a sterile neutrino, the rate of neutral-current events will be multiplied by $(1 - P_{\mu s})$. The usefulness of NC events for sterile neutrino searches in the context of beam experiments has been studied in [20,23,50,51].

In this article we present the capabilities of nuSTORM in some sterile neutrino searches as well as the search for nonunitarity of the neutrino mixing matrix. In Sec. II we

discuss the nuSTORM proposal and the simulation of the facility. We discuss the results obtained in our study in Sec. III, where Sec. III A focuses on the study of sterile neutrinos at nuSTORM, while the consideration of the nonunitarity of the neutrino mixing is presented in Sec. III B. Conclusions are presented in Sec. IV.

II. DETAILS OF SIMULATION

We follow the configuration and detector simulations from [29,30,52]. The unoscillated flux was taken from [29]. The simulation has been performed using the General Long Baseline Experiment Simulator (GLOBES) package [53,54]. The flux is based on the decay $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. The neutrino beam is generated with 50 GeV protons with 2×10^{21} protons on target over the duration of 10 years. Pions of 5 GeV are injected into the muon storage ring. Muons with energy of the order 3.8 GeV subsequently decay to give ν_e and $\bar{\nu}_\mu$. The ν_e flux peaks at 2.5 GeV, whereas the $\bar{\nu}_\mu$ flux peaks at 3 GeV. nuSTORM is simulated as described in [29,30].

The primary aim for nuSTORM is the study of neutrino-nucleon scattering. At energies $E_\nu < 2$ GeV quasielastic scattering and $1\pi(\Delta)$ resonance are the dominant processes. But, at energies $E_\nu > 2$ GeV, the processes with multipion resonances along with shallow- and deep-inelastic scattering processes starts contributing significantly with a deep-inelastic scattering process dominating at energies $E_\nu > 3$ GeV. These processes are not well understood yet. The nuSTORM facility [55] intends to study the interactions at these energies to understand these poorly known processes. Therefore, to study the neutrino interactions at such a wide range of energies the muon energy is expected to be between $1 < p_\mu < 6$ GeV/c. Additionally, the nuSTORM facility can also be optimized to study short-baseline oscillations with mass-squared difference $\Delta m_{\text{LSND}}^2 \sim 1\text{eV}^2$ which requires an $L/E \sim 1$ km/GeV. This can be achieved by nuSTORM with the neutrino beam in the vicinity of $E_\nu \sim 2$ GeV and a baseline of 2 km.

In our simulation we consider a far detector at a distance of 2 km from the source unless otherwise mentioned. The detector for the proposal has not yet been decided. In our case, following earlier studies [56] we chose a magnetized iron calorimeter detector because this detector can distinguish between ν_μ and $\bar{\nu}_\mu$ so we can study the $\nu_e \rightarrow \nu_\mu$ appearance channel as well as the $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ disappearance channel with the same beam. Alternatively, other detector choices can also be explored in the future. A 1.3 kt magnetized iron-scintillator calorimeter has been selected as the detector for short-baseline oscillation physics at nuSTORM as it has excellent charge selection and detection characteristics for muons. The neutrino-nucleon scattering is the dominant interaction in the energy range of the nuSTORM flux. The important channels for this

experiment are $\nu_e \rightarrow \nu_\mu$ appearance channel and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ disappearance channel.

The number of events in the i th energy bin are calculated as

$$n_\alpha^i = \frac{N}{L^2} \int_{E_i - \frac{\Delta E_i}{2}}^{E_i + \frac{\Delta E_i}{2}} dE' \times \int_0^\infty \epsilon(E) \phi_\beta(E) P_{\alpha\beta}(E) \sigma_\alpha(E) R^c(E, E') \epsilon^c(E') dE, \quad (1)$$

where E denotes the true neutrino energy and E' denotes the measured neutrino energy. $R^c(E, E')$ denotes the smearing matrix, which relates the true and the measured energy. This includes both kinematic smearing and the smearing due to energy reconstruction. This is often taken as a Gaussian. Migration matrices that give the probability for a neutrino generated in the i th energy bin to be reconstructed in the j th energy bin, if available from detector simulations, can also be used. $\epsilon^c(E')$ denotes the postsmeared efficiency which contains, for instance, the information on energy cuts used. $\epsilon(E)$ denotes the presmearing efficiency.

In our analysis we have taken the energy resolution as a

Gaussian with $R^c(E, E') = \frac{1}{\sigma(E)\sqrt{2\pi}} e^{-\frac{(E-E')^2}{2\sigma^2(E)}}$ and $\sigma(E) = 0.15E$. The energy cuts are incorporated as “postsmeared efficiencies” as follows:

$$\epsilon^c(E') = 0; \quad 0 \text{ GeV} < E' < 1 \text{ GeV}, \quad (2)$$

$$\epsilon^c(E') = 1; \quad E' > 1 \text{ GeV}. \quad (3)$$

The event rates at the detector (multiplied by the efficiencies) and the corresponding presmearing efficiencies are given in Table I and the unoscillated flux is given in Fig. 1.

The impact of the neutral current events is evaluated using a χ^2 which is defined as

$$\chi_{\text{tot}}^2 = \min_{\xi, \omega} \left\{ \sum_r (\chi_{\text{stat}}^2(\omega, \xi) + \chi_{\text{pull}}^2(\xi))_r \right\}. \quad (4)$$

The r denotes the “rules,” the statistical χ^2 is χ_{stat}^2 , and systematic uncertainties are incorporated by χ_{pull}^2 calculated

TABLE I. The events observed at the detector are equal to the expected number of events at the detector multiplied by their efficiencies according to [29,30].

