Implications of an Improved Neutron-Antineutron Oscillation Search for Baryogenesis: A Minimal Effective Theory Analysis

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(Received 19 July 2018; revised manuscript received 26 September 2018; published 23 October 2018)

Future neutron-antineutron ($n\bar{n}$) oscillation experiments, such as at the European Spallation Source and the Deep Underground Neutrino Experiment, aim to find first evidence of baryon number violation. We investigate implications of an improved $n\bar{n}$ oscillation search for baryogenesis via interactions of $n\bar{n}$ mediators, parametrized by an effective field theory (EFT). We find that even in a minimal EFT setup there is overlap between the parameter space probed by $n\bar{n}$ oscillation and the region that can realize the observed baryon asymmetry of the Universe. The mass scales of exotic new particles are in the tera-electron-volt–peta-electron-volt regime, inaccessible at the LHC or its envisioned upgrades. Given the innumerable high energy theories that can match, or resemble, the minimal EFT that we discuss, future $n\bar{n}$ oscillation experiments could probe many viable theories of baryogenesis beyond the reach of other experiments.

DOI: 10.1103/PhysRevLett.121.171801

Introduction.—The search for physics beyond the standard model (BSM) requires effort at both high energy and intensity frontiers. In this regard, a particularly powerful probe is offered by rare processes that violate (approximate) symmetries of the SM, such as baryon and lepton numbers (B and L), which can be inaccessible to high energy colliders but within reach of low-energy experiments. A well-known example is proton decay, whose nonobservation leads to strong constraints on $\Delta B = \Delta L = \pm 1$ new physics even at the scale of grand unified theories (GUTs), $\sim 10^{16}$ GeV [1,2].

Baryon and lepton number violation are intricately tied to one of the outstanding puzzles in fundamental physics, the origin of the baryon asymmetry in the Universe. If baryogenesis occurs at temperatures above the weak scale, B - L violation is required to avoid washout by electroweak sphalerons. In this regard, constraints from proton decay (which conserves $B - L$) are not applicable. Here we consider instead B -violating, L -conserving new physics at an intermediate (sub-GUT) scale so that baryogenesis may proceed both above and below weak scale temperatures. From the low-energy point of view, effects of heavy new particles are encoded in higher dimensional operators

in an effective field theory (EFT), where B -violating, L -conserving interactions can appear first at the dimension-9 level [3], in the form of $|\Delta B| = 2$, $\Delta L = 0$ operators. In this case, neutron-antineutron ($n\bar{n}$) oscillation (see Ref. [4] for a recent review) is well placed to search for B -violating phenomena and shed light on baryogenesis [5].

Current measurements constrain the free neutron oscillation time to be $\tau_{n\bar{n}} \gtrsim 10^8$ s [6,7]. Upcoming experiments, in particular at the European Spallation Source (ESS) and also potentially the Deep Underground Neutrino Experiment (DUNE), are poised to improve the reach up to 10^9 – 10^{10} s [8–12]. As we will see in detail below, such numbers translate into new physics scales of roughly $(\tau_{n\bar{n}} \Lambda_{\text{QCD}}^6)^{1/5} \sim O(10^{5-6} \text{ GeV})$, well above the energies directly accessible at existing or proposed colliders. Discussions of the physics implications of a potential $n\bar{n}$ oscillation discovery, in particular for baryogenesis, are therefore both important and timely.

The purpose of this Letter is to explore the connection between $n\bar{n}$ oscillation and baryogenesis in the context of a minimal EFT extension of the SM that realizes direct low scale baryogenesis from B -violating decays of new particles mediating $n\bar{n}$ oscillation. While there exist numerous baryogenesis frameworks, such as electroweak baryogenesis [13], Affleck-Dine baryogenesis [14], and leptogenesis [15] (see, e.g., [16–24] for reviews), the choice of our minimal EFT is motivated from the bottom up by imminent improvements in $n\bar{n}$ oscillation searches. Despite being simplistic, this minimal setup provides a useful template to identify viable baryogenesis scenarios—which may be

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realized in a similar manner in more complex and realistic theories—that are compatible with an n - $\bar{n}$ oscillation signal within experimental reach (for discussions of some other baryogenesis scenarios that can also involve n - $\bar{n}$ oscillation signals, see, e.g., [25–43]).

