Neutralino oscillations at the LHC

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We study a supersymmetric phenomenon that can give spectacular signals at the LHC: oscillations of neutralinos. Such oscillations can be naturally realized in R-symmetric models, where additional fields are introduced as Dirac mass partners of gauginos and Higgsinos. Majorana masses for gauginos, necessarily generated from anomaly mediation, can create tiny mass splittings between degenerate mass eigenstates, causing states produced at the LHC to oscillate between neutralinos and their Dirac partner fields. Scenarios where such states decay with displaced vertices can lead to striking signatures at the LHC, where the oscillation can be visible directly in the distribution of displaced vertex lengths. We elaborate on the theory and LHC phenomenology of this feature within a specific scenario of a Higgsino decaying with a displaced vertex into a gravitino and a Z boson.

I. INTRODUCTION

An extensive study of the theoretical and phenomenological aspects of supersymmetry (SUSY) has been one of the most prominent facets of high energy phenomenology for several decades, and these ideas are now finally being probed by the Large Hadron Collider (LHC). However, given the vast richness of theoretical and phenomenological possibilities that supersymmetry allows, it is plausible that signals of new physics can show up in spectacular, unexpected forms in the coming years. While unexpected signals are exciting for phenomenological reasons, they can also provide insights into the details of the underlying models. With the LHC rapidly providing new data at energy scales never probed before, the study of unexplored phenomenological signatures that could appear at the LHC has become extremely important and timely.

With this motivation, we study a novel phenomenon that can give spectacular signatures at the LHC but has remained hitherto unexplored: neutralino oscillations. Oscillations within the context of supersymmetry have been discussed in some earlier works, see e.g. [1–3], where the oscillation of a mesino leaves visible signatures in the content of decay products at a collider. What we have in mind in this work is a more spectacular signal, where the oscillation itself can be directly observed. Such scenarios can be naturally realized with Dirac gauginos in the context of R-symmetric models [4–6], where the traditional Majorana gaugino mass terms are forbidden by R symmetry, and new partner fields must be introduced to give Dirac masses to the gauginos. However, Majorana masses for gauginos will be generated from supergravity effects via anomaly mediation [7,8]. If these Majorana masses are

small, they introduce tiny mass splittings between degenerate mass eigenstates, enabling a system to oscillate between a gaugino or Higgsino and its partner field. This oscillation behavior can leave visible footprints in collider observables; in particular, if the states in question are long-lived and decay with displaced vertices within the detector, the oscillation can be directly observed in the distribution of lengths of displaced vertices.

The main purpose of this work is to draw attention to the possibility of this phenomenon and explore whether it can be observed at the LHC. For this reason, we will not discuss in full detail specific model-building questions or perform full-fledged detector level simulations of the signals; such details are premature until hints of such a signal are actually observed. We therefore only pursue these directions to a level sufficient to illustrate that the occurrence and observation of such a striking phenomenon is feasible at the LHC.

The paper is organized as follows. We begin by discussing the theoretical motivation and details for Dirac gauginos in R-symmetric models in Sec. II, followed by a discussion of the oscillation phenomenon in Sec. III. In Sec. IV we elaborate on the collider phenomenology within a specific model of a Higgsino next-to-lightest SUSY particle (NLSP) decaying into a gravitino and a Z boson, and discuss the reconstruction of the oscillation feature at the LHC. Section V contains a broader discussion of other scenarios where oscillations can be realized and some experimental aspects.

II. THEORETICAL MOTIVATION

We focus on gauginos and Higgsinos in the context of R-symmetric models—in particular, the minimal R-symmetric supersymmetric model (MRSSM) [4]— which is well motivated for several reasons. In this section we discuss how Dirac mass terms arise for the gauginos

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and Higgsinos in the MRSSM, and Majorana masses for gauginos are necessarily generated via anomaly mediation. We follow the notation in [4].

The R symmetry forbids Majorana mass terms for gauginos, requiring the addition of adjoint chiral superfields Φ_i for each gauge group i, with the corresponding fermion carrying the opposite R charge, to accommodate R-invariant Dirac masses. The R symmetry also forbids the μ term, hence also the Higgsino mass, in the Higgs sector, analogously requiring the introduction of R_u and R_d superfields to partner H_u and H_d.