Channel	N_{events}	Efficiency at the detector
$\nu_e \rightarrow \nu_\mu$ CC	61	0.18
$\nu_e \rightarrow \nu_e$ CC	39865	0.18
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ NC	8630	0.18
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ CC	114983	0.94
$\nu_e \rightarrow \nu_e$ NC	13605	0.18

FIG. 1. The unoscillated ν_e and $\bar{\nu}_\mu$ flux extracted from the storage ring. The flux is evaluated for (3.8 ± 0.38) GeV/ c muon decay at a distance of 2 km [29].

by the method of pulls with pull variables ξ . The significance over each rule is calculated separately, and the total χ^2 is calculated by summation over all the various rules. Each rule signifies a different channel. The total χ^2 is marginalized over the oscillation parameters. The relevant oscillation parameters are represented by ω . The statistical χ_{stat}^2 is calculated assuming Poisson distribution,

$$\chi_{\text{stat}}^2 = \sum_i 2 \left(N_i^{\text{test}} - N_i^{\text{true}} - N_i^{\text{true}} \log \frac{N_i^{\text{test}}}{N_i^{\text{true}}} \right). \quad (5)$$

Here, i stands for the number of bins and N_i^{test} and N_i^{true} stands for total number of test and true events, respectively. To include the effects of systematics in N_i^{test} , the normalization and energy calibration errors are parametrized using the “pull” and “tilt” variables, respectively. These are incorporated as follows:

$$N_i^{(k)\text{test}}(\omega, \xi) = \sum_{k=s,b} N_i^{(k)}(\omega) \left[1 + c_i^{(k)\text{norm}} \xi^{(k)\text{norm}} + c_i^{(k)\text{tilt}} \xi^{(k)\text{tilt}} \frac{E_i - \bar{E}}{E_{\text{max}} - E_{\text{min}}} \right], \quad (6)$$

where $k = s(b)$ represent the signal (background) events. The effect of the pull variable ξ^{norm} (ξ^{tilt}) on the number of events is denoted by c_i^{norm} (c_i^{tilt}). The bin-by-bin mean reconstructed energy is represented by E_i where i represents the bin. E_{min} , E_{max} and $\bar{E} = (E_{\text{max}} + E_{\text{min}})/2$ are the minimum energy, maximum energy, and the mean energy over this range.

FIG. 2. The distribution of events observed in the absence of oscillation. A bin with bin width of 0.3 GeV. The left plot shows the appearance events while the right is for the disappearance events.

The signal (background) normalization uncertainty for the appearance channel is taken as 1% (10%) [29,30] while for ν_μ channel they are kept at 5% (10%). For NC the signal and background errors are taken to be 5% and 10%, respectively. A background rejection factor of 10^{-3} is used for the disappearance channel while 10^{-5} is used for the appearance channel [29,30]. For NC events we use a background rejection factor of 10^{-4} . We have checked that χ^2 does not depend significantly on the background rejection factor for the NC analysis. The unoscillated events observed at the detector have been shown in Fig. 2.

Data are generated assuming the standard three-neutrino oscillations scenario as the null hypothesis and the new physics scenario under study is used as the alternative hypothesis. Schematically the number of events in the different channels can be written as

$$N_\mu^{\text{CC}} = \Phi(\nu_e) P_{e\mu} \sigma_{\text{CC}}, \quad (7)$$

$$N_{\bar{\mu}}^{\text{CC}} = \Phi(\bar{\nu}_\mu) P_{\bar{\mu}\bar{\mu}} \sigma_{\text{CC}}, \quad (8)$$

$$N_{\text{total}}^{\text{NC}} = \Phi(\bar{\nu}_\mu)(1 - P_{\mu s})\sigma_{\text{NC}} + \Phi(\nu_e)(1 - P_{es})\sigma_{\text{NC}}. \quad (9)$$

III. RESULTS AND DISCUSSIONS

A. Sterile neutrino

Since we are considering a distance of ~ 2 km and $E \sim 3$ GeV, there can be oscillations governed by a mass-squared difference of order eV^2 . Other terms do not contribute since the oscillation wavelengths are much larger. Thus we have the “one mass scale dominance” (OMSD) approximation in which the oscillation probabilities can be cast into an effective two flavor form. For the $3 + 1$ picture, under the OMSD approximation, one has

$$P_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) \quad (10)$$

and

$$P_{\alpha\alpha} = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right). \quad (11)$$

Bounds on individual mixing angles are derived using the parametrization

$$U = R_{34}\tilde{R}_{24}\tilde{R}_{14}R_{23}\tilde{R}_{13}R_{12}. \quad (12)$$

Since we are in an effective two-generation approximation, the phases do not appear in the oscillation probabilities, and ignoring them one has

TABLE II. The values of the three neutrino oscillation parameters [57,58] and the representative values for $3 + 1$ neutrino mixing [14] used in the present analysis.

Oscillation parameters	Value considered to simulate nuSTORM
$\sin^2 \theta_{13}$	0.022
$\sin^2 \theta_{12}$	0.31
$\sin^2 \theta_{23}$	0.558
Δm_{21}^2 (eV^2)	7.39×10^{-5}
$ \Delta m_{31}^2 $ (eV^2)	2.52×10^{-3}
δ	0°
$\sin^2 \theta_{14}$	0.025
$\sin^2 \theta_{24}$	0.0023
Δm_{41}^2 (eV^2)	0.89

$$\begin{aligned}
U_{e4} &= \sin \theta_{14}, \\
U_{\mu 4} &= \cos \theta_{14} \sin \theta_{24}, \\
U_{\tau 4} &= \cos \theta_{14} \sin \theta_{24}, \\
U_{s4} &= \cos \theta_{14} \cos \theta_{24} \cos \theta_{34}.
\end{aligned} \quad (13)$$

The relevant oscillation probabilities are given as

$$P_{e\mu} = 4 \cos^2 \theta_{14} \sin^2 \theta_{14} \sin^2 \theta_{24} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right), \quad (14)$$

$$\begin{aligned}
P_{\mu\mu} &= 1 - 4 \sin^2 \theta_{24} \cos^2 \theta_{14} (1 - \sin^2 \theta_{24} \cos^2 \theta_{14}) \\
&\times \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right), \quad (15)
\end{aligned}$$

$$P_{\mu s} = 4 \cos^4 \theta_{14} \cos^2 \theta_{24} \cos^2 \theta_{34} \sin^2 \theta_{24} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right), \quad (16)$$

$$P_{es} = 4 \cos^2 \theta_{14} \sin^2 \theta_{14} \cos^2 \theta_{24} \cos^2 \theta_{34} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right). \quad (17)$$