Improved n - $\bar{n}$ oscillation searches and sensitivity to the scale of new physics.—Neutron-antineutron oscillation has been searched for in the past with both free neutrons [6,44,45] and neutrons bound inside nuclei [7,46–50]. Among free neutron oscillation searches, the Institut Laue-Langevin experiment [6] sets the best limit to date on the oscillation time, $\tau_{n\bar{n}} > 0.86 \times 10^8$ s at 90% C.L. Among intranuclear searches, Super-Kamiokande (Super-K) [7] provides the best limit, which, after correcting for nuclear effects, corresponds to $\tau_{n\bar{n}} > 2.7 \times 10^8$ s at 90% C.L. for the free neutron oscillation time. Improved n - $\bar{n}$ oscillation searches with both free and bound neutrons are under consideration, with sensitivities up to 10^{9-10} s envisioned at the ESS and DUNE [8–12].

We now elucidate the connection between $\tau_{n\bar{n}}$ and the new physics scale in the EFT context. The lowest dimension effective operators contributing to n - $\bar{n}$ oscillation at tree level are dimension-9 operators of the form $O_{n\bar{n}} \sim (uudddd)$. The classification of these operators dates back to the 1980s [51–55] and was refined recently in [56], which established an alternative basis that is more convenient for renormalization group (RG) running. A concise review of the full set of tree-level n - $\bar{n}$ oscillation operators is given in the Supplemental Material [57]. In what follows, we focus on one of these operators for illustration,

$$\mathcal{L} \supset c_1 \frac{1}{2} \epsilon_{ijk} \epsilon_{i'j'k'} (\bar{u}_i^c P_R d_j) (\bar{u}_{i'}^c P_R d_{j'}) (\bar{d}_k^c P_R d_{k'}) + \text{H.c.},$$

$$\text{with } c_1 \equiv (\Lambda_{n\bar{n}}^{(1)})^{-5}. \quad (1)$$

Here u, d are SM up and down quark fields, respectively, and u^c, d^c are their charge conjugates. $i^{(t)}, j^{(t)}, k^{(t)}$ are color indices, and “H.c.” denotes Hermitian conjugate. The operator suppression scale $\Lambda_{n\bar{n}}^{(1)}$ is generally a weighted (geometric) average of new particle masses, modulo appropriate powers of couplings and loop factors.

If the operator is generated by integrating out new particles at a high scale M , computing $\tau_{n\bar{n}}$ requires RG evolving the EFT down to a low scale μ_0 (usually chosen to be 2 GeV), where it can be matched onto lattice QCD. The leading contribution to RG rescaling reads [55,56]

$$\begin{aligned} \frac{c_1(\mu_0)}{c_1(M)} &= \left(\frac{\alpha_s^{(4)}(m_b)}{\alpha_s^{(4)}(\mu_0)} \right)^{6/25} \left(\frac{\alpha_s^{(5)}(m_t)}{\alpha_s^{(5)}(m_b)} \right)^{6/23} \left(\frac{\alpha_s^{(6)}(M)}{\alpha_s^{(6)}(m_t)} \right)^{2/7} \\ &= \{0.726, 0.684, 0.651, 0.624\} \\ \text{for } M &= \{10^3, 10^4, 10^5, 10^6\} \text{ GeV}. \end{aligned} \quad (2)$$

Here $\alpha_s^{(n_f)}$ is the effective strong coupling with n_f light quark flavors, whose value is obtained with the RUNDEC package [58]. Corrections from two-loop running as well as one-loop matching onto lattice QCD operators were recently computed [56] and are small, and they will be neglected in our calculations. No additional operators relevant for n - $\bar{n}$ oscillation are generated from RG evolution.