One can consider the Dirac masses for the gauginos to be elements of a general softly broken supersymmetric theory. If SUSY breaking is assumed to originate from hidden sector spurions, both F- and D-type breaking are allowed, which can be written in terms of the spurions as $X = \theta^2 F$ and $W'_\alpha = \theta_\alpha D$. The W' can be thought of as a hidden sector U(1)' that acquires a D term [9]. The Dirac gaugino mass originates from the R-symmetric operator involving the D-type spurion [10]:

$$\int d^2\theta \frac{W'_\alpha}{M} W_i^\alpha \Phi_i \supset m_D \tilde{g}_i \tilde{g}'_i, \qquad (1)$$

where M is the mediation scale of SUSY breaking from the hidden sector to the visible sector, W_i represents the gauge superfield, $\tilde{g}$ is the gaugino, and $\tilde{g}'$ is the corresponding Dirac partner. Likewise, in the Higgs sector, the supersymmetric mass term $\mu_u H_u R_u + \mu_d H_d R_d$ arises from

$$\int d^4\theta \left(\frac{X^\dagger}{M} H_u R_u + \frac{X^\dagger}{M} H_d R_d \right). \qquad (2)$$

In addition, one also gets couplings of the electroweak Φ_i adjoint chiral superfields to the Higgs doublets

$$W_\Phi = \sum_{i=\tilde{B},\tilde{W}} \lambda_u^i H_u \Phi_i R_u + \lambda_d^i R_d \Phi_i H_d. \qquad (3)$$

These trilinear terms play a vital role, for instance, in electroweak baryogenesis, and large $\lambda_q (q = u, d)$ close to the perturbative limit are also favored by a Higgs mass close to 125 GeV [11]. These λ_q couplings are relevant for our analysis since they affect the mixing in the neutralino sector.

Despite the R symmetry, Majorana masses for gauginos cannot be completely eliminated. It is well known that supersymmetry breaking in a general hidden sector model necessarily generates gaugino masses at one loop as a consequence of the super-Weyl anomaly [7,8]. This anomaly mediated Majorana mass term m_λ can be obtained through an F-type spurion

$$\int d^2\theta \frac{F}{M_{\text{Pl}}} W_i^\alpha W_{\alpha i} \supset m_\lambda \tilde{g}^\alpha \tilde{g}_\alpha. \qquad (4)$$

The consequent Majorana mass for gauginos is given by

$$m_\lambda = \frac{\beta(g^2)}{2g^2} m_{3/2}, \qquad (5)$$

where $\beta(g^2) = dg^2/d \ln \mu$ is the gauge beta function and $m_{3/2}$ is the gravitino mass. Recall that $m_{3/2} = F/(\sqrt{3}M_{\text{Pl}})$; hence the sizes of the anomaly mediated Majorana masses are determined by $\sqrt{F}$, the fundamental scale of SUSY breaking. For a bino, for instance, this corresponds to [12]

$$m_1 = \frac{11\alpha}{4\pi\cos^2(\theta_W)} m_{3/2} \approx 8.9 \times 10^{-3} m_{3/2}. \qquad (6)$$

There are no analogous Majorana masses for the R partners, since the anomaly mediated mass term is given by the running of anomalous dimension and gauge coupling in the field strength tensor, which does not exist for the R partners in the superpotential. Likewise, the couplings of the R partners to Standard Model states are suppressed due to the R-charge assignments, and the only fields they couple significantly to are the corresponding R scalars. The R partners therefore have negligible decay widths of their own when these R scalars are heavier. In the remainder of this paper we assume that this is the case and simply set their widths to zero.

In summary, the MRSSM has Dirac masses for gauginos, which requires the introduction of new partner fields. Majorana masses for gauginos are necessarily introduced from anomaly mediation, with their sizes determined by the scale of SUSY breaking. The interplay between the Dirac and Majorana masses can have interesting phenomenological consequences. We have in mind a Dirac mass of $\mathcal{O}(100)$ GeV and a Majorana mass of $\mathcal{O}(10^{-5})$ eV. This hierarchy opens the possibility of neutralino oscillations, to which we now switch our attention.

III. OSCILLATIONS

To understand the oscillation phenomenon, consider a gaugino $\tilde{g}$ and its adjoint Dirac partner $\tilde{g}'$. In the $(\tilde{g}, \tilde{g}')$ basis, the Hamiltonian takes the form (see for example [13,14])

$$\mathcal{H} = \begin{pmatrix} m_M - i\Gamma/2 & m_D \\ m_D & 0 \end{pmatrix}, \qquad (7)$$

where m_M and m_D are the Majorana and Dirac masses for the gauginos respectively, and Γ is the decay width of the gaugino. As discussed in the previous section, we assume that $\tilde{g}'$ has a negligible decay width and no Majorana mass. Note that this negligible decay width of $\tilde{g}'$ is also responsible for the vanishing of the decay widths in the off-diagonal entries of the Hamiltonian.