The comparison between the event spectrum three neutrino scenarios and 3 + 1 neutrino mixing is shown in Fig. 3 for the appearance channel and the disappearance channel using the oscillations parameters from Table II. In the case of the appearance channel the oscillations due to Δm_{31}^2 are yet to develop so there are no events for three neutrino mixing. But such short baselines are enough to develop oscillations due to $\Delta m_{41}^2 \sim 1\text{eV}^2$. Therefore, the appearance flux is nonzero in the case of 3 + 1 neutrino mixing, which makes such experiments ideal for new physics searches. The same

reason is also valid for the disappearance channel where the flux in the case of 3 + 1 neutrino mixing is less compared to that of three neutrino mixing,

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 = 4s_{14}^2 c_{14}^2 s_{24}^2, \quad (18)$$

$$\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) = 4c_{14}^2 s_{24}^2(1 - c_{14}^2 s_{24}^2). \quad (19)$$

Figure 4 shows the bounds on Δm_{41}^2 with respect to the effective mixing angles $\theta_{\mu e}$ and $\theta_{\mu\mu}$ for baselines of 2 km and 3.5 km. The oscillation amplitudes satisfy $P_{e\mu} \propto s_{14}^2 s_{24}^2$; $P_{\mu\mu} \propto 1 - s_{24}^2$; and $P_{es} + P_{\mu s} \propto s_{14}^2 + s_{24}^2$ [see Eqs. (14)–(17)]. Therefore, in the case of the appearance channel, $P_{e\mu}$ can constrain the effective mixing angle $\sin^2 2\theta_{\mu e}$ which is a product of $s_{14}^2 s_{24}^2$ while the neutral-current channel cannot constrain the product of $s_{14}^2 s_{24}^2$ and hence cannot efficiently constrain $\sin^2 2\theta_{\mu e}$. The disappearance channel effectively probes the parameter $\theta_{\mu\mu}$ in terms of the parameter s_{24}^2 , also the neutral current channel probes $s_{14}^2 + s_{24}^2$; hence, the neutral current channel can significantly constrain the parameter $\theta_{\mu\mu}$. From [17] we can see that the current global best fit in the Δm_{41}^2 - $\sin^2 2\theta_{\mu e}$ plane lies around $\Delta m_{41}^2 \sim 1\text{eV}^2$ and $\sin^2 2\theta_{\mu e} \sim 10^{-3}$, so nuSTORM has the capability to test the current best fit and can constrain the parameter space further up to $\sin^2 2\theta_{\mu e} \sim 10^{-4}$. The current best fit for the Δm_{41}^2 - $\sin^2 2\theta_{\mu\mu}$ plane which is $\Delta m_{41}^2 \sim 1\text{eV}^2$ and $\sin^2 2\theta_{\mu\mu} \sim 10^{-1}$ also lies within the testable region of the nuSTORM experiment. Therefore, nuSTORM not only can test the current allowed parameter space but also can put further constraints on the currently allowed parameter space. The 2 km baseline was

FIG. 3. The distribution of events observed 3 neutrino and 3 + 1 neutrino scenarios. A bin with bin width of 0.3 GeV. The left plot shows the appearance events while the right is for the disappearance events. The magenta histograms are for events for standard three neutrino scenario while the black histograms are for 3 + 1 neutrino mixing.

FIG. 4. The testable regions for sterile neutrinos as predicted by nuSTORM in terms of Δm_{41}^2 vs $\sin^2 \theta_{\mu e}$ for the left plots and Δm_{41}^2 vs $\sin^2 \theta_{\mu\mu}$ for the right. The first row indicates the sensitivities or baseline of 2 km while the second row for 3.5 km. Each plot consists of 3 contours of 99% confidence level significance exclusion regions for various channels as labeled in the plots.

chosen for comparison to the results presented in [59]. The choice of the 3.5 km baseline was motivated by the fact that this places the detector at oscillation maxima for $\Delta m_{41}^2 \sim 1 \text{ eV}^2$. If we study the bottom panel of Fig. 4, we observe that the best sensitivities for both $\theta_{\mu e}$ and $\theta_{\mu\mu}$ are observed around $\Delta m_{41}^2 \sim 1 \text{ eV}^2$, which is expected. Proceeding to the top panel of Fig. 4 we find that the most sensitive region has shifted to $\Delta m_{41}^2 \sim 1.2 \text{ eV}^2$; this is expected because $\Delta m_{41}^2 L \approx 3.7 \text{ eV}^2 \text{ km}$. However, the overall sensitivity is better for the lower baseline of 2 km as the lower baseline has a lower statistical uncertainty because of a higher flux at the detector.

Figure 5 presents the predicted θ_{14} , θ_{24} , and θ_{34} bounds expected from nuSTORM. The first plot from Fig. 5 shows the θ_{14} versus θ_{24} exclusion region considering the data generated from three flavor oscillations with parameters as given in Table II, but setting the fourth generation parameters to zero. The solid orange line shows the θ_{14} versus θ_{24} exclusion region predicted from the appearance channel;

the relevant probability for this channel is $P_{e\mu}$ given by the expression in Eq. (14). As, the allowed regions for θ_{14} and θ_{24} are small; hence the expression for $P_{e\mu}$ at constant energy and baseline is roughly $\propto \theta_{14}^2 \theta_{24}^2$ which explains the hyperbolic nature of the charged current appearance plot. The disappearance probability $P_{\bar{\mu}\bar{\mu}}$ approximately reduces to $1 - 4\theta_{24}^2$, which is independent of θ_{14} , so θ_{14} remains unaffected by the disappearance channel. Another important channel that can be probed is the neutral-current channel. The total contribution to the neutral-current channel comes from $P_{\mu s} + P_{e s}$ because neutral-current events from neutrinos and antineutrinos cannot be differentiated by the detector. The total neutral-current probability approximately reduces to $P_{\mu s} + P_{e s} \propto \theta_{14}^2 + \theta_{24}^2$, which describes the approximate elliptical nature of the neutral current channel given by red dashed lines in Fig. 5. The total charged current (CC) event curve (blue dashed curve) is the total contribution of appearance CC and disappearance CC. While the green dotted curve presents