The $n \rightarrow \bar{n}$ transition rate is determined by the matrix element of the low-energy effective Hamiltonian between the neutron and antineutron states. Thus, once $\langle \bar{n} | O_{n\bar{n}}(\mu_0) | n \rangle$ are known, we can relate $\tau_{n\bar{n}} = |\langle \bar{n} | \mathcal{H}_{\text{eff}} | n \rangle|^{-1}$ to the six-quark operator coefficients. Recent progress in lattice calculations [59–61] has greatly improved the accuracy on $\langle \bar{n} | O_{n\bar{n}}(\mu_0) | n \rangle$ compared to previous bag model calculations [53,54] often used in the literature. Using the central values presented in [61], and assuming that the operator in Eq. (1) gives the dominant contribution to n - $\bar{n}$ oscillation, we can translate the Super-K limit into $\Lambda_{n\bar{n}}^{(1)} \gtrsim 3.8 \times 10^5$ GeV (for a representative RG rescaling factor of 0.7). An improvement on $\tau_{n\bar{n}}$ up to 10^9 ($10^{10}, 10^{11}$) s will correspond to probing $\Lambda_{n\bar{n}}^{(1)} \sim 4.9(7.8, 12.4) \times 10^5$ GeV. These numbers are representative of the whole set of $n - \bar{n}$ oscillation operators and do not vary significantly with the starting point of RG evolution M (see the Supplemental Material [57] for details).

A minimal EFT for n - $\bar{n}$ oscillation and baryogenesis.—One of the simplest possibilities for generating the operator in Eq. (1) at tree level is with a Majorana fermion X of mass M that couples to the SM via a dimension-6 operator of the form $(1/\Lambda^2) X u d d$, which originates at an even higher scale $\Lambda \gg M$ via some UV completion that we remain agnostic about. A familiar scenario that realizes this EFT setup is supersymmetry (SUSY) with R -parity violation (RPV), where the bino plays the role of X and the dimension-6 operator is obtained by integrating out squarks at a heavier scale. However, this simple EFT with a single BSM state does not allow for sufficient baryogenesis due to unitarity relations: in the absence of B -conserving decay channels, X decay cannot generate a baryon asymmetry at leading order in the B -violating coupling, a result known as the Nanopoulos-Weinberg theorem [62] (see [63] for a recent discussion); meanwhile, $2 \rightarrow 2$ processes $uX \rightarrow \bar{d}\bar{d}$ and $\bar{u}X \rightarrow dd$ are forced to have the same rate and thus do not violate CP .

A minimal extension that can accommodate both n - $\bar{n}$ oscillation and the observed baryon asymmetry involves two Majorana fermions X_1, X_2 (with $M_{X_1} < M_{X_2}$), each having a B -violating interaction $(1/\Lambda^2) X u d d$. In addition, a B -conserving coupling between the two is necessary to evade constraints from unitarity relations. In the context of RPV SUSY, this corresponds to the presence of a wino or gluino in addition to the bino, which is known to allow for sufficient baryogenesis [63–65].

Guided by minimality, we assume that $X_{1,2}$ are both SM singlets and consider just one of the many possible

B -conserving operators in addition to the two B -violating ones. Our minimal EFT thus consists of the following dimension-6 operators that couple $X_{1,2}$ to the SM [66]:

$$\begin{aligned}\mathcal{L} \supset & \eta_{X_1} \epsilon^{ijk} (\bar{u}_i^c P_R d_j) (\bar{d}_k^c P_R X_1) \\ & + \eta_{X_2} \epsilon^{ijk} (\bar{u}_i^c P_R d_j) (\bar{d}_k^c P_R X_2) \\ & + \eta_c (\bar{u}^i P_L X_1) (\bar{X}_2 P_R u_i) + \text{H.c.},\end{aligned}$$

$$\text{with } |\eta_{X_1}| \equiv \Lambda_{X_1}^{-2}, \quad |\eta_{X_2}| \equiv \Lambda_{X_2}^{-2}, \quad |\eta_c| \equiv \Lambda_c^{-2}. \quad (3)$$