The eigenvalues of this Hamiltonian are

$$\mu_{1,2} = \frac{1}{2} \left(m_M - \frac{i\Gamma}{2} \pm \sqrt{\left(m_M + \frac{i\Gamma}{2}\right)^2 + 4m_D^2} \right). \qquad (8)$$

For $m_D \gg \Gamma, m_M$, the eigenvalues are approximately

$$\mu_{1,2} \approx m_D \pm \frac{1}{2}m_M - \frac{i\Gamma}{2}\left(1 \pm \frac{m_M}{4m_D}\right). \quad (9)$$

The two eigenstates are therefore approximately degenerate with a common mass m_D, with a small mass splitting m_M between them. In this case, the traditional dimensionless ratios x and y are

$$x \equiv \frac{\Delta m}{\Gamma} = \frac{m_M}{\Gamma}, \qquad y \equiv \frac{\Delta \Gamma}{2\Gamma} = \frac{m_M}{8m_D}. \quad (10)$$

Since we are working in the $m_D \gg \Gamma, m_M$ regime, we set $y = 0$ from here on.

Next, let ψ_1 and ψ_2 be the two mass eigenstates, with eigenvalues μ_1 and μ_2 respectively. For infinitesimal mass splitting, one has close to maximal mixing, such that we can write

$$\psi_{1,2} \approx \frac{1}{\sqrt{2}}(\tilde{g} \pm \tilde{g}'), \qquad \tilde{g}, \tilde{g}' \approx \frac{1}{\sqrt{2}}(\psi_1 \pm \psi_2). \quad (11)$$

First, consider the more general case

$$\psi_a = c_{a1}\tilde{g} + c_{a2}\tilde{g}', \quad (12)$$

where $a = 1, 2$. If, at proper time $t = 0$, the system is $\psi = x_1\tilde{g} + x_2\tilde{g}'$, its evolution over time is given by

$$\begin{aligned}
\psi(t) = &[e^{-i\mu_1 t}c_{11}(x_1c_{22} + x_2c_{21}) \\
&- e^{-i\mu_2 t}c_{12}(x_1c_{21} + x_2c_{22})]\tilde{g} \\
&+ [e^{-i\mu_1 t}c_{12}(x_1c_{22} + x_2c_{21}) \\
&- e^{-i\mu_2 t}c_{22}(x_1c_{12} + x_2c_{11})]\tilde{g}'. \quad (13)
\end{aligned}$$

Next, consider an interaction that produces a pure gaugino state at $t = 0$; this is represented by $(x_1, x_2) = (1, 0)$. As evident from Eq. (13), at later times this state evolves into a combination of the gaugino $\tilde{g}$ and its partner $\tilde{g}'$. In particular, at time t the gaugino fraction of the state is

$$\begin{aligned}
\langle \tilde{g}|\psi(t)\rangle &= e^{-i\mu_1 t}c_{11}c_{22} - e^{-i\mu_2 t}c_{12}c_{21} \\
&\approx \frac{1}{2}e^{-i\mu_1 t}(1 + e^{-im_M t}). \quad (14)
\end{aligned}$$

This shows that the gaugino fraction in the produced state oscillates over time. Since only the gaugino, not the Dirac partner, can decay, the probability of decay of the state ψ is also correlated to the gaugino fraction and is proportional to

$$|\langle \tilde{g}|\psi(t)\rangle|^2 = \frac{1}{2}e^{-\Gamma t}[1 + \cos(m_M t)]. \quad (15)$$

We are therefore led to a scenario where an oscillation is superimposed on the exponential decay traditionally expected of an unstable state. If the state in question travels a measurable distance in the detector before decaying, the oscillation can be observed in spectacular fashion: if a large number of such displaced decays are measured, the distribution of the displaced vertex lengths will follow

Eq. (15), offering a tantalizing collider signature of the phenomenon.