FIG. 5. The testable regions for sterile neutrinos at nuSTORM for $\Delta m_{41}^2 = 1 \text{ eV}^2$ and baseline of 2 km in terms of θ_{14} , θ_{24} , and θ_{34} bounds. Here, θ_{14} , θ_{24} , and θ_{34} are in degrees. The first, second, and third plots present the $\theta_{14}(\text{test})$ vs $\theta_{24}(\text{test})$, $\theta_{14}(\text{test})$ vs $\theta_{34}(\text{test})$, and $\theta_{24}(\text{test})$ vs $\theta_{34}(\text{test})$ contours, respectively. Each plot consists of 5 contours of 99% confidence level significance exclusion regions for various channels as labeled in the plots.

the contribution of all the above channels, i.e., the total CC and NC event samples, it is clear from the figure that the inclusion of NC events can put stringent bounds on both θ_{14} and θ_{24} . We can conclude from this study that nuSTORM will be able to test θ_{14} and θ_{24} up to 6° and 7.5° , respectively. Comparing the results obtained with the expected sensitivity of DUNE [60] it was found that neutral current events from DUNE can resolve θ_{14} up to 10° and θ_{24} up to 15° with 5% systematics for $\Delta m_{41}^2 = 0.5 \text{ eV}^2$.

The second and third plots in the figure show the ability of nuSTORM to constrain θ_{14} and θ_{24} with respect to θ_{34} . Taking all the channels into account both θ_{14} and θ_{24} can be approximately constrained up to 4° at nuSTORM. In both the plots it is clear that the charged current interactions are independent of θ_{34} , which is also understood from the expressions for $P_{e\mu}$ and $P_{\bar{\mu}\bar{\mu}}$. The only dependence on θ_{34} can come from the neutral current channel. However, $P_{e\mu} + P_{\bar{\mu}\bar{\mu}} \propto \cos^2 \theta_{34}$, as a result of which there is weak dependence of θ_{34} on the neutral current events; hence θ_{34} cannot be constrained by neutral current events in nuSTORM.

The left plot in Fig. 6 shows the effect of varying the baseline of nuSTORM on the bounds in the θ_{14} and θ_{24} planes for $\Delta m_{41}^2 = 1 \text{ eV}^2$. The best sensitivity of an experiment is observed at the oscillation maxima. The first oscillation maximum is given by $1.27\Delta m_{41}^2 L/E = \pi/2$. As the mean energy of the experiment is $\sim 3 \text{ GeV}$,

$\Delta m_{41}^2 L \approx 3.7 \text{ eV}^2 \text{ km}$. It is evident from the relation that probing a larger Δm_{41}^2 requires a smaller baseline (L) and vice versa. Analyzing the red curves in Fig. 6, which show the result for the baseline of 100 m, we observe that as Δm_{41}^2 is increased the sensitivity also increases. Similarly, if we observe the green curves representing a 1 km baseline, we observe that the best sensitivity is obtained for the case $\Delta m_{41}^2 = 3.5 \text{ eV}^2$ which is expected from the above relation. Deviation from $\Delta m_{41}^2 = 3.5 \text{ eV}^2$ on either side compromises the sensitivity. The blue curves demonstrate the sensitivities of the 2 km baseline for nuSTORM. The $\Delta m_{41}^2 \approx 1.8 \text{ eV}^2 \text{ km}$ is expected to have the best sensitivity for the 2 km baseline. As we increase the Δm_{41}^2 gradually the sensitivity decreases with increasing Δm_{41}^2 . We observe that the 1 km baseline has good sensitivity for both θ_{14} and θ_{24} consistently over the range of Δm_{41}^2 .

B. Nonunitarity

In the presence of nonunitarity, the time evolution of the mass eigenstate in vacuum is

$$i \frac{d|\nu_i\rangle}{dt} = H|\nu_i\rangle, \quad (20)$$

where H is the Hamiltonian in the mass basis. After time $t(\equiv L)$, the flavor state can be written as

FIG. 6. The testable regions for sterile neutrinos at nuSTORM in terms of θ_{14} vs θ_{24} bounds. Here, θ_{14} and θ_{24} are in degrees. The first plot presents the $\theta_{14}(\text{test})$ vs $\theta_{24}(\text{test})$ for $\Delta m_{41}^2 = 1 \text{ eV}^2$, the second plot for $\Delta m_{41}^2 = 3.5 \text{ eV}^2$, and the third plot for $\Delta m_{41}^2 = 10 \text{ eV}^2$. Each plot consists of 3 contours of 99% confidence level significance exclusion regions for various baselines as labeled in the plots.

$$|\nu_\alpha(t)\rangle = N_{ai}^* |\nu_i(t)\rangle = N_{ai}^* (e^{-iHt})_{ij} |\nu_j(t=0)\rangle. \quad (21)$$

In this framework the mixing matrix N can be parametrized as

$$N = N^{NP} U = \begin{bmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{bmatrix} U; \quad (22)$$

where U is the PMNS matrix, N^{NP} is the left triangle matrix which parametrizes the nonunitarity. In the matrix N^{NP} the diagonal elements are real and the off-diagonal elements can be complex.