Both X_1 and X_2 mediate n - $\bar{n}$ oscillation—integrating them out at tree level gives

$$c_1 = \frac{1}{(\Lambda_{n\bar{n}}^{(1)})^5} = \frac{1}{M_{X_1} \Lambda_{X_1}^4} + \frac{1}{M_{X_2} \Lambda_{X_2}^4}. \quad (4)$$

This setup contains all of the necessary ingredients for baryogenesis [67]: the Lagrangian in Eq. (3) violates B and P , while nonzero phases of η_{X_1} , η_{X_2} , and η_c can lead to CP violation; departure from equilibrium can occur in multiple ways, as we discuss below. Although a clear simplification, we expect the minimal set of operators in Eq. (3) to capture the generic qualitative features possible in a two n - $\bar{n}$ mediator setup, which can be realized in more complicated and realistic frameworks.

Calculation of the baryon asymmetry.—The relevant processes for baryogenesis include (1) B -violating processes: single annihilation $uX_{1,2} \rightarrow \bar{d}\bar{d}$, $dX_{1,2} \rightarrow \bar{u}\bar{d}$, decay $X_{1,2} \rightarrow udd$, and off-resonance scattering $udd \rightarrow \bar{u}\bar{d}\bar{d}$; and (2) B -conserving processes: scattering $uX_1 \rightarrow uX_2$, coannihilation $X_1X_2 \rightarrow \bar{u}u$, and decay $X_2 \rightarrow X_1\bar{u}u$, as well as their inverse and CP conjugate processes. CP violation arises from interference between tree and one-loop diagrams in $uX_{1,2} \leftrightarrow \bar{d}\bar{d}$, $uX_1 \leftrightarrow uX_2$, and $X_2 \leftrightarrow uud$, and additionally from $udd \leftrightarrow \bar{u}\bar{d}\bar{d}$ (in a way that is related to $X_2 \leftrightarrow uud$ by unitarity). In each case, CP violation is proportional to $\text{Im}(\eta_{X_1}^* \eta_{X_2} \eta_c) \sim \Lambda^{-6}$. We work at leading order in the EFT expansion, i.e., $O(\Lambda^{-4})$ for the rates of CP -conserving processes and the CP -symmetric components of CP -violating processes, and $O(\Lambda^{-6})$ for the CP -violating rates. We choose a mass ratio $M_{X_2}/M_{X_1} = 4$, which maximizes $\Gamma(X_2 \rightarrow udd) - \Gamma(X_2 \rightarrow \bar{u}\bar{d}\bar{d})$ for fixed M_{X_2} .

We calculate the baryon asymmetry by numerically solving a set of coupled Boltzmann equations to track the abundances of $X_{1,2}$ and B - L (B) above (below) $T = 140$ GeV (we assume that sphalerons are active when $T > 140$ GeV, resulting in $Y_B = \frac{28}{79} Y_{B-L}$). Our aim is to find regions of parameter space that can achieve the observed $Y_B = 8.6 \times 10^{-11}$ [68,69], with suitable choice of CP phases. Technical details of this calculation can be found in the Supplemental Material [57].

If all three operator coefficients have similar sizes, $\Lambda_{X_1} \sim \Lambda_{X_2} \sim \Lambda_c$, it is difficult to obtain the observed baryon asymmetry in the region of parameter space probed by n - $\bar{n}$ oscillation. For $M_{X_{1,2}} \gtrsim 10^4$ GeV, the Λ 's that can be probed are sufficiently low for $X_{1,2}$ to remain close to equilibrium until their abundances become negligible, while efficient washout suppresses $B(-L)$ generation. For lower masses and higher Λ 's, on the other hand, X_2 may freeze out with a significant abundance, and decay out of equilibrium at later times when washout has become inefficient, so that both limitations from the higher mass regime are overcome. However, its CP -violating branching fraction $\epsilon_{CP} \sim M_{X_2}^2/\Lambda^2$ is too small to generate the desired Y_B . We find that for $\Lambda_{X_1} = \Lambda_{X_2} = \Lambda_c$, the maximum Y_B possible in the ESS-DUNE sensitivity region is $O(10^{-13})$, well below the observed value.