IV. A SPECIFIC SCENARIO: HIGGSINO OSCILLATION AT THE LHC

We now elaborate on the details of the oscillation behavior and the corresponding signal at the LHC within the framework of a specific scenario. We choose a setup that has been used in the literature to study the reconstruction of displaced vertices [15]: the decay of a Higgsino NLSP into a gravitino lightest supersymmetric partner (LSP) and a Z boson (see also [16]). We adopt this process into a MRSSM framework together with small anomaly mediated Majorana masses for the gauginos. The Higgsinos have no Majorana masses of their own but mix with the gauginos in the neutralino sector and inherit the oscillation behavior discussed in the previous section. The leptonic decay channels of the Z boson enable clean reconstruction of the positions of the displaced vertices, making this an ideal setup in which to study the phenomenon.

A. Parameters

For simplicity, we assume that the lightest neutralino is a pure up-type Higgsino, $\tilde{H}_u$, which can decay into the gravitino LSP and the longitudinal component of the Z boson. The decay length of the Higgsino is given by [15,17]

$$c\tau \approx \left(\frac{\sqrt{F}}{100\text{ TeV}}\right)^4\left(\frac{100\text{ GeV}}{m_{\tilde{\chi}_1^0}}\right)^5\left(1 - \frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2}\right)^{-4} \times 0.2\text{ mm},$$

$$(16)$$

where we have assumed $\sin^2\beta \approx 1$. Thus the decay width depends mainly on the SUSY-breaking scale $\sqrt{F}$ and the neutralino mass $m_{\tilde{\chi}_1^0}$.

The mass splitting in this case is slightly involved due to the mixing between the gauginos and the Higgsinos in the neutralino sector. Since there is no Majorana mass for Higgsinos, the mass splitting between the lightest degenerate eigenstates (combinations of $\tilde{H}_u$ and $\tilde{R}_u$) arises through the mixing with the gauginos. We set the wino mass at 1 TeV, hence it decouples from our analysis.[1] Note that if unification of gaugino masses is assumed, this also drives the gluino mass to several TeV, which leads to squark-initiated SUSY processes at the LHC as discussed in [18]. The neutralino sector is then essentially reduced to the $\tilde{B} - \tilde{H}_u$ system (while the wino decouples because it is

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[1]We found a wino mass above around 1 TeV is required in order to satisfy precision electroweak limits on the ρ parameter [4] for the value of the electroweak scale μ term we use. It should be noted, however, that this is not a strict limit, since it is the vacuum expectation value of the triplet scalar that the ρ parameter constrains. Hence the ρ parameter constraint can be relaxed with an additional F-term mass for the adjoint scalar.

heavy, $\tilde{H}_d$ can be decoupled assuming negligible mixing with this system), for which the neutralino mass matrix in the $\{\tilde{B}, \tilde{B}', \tilde{H}_u, \tilde{R}_u\}$ basis is

$$M_N = \begin{pmatrix} m_{M(\tilde{B})} & m_{D(\tilde{B})} & m_Z \sin\theta_W \sin\beta & 0 \\ m_{D(\tilde{B})} & 0 & 0 & 0 \\ m_Z \sin\theta_W \sin\beta & 0 & 0 & -\mu_u \\ 0 & 0 & -\mu_u & 0 \end{pmatrix}. \tag{17}$$

Here we have also ignored the λ_q couplings from Eq. (3) for simplicity. Nonzero values for these couplings do not destroy the oscillation behavior discussed in this section; in particular, corrections from their inclusion are negligible for sufficiently heavy R scalars. These have been checked explicitly.

With the bino sufficiently heavier than the Higgsino (necessary for the lightest neutralino to be a pure H_u), the mass splitting between the two lightest neutralino eigenstates is given by

$$\Delta m_{\tilde{H}_u} \approx \left(\frac{m_Z \sin\theta_W \sin\beta}{m_{D(\tilde{B})}}\right)^2 \left(\frac{m_{\tilde{\chi}_1^0}}{m_{D(\tilde{B})}}\right)^2 m_{M(\tilde{B})}. \tag{18}$$

Since R symmetry is preserved in the absence of Majorana masses, the dependence on the bino Majorana mass is understandable. The splitting is additionally suppressed by the off-diagonal bino-Higgsino mixing as well as the hierarchy between the bino and Higgsino mass scales; this additional suppression is desirable since it translates into larger oscillation lengths at the LHC, increasing the likelihood of reconstructing the oscillation feature. Since the lightest eigenstate is made up of $\tilde{H}_u$ and $\tilde{R}_u$, we also have $m_{\tilde{\chi}_1^0} = \mu_u$.