The above discussions lead us to the transition probability:

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = |N_{ai}^* \text{diag}(e^{-i\Delta m_{i1}^2 t/2E})_{ij} N_{\beta j}|^2. \quad (23)$$

Using the above parametrization the transition probabilities $P_{\mu e}$ and $P_{\mu\mu}$ can be written

$$P_{e\mu} = \alpha_{11}^2 |\alpha_{21}|^2 - 4 \sum_{j>i} \text{Re}[N_{\mu j}^* N_{ej} N_{\mu i} N_{ei}^*] \sin^2\left(\frac{\Delta m_{ji}^2 L}{4E}\right) + 2 \sum_{j>i} \text{Im}[N_{\mu j}^* N_{ej} N_{\mu i} N_{ei}^*] \sin\left(\frac{\Delta m_{ji}^2 L}{2E}\right), \quad (24)$$

$$P_{\mu\mu} = (|\alpha_{21}|^2 + \alpha_{22}^2)^2 - 4 \sum_{j>i} |N_{\mu j}|^2 |N_{\mu i}|^2 \sin^2\left(\frac{\Delta m_{ji}^2 L}{4E}\right). \quad (25)$$

For nuSTORM, with a baseline of 2 km, the transition probabilities become independent of the baseline length because $\frac{\Delta m^2 L}{E} \ll 1$. Therefore, the relevant transition probabilities are

$$P_{e\mu} = \alpha_{11}^2 |\alpha_{21}|^2, \text{ and} \quad (26)$$

$$P_{\mu\mu} = (|\alpha_{21}|^2 + \alpha_{22}^2)^2. \quad (27)$$

Along with the charged current events, neutral-current events can also be helpful in studying the nonunitarity of the mixing matrix. The important probabilities for the inclusion of the neutral current events are

$$P_{es} = 1 - (\alpha_{11}^2 (\alpha_{11}^2 + |\alpha_{21}|^2 + |\alpha_{31}|^2)); \text{ and} \quad (28)$$

$$P_{\mu s} = 1 - (\alpha_{11}^2 |\alpha_{21}|^2 + \alpha_{22}^4 + 2\alpha_{22}^2 |\alpha_{21}|^2 + \alpha_{22}^2 |\alpha_{32}|^2). \quad (29)$$

The detector cannot distinguish the various kinds of neutral current events, so we can probe the total neutral current probability:

$$P_{es} + P_{\mu s} = 2 - (\alpha_{11}^2 (\alpha_{11}^2 + 2|\alpha_{21}|^2 + |\alpha_{31}|^2) + \alpha_{22}^2 (\alpha_{22}^2 + 2|\alpha_{21}|^2 + |\alpha_{32}|^2)). \quad (30)$$

The capability of nuSTORM to probe the nonunitarity parameters α_{11} , $|\alpha_{21}|$, and α_{22} are shown in Fig. 7. Each plot presents three cases for three different baselines: 100 m; 1 km; and 2 km, plotted with magenta, green, and blue curves, respectively. The first plot in Fig. 7 presents the sensitivity of nuSTORM to the parameter α_{11} , with the diagonal parameters $\alpha_{22} = \alpha_{33} = 1.0$ and the off-diagonal parameters $|\alpha_{21}|$, $|\alpha_{31}|$, and $|\alpha_{32}|$ fixed at 0.01. Unitarity requires that the parameters be set to zero. However, the value of -0.01 has been drawn so that a contribution from the $\nu_e \rightarrow \nu_\mu$ channel remains. Beginning with the first case, which shows χ^2 as a function of α_{11} , under the condition that the parameters $|\alpha_{21}| = 0.1$ and $\alpha_{22} = 1.0$. The true data have been generated keeping α_{11} fixed at unity while the test data have been generated by varying α_{11} between 0.9 and 1.0 while keeping all other parameters fixed. The relevant channel to study the α_{11} sensitivity is the $P_{e\mu}$

appearance channel because the probability $P_{\bar{\mu}\bar{\mu}}$ is independent of α_{11} . Under the above conditions $P_{e\mu} \sim 0.01\alpha_{11}^2$, therefore, the sensitivity plot has a quadratic dependence on α_{11} . From the expression it is clear that $P_{e\mu}$ is independent of the baseline so a change in sensitivity to α_{11} by varying the baseline is due to the change in the flux which occurs due to the change in the baseline. Hence, we observe that the sensitivity increases as the baseline is reduced. The 3σ sensitivity for α_{11} is achieved for $\alpha_{11} = 0.93$ for a 2 km baseline, which increases to 0.96 for the 1 km baseline, and the best result is achieved for the 100 m baseline where the same sensitivity is achieved for $\alpha_{11} = 0.99$. If neutral current events are also combined, in the charged current events a substantial improvement in the sensitivity is observed. The 3σ sensitivity for $\alpha_{11} = 0.995$ when CC and NC both are taken into consideration. Similar studies have been performed at DUNE and T2HK [48] where the 3σ sensitivity for $\alpha_{11} \approx 0.94$ for DUNE and $\alpha_{11} \approx 0.96$ for T2HK. Therefore, we can see that nuSTORM with a 2 km baseline has sensitivity similar to DUNE and with baseline 1 km has similar sensitivity to T2HK; when the baseline is decreased further, the sensitivity increases further exceeding the sensitivities attained by DUNE or T2HK.

The second plot in Fig. 7 shows the χ^2 vs $|\alpha_{21}|$ sensitivity with both the nonunitarity parameters α_{11} and α_{22} taken to be unity. Under such conditions $P_{e\mu}$ just reduces to $|\alpha_{21}|^2$ and $P_{\bar{\mu}\bar{\mu}}$ becomes $(1 + |\alpha_{21}|^2)^2$ which can be approximated

FIG. 7. The sensitivity to nuSTORM for the nonunitarity parameters α_{11} , $|\alpha_{21}|$, and α_{22} . The y axis in the plots represent χ^2 , while the x axis denotes α_{11} , $|\alpha_{21}|$, and α_{22} for plots, respectively. In each plot the dashed lines are for the contribution of only charge current interactions while the solid lines are for the combination of charge current and neutral current. The magenta, green, and blue curves represent the sensitivities at the baseline of 100 m, 1 km, and 2 km, respectively.