Achieving the desired baryon asymmetry in the ESS-DUNE reach region therefore requires hierarchical Λ 's; such scenarios can arise if new particles in the UV theory that mediate the corresponding operators have hierarchical masses and/or couplings, or if the EFT operators are generated at different loop orders. We find compatible regions of parameter space in two distinct scenarios, one with late decays of X_2 and the other with earlier decays. These are schematically illustrated in Fig. 1 and discussed in turn below (a detailed analysis with benchmark numerical solutions is presented in the Supplemental Material [57]).

Late decay scenario.—For $\Lambda_{X_2} \sim \Lambda_c \gg \Lambda_{X_1}$, n - $\bar{n}$ oscillation is dominated by X_1 exchange and probes the M_{X_1} - Λ_{X_1} parameter space (see Fig. 2). This hierarchy leads to weaker interactions for X_2 compared to the degenerate case, causing it to freeze out with a higher abundance $Y_{X_2}^{\text{fo}}$.

FIG. 1. Sketches of the evolution of the heavier n - $\bar{n}$ mediator abundance Y_{X_2} , washout rate Γ_{w0} , and baryon asymmetry Y_B in the two scenarios considered in this Letter (arbitrary normalization). In the late decay scenario, the n - $\bar{n}$ mediator is long-lived and decays out of equilibrium to generate a baryon asymmetry. In the early decay scenario, departure from equilibrium (thin dotted curve) is small, but suppressed washout enables efficient baryogenesis. See the text for details.

FIG. 2. Parameter space of the minimal EFT probed by $n-\bar{n}$ oscillation for the late decay scenario, assuming that $M_{X_2} = 4M_{X_1}$. The thicker (solid and dashed) black lines are obtained using central values of nuclear matrix elements from [61], while the thinner dotted lines show the effect of current lattice calculation uncertainty on the Super-K limit. For $\Lambda_{X_2} = \Lambda_c = 50\Lambda_{X_1}$, the green shaded region can accommodate $Y_B = 8.6 \times 10^{-11}$. For $\Lambda_{X_2} = \Lambda_c = 25\Lambda_{X_1}$ ($100\Lambda_{X_1}$), the viable region is between the dashed red (dotted-dashed blue) lines. The gray shaded region marks $\Lambda_{X_1} < M_{X_2}$, where EFT validity requires greater than $O(1)$ coupling.

Also, X_2 becomes long-lived and decays after washout processes have become ineffective, thereby creating substantial baryon asymmetry (see Fig. 1). In this case, its CP -violating branching fraction scales as $\epsilon_{CP} \sim M_{X_2}^2 \eta_{X_1} \eta_{X_2} \eta_c / \max(\eta_{X_2}^2, \eta_c^2) \sim M_{X_2}^2 / \Lambda_{X_1}^2$ and does not decouple as Λ_{X_2} and Λ_c are both increased, enabling $Y_B \sim Y_{X_2}^{\text{fo}} \epsilon_{CP}$ to reach the observed value.

Numerically, we find that this baryogenesis scenario is viable with $\Lambda_{X_2}, \Lambda_c \gtrsim 20\Lambda_{X_1}$ in the parameter space probed by $n-\bar{n}$ oscillation. In Fig. 2, we show regions in the M_{X_1} - Λ_{X_1} plane that can accommodate the observed baryon asymmetry for various choices of $\Lambda_{X_2}/\Lambda_{X_1} = \Lambda_c/\Lambda_{X_1}$. In each case, the lower boundary of the viable region is effectively determined by the requirement that X_2 freezes out with sufficient abundance. As we move upward from this lower boundary, increasing all three Λ 's while keeping their ratios fixed, at some point we enter a regime where X_2 decouples from the SM bath while relativistic, and $Y_{X_2}^{\text{fo}}$ saturates at $Y_{X_2}^{\text{eq}}(T \gg M_{X_2}) = (1/\pi^2)(T^3/s)$, so that further increasing the Λ 's only reduces ϵ_{CP} and hence the final Y_B . Furthermore, for sufficiently high Λ_{X_2} and Λ_c , X_2 dominates the energy density of the Universe before it decays (this does not happen for X_1 in the parameter space we