For the oscillation to be observable at the LHC, both the oscillation scale and the neutralino decay length in the collider frame must be around the mm to m scale, with the decay length greater than the oscillation length so that one or more oscillations can be reconstructed. From Eqs. (6), (16), and (18), we see that these two scales depend on the SUSY-breaking scale $\sqrt{F}$ and the neutralino mass $m_{\tilde{\chi}_1^0}$.

We assume the mass spectrum given in Table I. The scalars are assumed to be sufficiently heavy to be decoupled and not listed; the choice of the stop mass is motivated by the CMS search of stop pair production in [19]. A mass splitting tiny enough to slow down oscillations to the collider scale requires a low scale of SUSY breaking. With

$$\sqrt{F} \simeq 3 \times 10^2 \text{ TeV}, \tag{19}$$

the mass splitting between the lightest eigenstates is

$$\Delta m_{\tilde{H}_u} \approx 10^{-5} \text{ eV}. \tag{20}$$

This corresponds to an oscillation scale of $c\tau \approx 2\pi/\Delta m_{\tilde{H}_u} \approx 4$ cm. With these scales of SUSY breaking and Higgsino mass, the proper lifetime of the neutralino is $c\tau \approx 20$ cm. These decay and oscillation scales are therefore ideal for the observation of this phenomenon at the LHC. The above SUSY-breaking scale also sets the gravitino mass at the eV scale, making it the LSP, as required for the decay channel we are interested in.

All simulations, plots, and discussions in the following sections are specific to these parameter values, unless specified otherwise. The approximations and discussions of Eqs. (17) and (18) are provided for intuition only; in our runs, we diagonalize the full neutralino mass matrix and obtain the eigenvalues numerically.

B. LHC phenomenology: Vertex and oscillation reconstruction

We focus on event reconstruction at the ATLAS detector; the general idea is the same at CMS. The Higgsino NLSP is promptly produced at the interaction point through the decays of stops. Once produced, it travels a macroscopic distance in the collider frame before decaying with a displaced vertex into a gravitino and a Z boson. We focus on events where the Z boson decays into $e^+ e^-$, which allows for clean reconstruction of the displaced vertex using measurements in the electromagnetic calorimeter (ECAL) and tracker. The ECAL can measure energy, timing, and pointing information, and this is sufficient to reconstruct the vertex as well as the three-momenta of the electron pair. Details of the reconstruction procedure are described in [15] and will not be repeated here. The background for such displaced vertex events should be negligible, particularly since the lepton pair will also satisfy a Z mass window cut.

As mentioned earlier, the distribution of displaced vertex lengths should show the oscillation feature denoted in Eq. (15). There are three main factors that can potentially distort the oscillation signal and make it irrevocable; we now discuss each of them in turn.

1. Interaction with detector material

The Higgsino travels through material in the detector before decaying. Although hard scatterings are unlikely since the Higgsino only interacts weakly, passage through detector material can change the oscillation behavior through coherent forward scattering. This is analogous to the matter effect or Mikheyev-Smirnov-Wolfenstein (MSW) effect for neutrinos [20,21], and its relevance for neutralinos can be estimated by using results from the neutrino MSW effect.

TABLE I. Mass spectrum for Monte Carlo simulations.

	$\bar{\bar{\tilde{g}}}\tilde{g}'$	$\bar{\bar{\tilde{W}}}\tilde{W}'$	$\bar{\bar{\tilde{B}}}\tilde{B}'$	$\bar{\bar{\tilde{h}}}_u\tilde{h}'_u$	$\tilde{t}^*_{L,R}\tilde{t}_{L,R}$	$\bar{\bar{\tilde{G}}}\tilde{G}'$
Mass (TeV)	3	1	0.5	0.12	0.65	F/M_{pl}

For neutrinos, interaction with electrons in matter induces an effective potential

$$V = \sqrt{2} G_F N_e, \qquad (21)$$

where G_F is the Fermi constant and N_e is the electron density. This can be written as [22]

$$V = 7.56 \times 10^{-14} \left(\frac{\rho}{\text{g/cm}^3} \right) Y_e \text{ eV}, \qquad (22)$$

where ρ is the density of the material and Y_e is the number of electrons per nucleon. Since the matter interaction for neutralinos is also mediated by the weak force, and the number density of quarks in the detectors is of the same order as N_e, Eqs. (21) and (22) should provide a reasonable estimate of the effective potential for the neutralino. With $\rho = 10$ g/cm^3 and $Y_e = 1$, one obtains $V \approx 10^{-12}$ eV. This is several orders of magnitude smaller than the mass splitting in Eq. (20). Neutralino interaction with detector material is therefore irrelevant for our study.