to be $\sim 1 + 2|\alpha_{21}|^2$. Unlike the case discussed above, where only the appearance channel contributes, both the appearance and the disappearance channels contribute to the sensitivity to $|\alpha_{21}|$. Since both the channels depend on $|\alpha_{21}|^2$, we get a quadratic dependence of the χ^2 on $|\alpha_{21}|$. In this case the true data have been generated at $\alpha_{11} = \alpha_{22} = \alpha_{33} = 1.0$, $|\alpha_{21}| = |\alpha_{31}| = |\alpha_{32}| = 0$, and $\alpha_{22} = 1.0$, and the test data have been generated with $|\alpha_{21}|$ varying in the range 0.0 to 0.01. In this case also we find that the sensitivity is dependent on the baseline for the same reason as discussed previously. The $|\alpha_{21}|$ sensitivity reaches 3σ for $|\alpha_{21}| = 0.011$ at the 2 km baseline, $|\alpha_{21}| = 0.006$ at the baseline 1 km, and $|\alpha_{21}| = 0.003$ at the baseline 100 m. Neutral current events do not contribute to the $|\alpha_{21}|$ sensitivity; this is because $P_{\text{NC}} \approx 2 - (\alpha_{11}^2 + \alpha_{22}^2)(\alpha_{11}^2 + 2|\alpha_{21}|^2 + |\alpha_{31}|^2)$ where $(\alpha_{11}^2 + 2|\alpha_{21}|^2 + |\alpha_{31}|^2) \approx 1$ and as a result the NC channel cannot probe $|\alpha_{21}|$ independently. Comparing the sensitivities with DUNE and T2HK [48] we observe that nuSTORM can reach 3σ sensitivity for $|\alpha_{21}|$ for an order of magnitude smaller values of $|\alpha_{21}|$. nuSTORM has a significant advantage over DUNE and T2HK which can reach 3σ sensitivities for $|\alpha_{21}| = 0.08$ and 0.04, respectively.

The third figure presents the sensitivity to the parameter α_{22} . $P_{e\mu}$ is independent of α_{22} but $P_{\bar{\mu}\bar{\mu}}$ is sensitive to α_{22} . The true data have been generated by considering unitary evolution, i.e., $\alpha_{11} = 1.0$, $|\alpha_{21}| = 0$, and $\alpha_{22} = 1.0$, which reduces $P_{\bar{\mu}\bar{\mu}}$ to α_{22}^4 . The test data have been generated by taking $\alpha_{11} = 1.0$, $|\alpha_{21}| = 0$ and varying α_{22} from 0.9 to 1.0. An interesting feature observed here is the independence of α_{22} on the baseline. This can be attributed to the fact that the sensitivity is solely dependent on the disappearance channel which already has enough statistics at 2 km; hence reducing the baseline does not help. The introduction of neutral current events is expected to increase the α_{22} sensitivity because of the dependence of P_{NC} on α_{22}^2 . However, no improvement is observed because the introduction of the channel increases the statistics but it already had enough statistics from the disappearance channel itself. The 3σ sensitivity is reached at $\alpha_{22} = 0.97$ for all baselines. Again from [48], the 3σ sensitivities for DUNE and T2HK for α_{22} can be attained for $\alpha_{22} \approx 0.98$ for both the experiments.

IV. CONCLUSIONS

In this work we have investigated the capabilities of nuSTORM to explore two new physics scenarios: (i) the existence of eV^2 scale oscillation, suggested as an explanation of LSND/MiniBOONE anomalies, and (ii) the nonunitarity of the neutrino mixing matrix. nuSTORM is proposed primarily to measure the $\nu_e N$ and $\nu_\mu N$ cross

sections. It was shown in [29,30] that nuSTORM can also play an important role to study active-sterile oscillations governed by an eV^2 mass squared difference. In this work, we have studied the effect of including neutral current events and checked whether this can give improved sensitivity to sterile-neutrino searches. nuSTORM will have the capability to study two main channels, the conversion probability $P_{\mu e}$, and the survival probability $P_{\bar{\mu}\bar{\mu}}$ with the proposed MIND detector. Whereas for oscillations involving active neutrinos the NC events are not sensitive to oscillation parameters, for oscillations involving the sterile neutrinos the neutral current events are also sensitive to the oscillation parameters through the probabilities involving conversion to sterile neutrinos $P_{\mu s}$ and P_{es} . Considering a 2 km baseline it is observed that taking only CC interactions can constrain the mixing angle $\theta_{24} \lesssim 7.5^\circ$ but cannot constrain θ_{24} , which can be achieved with the inclusion of NC interactions. For nonzero values of θ_{24} , the constraint on θ_{14} also improves with inclusion of NC events. Since nuSTORM is a proposed experiment, baseline optimization is important to maximize physics output. When we consider various baselines we find that the baseline of 1 km gives a good overall sensitivity for both θ_{14} and θ_{24} over a wide range of Δm_{41}^2 .

For the other new-physics scenario, nonunitarity of the lepton mixing matrix, studied in this work, we find that nuSTORM can probe the nonunitarity parameters α_{11} , $|\alpha_{21}|$, and α_{22} . The 3σ sensitivities for α_{11} , $|\alpha_{21}|$, and α_{22} are obtained at 0.995, 0.011, and 0.97, respectively, for 2 km baselines combining both CC and NC events. The sensitivities for α_{11} and $|\alpha_{21}|$ significantly improve as the baseline is reduced.

In conclusion, we find that apart from measuring neutrino cross sections with per mil precision, nuSTORM can also contribute significantly by probing new physics scenarios beyond the Standard Model.