FIG. 3. Parameter space of the minimal EFT probed by $n-\bar{n}$ oscillation for the early decay scenario, assuming that $M_{X_2} = 4M_{X_1}$. The thicker (solid and dashed) black lines are obtained using central values of nuclear matrix elements from Ref. [61], while the thinner dotted lines show the effect of current lattice calculation uncertainty on the Super-K limit. Points represent solutions with $Y_B = 8.6 \times 10^{-11}$ found for several fixed $\Lambda_{X_1}/\Lambda_{X_2}$ ratios while scanning over $\Lambda_c \in (M_{X_2}, \Lambda_{X_2})$. The gray shaded region marks $\Lambda_{X_2} < M_{X_2}$, where EFT validity requires greater than $O(1)$ coupling.

consider), so that its decay injects significant entropy into the plasma, diluting the baryon asymmetry. Both of these effects—saturation and dilution—determine the upper boundary of the viable region.

Early decay scenario.—For the opposite hierarchy $\Lambda_{X_1} \gg \Lambda_{X_2}$, $n-\bar{n}$ oscillation is dominated by X_2 exchange and probes the M_{X_2} - Λ_{X_2} parameter space (see Fig. 3). In this case, X_2 is short-lived, and its abundance closely follows the equilibrium curve. However, small departures from equilibrium, always present in an expanding Universe because interaction rates are finite, can be sufficient for baryogenesis if washout can be suppressed. The rates for washout processes involving X_1 and X_2 are proportional to $n_1 \Lambda_{X_1}^{-4}$ and $n_2 \Lambda_{X_2}^{-4}$, respectively, where $n_{1,2}$ are the number densities of $X_{1,2}$. If $\Lambda_{X_1} \sim \Lambda_{X_2}$, washout would be efficient until $T \sim M_{X_1}$, i.e., until n_1 starts to fall exponentially. By contrast, by increasing Λ_{X_1} , we enter a regime where washout is dominated by X_2 processes at high temperatures and becomes inefficient as soon as the temperature falls below M_{X_2} (washout due to $udd \leftrightarrow \bar{u}\bar{d}\bar{d}$, whose rate $\sim T^{11}/M^2 \Lambda^8$ falls steeply with T , is also irrelevant at this point), resulting in a short period of baryon asymmetry generation from X_2 decays (see Fig. 1). Note that increasing Λ_{X_1} with respect to Λ_{X_2} also helps to increase departures from equilibrium compared to the degenerate case.

Figure 3 shows points in the M_{X_2} - Λ_{X_2} plane that can realize the observed Y_B through this early decay process for several fixed values of $\Lambda_{X_1}/\Lambda_{X_2}$ —5, 10, and 20—based on a numerical scan over $M_{X_2} < \Lambda_c < \Lambda_{X_2}$. We find that 5 and 20 are about the smallest and largest $\Lambda_{X_1}/\Lambda_{X_2}$ ratios that can accommodate the observed Y_B , while for the majority of the points shown, $\Lambda_c \lesssim 3M_{X_2}$. The results can be understood from the competing effects of baryon asymmetry generation and washout, $\Gamma_{\Delta B \neq 0}/\Gamma_{\text{wo}} \sim M^2 n_2 (\Lambda_{X_1}^2 \Lambda_{X_2}^2 \Lambda_c^2)^{-1} / (n_1 \Lambda_{X_1}^{-4} + n_2 \Lambda_{X_2}^{-4}) \sim (M^2/\Lambda_c^2) \times \min \{ \Lambda_{X_2}^2/\Lambda_{X_1}^2, \Lambda_{X_1}^2/\Lambda_{X_2}^2 e^{-(M_{X_2}-M_{X_1})/T} \}$, where the rate of baryon asymmetry generation $\Gamma_{\Delta B \neq 0}$ is calculated from CP -violating X_2 decays. First of all, a lower ratio Λ_c/M_{X_2} is always preferable (within the range of EFT validity), while the ratio $\Lambda_{X_1}/\Lambda_{X_2}$ has an optimal value of ~ 10 as a result of balancing between faster baryon asymmetry generation at higher temperatures (which favors lower $\Lambda_{X_1}/\Lambda_{X_2}$) and later transition to X_1 -dominated washout (which favors a higher $\Lambda_{X_1}/\Lambda_{X_2}$). The requirement of sufficient departure from equilibrium precludes an arbitrarily low Λ_c and leads to a minimum M_{X_2} for this scenario to work, which we see from Fig. 3 is a few $\times 10^4$ GeV. Finally, the overall size of $\Lambda_{X_{1,2}}$ is essentially determined by the requirement that Y_B freezes out around the time that $\Gamma_{X_2}^{\Delta B \neq 0}/\Gamma_{\text{wo}}$ reaches its maximum, and it is higher for a higher M_{X_2} .