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- [1] C. Athanassopoulos *et al.* (LSND Collaboration), Evidence for Anti-Muon-Neutrino $\rightarrow$ Anti-Electron-Neutrino Oscillations from the LSND Experiment at LAMPF, *Phys. Rev. Lett.* **77**, 3082 (1996).
- [2] A. Aguilar-Arevalo *et al.* (LSND Collaboration), Evidence for neutrino oscillations from the observation of anti-neutrino(electron) appearance in a anti-neutrino(muon) beam, *Phys. Rev. D* **64**, 112007 (2001).
- [3] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), Improved Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillations in the Mini-BooNE Experiment, *Phys. Rev. Lett.* **110**, 161801 (2013).
- [4] A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), Significant Excess of ElectronLike Events in the Mini-BooNE Short-Baseline Neutrino Experiment, *Phys. Rev. Lett.* **121**, 221801 (2018).
- [5] M. A. Acero, C. Giunti, and M. Laveder, Limits on $\nu(e)$ and anti- $\nu(e)$ disappearance from Gallium and reactor experiments, *Phys. Rev. D* **78**, 073009 (2008).
- [6] T. A. Mueller *et al.*, Improved Predictions of reactor anti-neutrino spectra, *Phys. Rev. C* **83**, 054615 (2011).
- [7] G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier, and A. Letourneau, The reactor antineutrino anomaly, *Phys. Rev. D* **83**, 073006 (2011).
- [8] M. Maltoni, T. Schwetz, M. Tortola, and J. Valle, Constraining neutrino oscillation parameters with current solar and atmospheric data, *Phys. Rev. D* **67**, 013011 (2003).
- [9] S. Goswami, Accelerator, reactor, solar and atmospheric neutrino oscillation: Beyond three generations, *Phys. Rev. D* **55**, 2931 (1997).
- [10] X. Chu, B. Dasgupta, M. Dentler, J. Kopp, and N. Saviano, Sterile neutrinos with secret interactions—Cosmological discord?, *J. Cosmol. Astropart. Phys.* **11** (2018) 049.
- [11] G. Gelmini, S. Palomares-Ruiz, and S. Pascoli, Low Reheating Temperature and the Visible Sterile Neutrino, *Phys. Rev. Lett.* **93**, 081302 (2004).
- [12] C. E. Yaguna, Sterile neutrino production in models with low reheating temperatures, *J. High Energy Phys.* **06** (2007) 002.
- [13] P. de Salas, M. Lattanzi, G. Mangano, G. Miele, S. Pastor, and O. Pisanti, Bounds on very low reheating scenarios after Planck, *Phys. Rev. D* **92**, 123534 (2015).
- [14] S. Gariazzo, C. Giunti, M. Laveder, and Y. Li, Updated Global $3 + 1$ analysis of short-Baseline neutrino oscillations, *J. High Energy Phys.* **06** (2017) 135.
- [15] M. Dentler, J. Hernandez-Cabezudo, J. Kopp, P. A. Machado, M. Maltoni, I. Martinez-Soler, and T. Schwetz, Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos, *J. High Energy Phys.* **08** (2018) 010.
- [16] M. Maltoni, T. Schwetz, M. A. Tortola, and J. W. F. Valle, Ruling out four neutrino oscillation interpretations of the LSND anomaly?, *Nucl. Phys.* **B643**, 321 (2002).
- [17] A. Diaz, C. A. Argüelles, G. H. Collin, J. M. Conrad, and M. H. Shaevitz, Where are we with light sterile neutrinos?, *Phys. Rep.* **884**, 1 (2020).
- [18] F. Dydak *et al.*, A search for muon-neutrino oscillations in the Δm^2 range $0.3 - 90$ eV 2 , *Phys. Lett.* **134B**, 281 (1984).
- [19] M. G. Aartsen *et al.* (IceCube Collaboration), Observation and characterization of a cosmic muon neutrino flux from the northern hemisphere using six years of IceCube data, *Astrophys. J.* **833**, 3 (2016).
- [20] P. Adamson *et al.* (MINOS Collaboration), Active to Sterile Neutrino Mixing Limits from Neutral-Current Interactions in MINOS, *Phys. Rev. Lett.* **107**, 011802 (2011).
- [21] K. Abe *et al.* (Super-Kamiokande Collaboration), Limits on sterile neutrino mixing using atmospheric neutrinos in Super-Kamiokande, *Phys. Rev. D* **91**, 052019 (2015).
- [22] M. G. Aartsen *et al.* (IceCube Collaboration), Search for sterile neutrino mixing using three years of IceCube Deep-Core data, *Phys. Rev. D* **95**, 112002 (2017).
- [23] P. Adamson *et al.* (NOvA Collaboration), Search for active-sterile neutrino mixing using neutral-current interactions in NOvA, *Phys. Rev. D* **96**, 072006 (2017).
- [24] C. Rott (JSNS 2 Collaboration), Status and prospects of the JSNS 2 experiment, *Proc. Sci., ICHEP2018* (2019) 185 [arXiv:1811.03321].
- [25] Y. J. Ko *et al.* (NEOS Collaboration), Sterile Neutrino Search at the NEOS Experiment, *Phys. Rev. Lett.* **118**, 121802 (2017).
- [26] A. P. Serebrov *et al.* (NEUTRINO-4 Collaboration), First observation of the oscillation effect in the neutrino-4 experiment on the search for the sterile neutrino, *Pis'ma Zh. Eksp. Teor. Fiz.* **109**, 209 (2019) [*JETP Lett.* **109**, 213 (2019)].
- [27] A. Haghighat, P. Huber, S. Li, J. M. Link, C. Mariani, J. Park, and T. Subedi, Observation of reactor antineutrinos with a rapidly-deployable surface-level detector, *Phys. Rev. Applied* **13**, 034028 (2020).
- [28] I. Alekseev *et al.* (DANSS Collaboration), Search for sterile neutrinos at the DANSS experiment, *Phys. Lett. B* **787**, 56 (2018).
- [29] C. D. Tunnell, Sterile neutrino sensitivity with wrong-sign muon appearance at nuSTORM, arXiv:1205.6338.
- [30] D. Adey *et al.* (nuSTORM Collaboration), Light sterile neutrino sensitivity at the nuSTORM facility, *Phys. Rev. D* **89**, 071301 (2014).
- [31] N. Allemandou *et al.* (STEREO Collaboration), The STEREO experiment, *J. Instrum.* **13**, P07009 (2018).
- [32] R. Acciarri *et al.* (DUNE Collaboration), Long-Baseline Neutrino Facility (LBNF) and deep underground neutrino experiment (DUNE), arXiv:1512.06148.
- [33] K. Abe *et al.* (Hyper-Kamiokande proto- Collaboration), Physics potentials with the second hyper-Kamiokande detector in Korea, *Prog. Theor. Exp. Phys.* **2018**, 063C01 (2018).
- [34] S. Weinberg, Baryon and Lepton Nonconserving Processes, *Phys. Rev. Lett.* **43**, 1566 (1979).
- [35] R. N. Mohapatra and G. Senjanovic, Neutrino Mass and Spontaneous Parity Nonconservation, *Phys. Rev. Lett.* **44**, 912 (1980).
- [36] S. Goswami and T. Ota, Testing non-unitarity of neutrino mixing matrices at neutrino factories, *Phys. Rev. D* **78**, 033012 (2008).
- [37] W. Rodejohann, Non-unitary lepton mixing matrix, leptogenesis and low energy CP violation, *Europhys. Lett.* **88**, 51001 (2009).
- [38] M. Malinsky, T. Ohlsson, and H. Zhang, Non-unitarity effects in a realistic low-scale seesaw model, *Phys. Rev. D* **79**, 073009 (2009).