Complementary probes.—In the region of parameter space that is allowed by existing n - $\bar{n}$ oscillation searches, within reach of future experiments such as the ESS and DUNE, and realizes the observed baryon asymmetry, we find that $M_{X_{1,2}} \gtrsim 10^3 (10^4)$ GeV in the late (early) decay scenario. Given that $X_{1,2}$ are SM singlets that couple to the SM only via higher dimensional operators, it is unlikely that they can be detected at the LHC or its envisioned upgrades. Likewise, there are no strong flavor physics constraints on our minimal EFT with just the operators in Eq. (3). We note, however, that this outlook can change in a more complicated model that preserves the general features of baryogenesis of our minimal EFT if at least one of $X_{1,2}$ carries SM charges or couples to other fermion species. For example, colored particles at the tera-electron-volt scale, such as the gluino in RPV SUSY, could be within LHC reach. Likewise, extending the exotic fermion couplings to other quark flavors can introduce potential constraints from flavor violation considerations such as K^0 - $\bar{K}^0$ mixing [70]. Nevertheless, our minimal EFT study illustrates that n - $\bar{n}$ oscillation might be uniquely placed to probe realistic baryogenesis scenarios that are inaccessible via other searches.

Conclusions.—Establishing baryon number violation (or the absence thereof up to a certain scale) will have far-reaching implications on our understanding of fundamental particle interactions, in particular on the mechanism that

generates the observed baryon asymmetry in our Universe. Motivated by the unprecedented sensitivity to n - $\bar{n}$ oscillation that can be achieved at future facilities, the ESS and DUNE in particular, which offers new opportunities to probe $|\Delta B| = 2$, $\Delta L = 0$ interactions, we studied implications of a potential discovery for baryogenesis scenarios involving n - $\bar{n}$ mediators. We took a bottom-up EFT approach with a minimal set of four-fermion operators coupling the n - $\bar{n}$ mediators to the SM, which, despite being simplistic, sets a useful template that more sophisticated theories can build upon. We identified two viable baryogenesis scenarios—one involving late out-of-equilibrium decays of a heavy Majorana fermion, and another involving earlier decays assisted by a suppressed washout rate—that can be realized in the parameter space to be probed by future n - $\bar{n}$ oscillation searches, with no corresponding collider or flavor signals. These results highlight the capability of n - $\bar{n}$ oscillation experiments to probe an important BSM phenomenon, that of baryogenesis, beyond the scope of other searches.

We thank J. Barrow, G. Brooijmans, C. Csáki, and E. Rinaldi for the helpful comments and discussions. C. G. was supported by the European Commission through Marie Curie Career Integration Grant No. 631962, and by the Helmholtz Association. B. S. was partially supported by NSF CAREER Grant No. PHY-1654502 and thanks the CERN and DESY theory groups, where part of this work was conducted, for the hospitality. The work of J. D. W. was supported by DOE Grant No. DE-SC0007859 and the Humboldt Research Award. The work of Z. Z. was supported by DOE Grant No. DE-SC0007859, the Rackham Dissertation Fellowship, and the Summer Leinweber Research Award. J. D. W. and Z. Z. also thank the DESY theory group for the hospitality. This work was performed in part at the Aspen Center for Physics, which was supported by National Science Foundation Grant No. PHY-1066293.

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