- [39] S. Antusch, C. Biggio, E. Fernandez-Martinez, M. B. Gavela, and J. Lopez-Pavon, Unitarity of the leptonic mixing matrix, *J. High Energy Phys.* **10** (2006) 084.
- [40] S. Antusch, M. Blennow, E. Fernandez-Martinez, and J. Lopez-Pavon, Probing non-unitary mixing and CP -violation at a neutrino factory, *Phys. Rev. D* **80**, 033002 (2009).
- [41] M. Malinsky, T. Ohlsson, Z.-z. Xing, and H. Zhang, Non-unitary neutrino mixing and CP violation in the minimal inverse seesaw model, *Phys. Lett. B* **679**, 242 (2009).
- [42] M. Blennow, P. Coloma, E. Fernandez-Martinez, J. Hernandez-Garcia, and J. Lopez-Pavon, Non-unitarity, sterile neutrinos, and non-standard neutrino Interactions, *J. High Energy Phys.* **04** (2017) 153.
- [43] S. Antusch and O. Fischer, Non-unitarity of the leptonic mixing matrix: Present bounds and future sensitivities, *J. High Energy Phys.* **10** (2014) 094.
- [44] F. J. Escrihuela, D. V. Forero, O. G. Miranda, M. Tortola, and J. W. F. Valle, On the description of nonunitary neutrino mixing, *Phys. Rev. D* **92**, 053009 (2015); Erratum, *Phys. Rev. D* **93**, 119905 (2016).
- [45] D. Dutta and P. Ghoshal, Probing CP violation with T2K, NO ν A and DUNE in the presence of non-unitarity, *J. High Energy Phys.* **09** (2016) 110.
- [46] L. S. Miranda, P. Pasquini, U. Rahaman, and S. Razzaque, Searching for non-unitary neutrino oscillations in the present T2K and NO ν A data, [arXiv:1911.09398](https://arxiv.org/abs/1911.09398).
- [47] A. De Gouvea, K. J. Kelly, G. V. Stenico, and P. Pasquini, Physics with near tau-neutrino appearance at DUNE, *Phys. Rev. D* **100**, 016004 (2019).
- [48] D. Dutta and S. Roy, Non unitarity at DUNE and T2HK with charged and neutral current measurements, [arXiv:1901.11298](https://arxiv.org/abs/1901.11298).
- [49] S. P. Behera, A. Ghosh, S. Choubey, V. M. Datar, D. K. Mishra, and A. K. Mohanty, Search for the sterile neutrino mixing with the ICAL detector at INO, *Eur. Phys. J. C* **77**, 307 (2017).
- [50] K. Abe *et al.* (T2K Collaboration), Search for light sterile neutrinos with the T2K far detector super-Kamiokande at a baseline of 295 km, *Phys. Rev. D* **99**, 071103 (2019).
- [51] R. Gandhi, B. Kayser, S. Prakash, and S. Roy, What measurements of neutrino neutral current events can reveal, *J. High Energy Phys.* **11** (2017) 202.
- [52] J. Evans (MINOS Collaboration), The MINOS experiment: Results and prospects, *Adv. High Energy Phys.* **2013**, 182537 (2013).
- [53] P. Huber, M. Lindner, and W. Winter, Simulation of long-baseline neutrino oscillation experiments with GLOBES, *Comput. Phys. Commun.* **167**, 195 (2005).
- [54] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, New features in the simulation of neutrino oscillation experiments with GLOBES 3.0, *Comput. Phys. Commun.* **177**, 432 (2007).
- [55] K. Long, https://indico.cern.ch/event/765096/contributions/3296001/attachments/1785344/2906412/nuSTORM_Executive_Summary.pdf, European Particle Physics Strategy Update.
- [56] D. Adey *et al.* (nuSTORM Collaboration), nuSTORM–Neutrinos from STORed muons: Proposal to the Fermilab PAC, [arXiv:1308.6822](https://arxiv.org/abs/1308.6822).
- [57] N. 4.1, www.nu-fit.org, 2019.
- [58] I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, and T. Schwetz, Global analysis of three-flavour neutrino oscillations: Synergies and tensions in the determination of θ_{23} , δ_{CP} , and the mass ordering, *J. High Energy Phys.* **01** (2019) 106.
- [59] J.-B. Lagrange, Neutrinos from stored muons, nustorm, *Nucl. Part. Phys. Proc.* **273–275**, 1771 (2016).
- [60] P. Coloma, D. V. Forero, and S. J. Parke, DUNE sensitivities to the mixing between sterile and tau neutrinos, *J. High Energy Phys.* **07** (2018) 079.

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