It might appear surprising that the MSW effect is negligible for neutralinos in this case, where the mass splitting is only $\Delta m \approx 10^{-5}$ eV, but can be relevant for neutrinos, where the mass splitting is $\Delta m_\nu^2 \approx 10^{-5}$ eV^2. The main point is that for the MSW effect to be negligible, the size of the effective potential should be small compared to the oscillation scale, which is given by the difference between the energy eigenvalues. For neutralinos, this is given by Δm; for neutrinos, it is given by $\Delta m_\nu^2 / E$, where E is the neutrino energy. This difference comes from the neutralino being massive, which leads to a different subleading term in the expansion of the energy eigenvalue. For neutrino energy $E \approx 10$ MeV, we have $\Delta m_\nu^2 / E \approx 10^{-12}$ eV, which is the same scale as the effective potential V.

2. Boost factors

The convolution of the neutralino lifetime with the effects of boosting to the reference frame of the detector can potentially wash out the oscillation feature. Variations in boost factors arise due to convolution with the parton distribution functions (PDFs) for the proton and due to kinematics of the various decay processes. The decay probability in the rest frame of the Higgsino is

$$\mathcal{P}(\tilde{h} \to \tilde{G}Z) \propto e^{-\Gamma t_0} [1 + \cos(\Delta m t_0)]. \qquad (23)$$

In terms of the time measured in the lab frame, this is

$$\mathcal{P}(\tilde{h} \to \tilde{G}Z) \propto e^{-\Gamma t_{\text{lab}}/\gamma} [1 + \cos(\Delta m t_{\text{lab}}/\gamma)], \qquad (24)$$

where γ is the Lorentz boost factor. The uncertainty comes from not knowing the value of γ on an event-by-event basis.

To overcome this hurdle, we make use of the fact that events with larger γ corresponding to more boosted Higgsinos are generally correlated with more energetic leptons. Performing appropriate cuts on the energies of

the leptons should therefore pick out events with approximately similar boost factors, thereby restoring the oscillation. We verify the efficiency of this method with Monte Carlo simulations. To simulate this process, we generate parton-level events with a Higgsino NLSP decaying into a Z and gravitino in MadGraph 5 [23] for the following process at the the 14 TeV LHC:

$$pp \to \tilde{t}_1^* \tilde{t}_1, \quad \tilde{t}_1 \to t\tilde{h}, \quad \tilde{h} \to \tilde{G}Z, \quad Z \to l^+ l^-. \quad (25)$$

We implement parton-level cuts of $|\eta| \le 1.5$, lepton $p_T > 20$ GeV, and an angular separation $\Delta R > 0.4$ between leptons for greater lepton identification efficiency. In order to reduce the uncertainty of the angular measurement in the ECAL, we also require each lepton to have $E > 100$ GeV. Note that there might be some combinatoric background when both stop decays result in the production of a lepton pair via a Z and the wrong leptons get paired, but this should be negligible given the small branching fraction into this final state and the Z mass window cut that the lepton pair is required to satisfy.

The result of performing various cuts on the lepton pair energy is shown in Fig. 1. For various cuts, the left column shows the distribution of boost factors and the right column shows the corresponding distribution of displaced vertices for the surviving sample (the red line corresponds to what would be observed if the process involved a pure decay with no oscillations). It is evident that although the convolution with boost factors obfuscates the oscillation, a narrower cut on the lepton pair energy, which picks out a narrower distribution of γ, can recover the oscillation feature in the distribution of decay lengths. Note that the energy cut $E > 100$ GeV on each lepton also serves as a lower cut on the Higgsino energy and therefore on the value of γ. This serves to eliminate oscillation modes with very short oscillation lengths that contribute strongly in washing out the oscillation feature and is therefore beneficial. It is also worth noting that the Higgsino lifetime in the lab frame is $\mathcal{O}(\text{ns})$ (for the γ factors in Fig. 1), which will not run into problems with the ATLAS trigger time delay [24].

With a stringent enough cut on the lepton pair energy, the above method is already sufficient to recover the oscillation, albeit at the cost of retaining only a small fraction of the events. More efficient ways of correcting for the boost factor can be implemented if data are scarce. Another approach that uses the correlation between the boost factor and lepton pair energy without throwing away events is scaling down the neutralino decay length by the lepton pair energy, which approximately corrects for the boost factor. For this purpose, we define the following quantity to be plotted:

$$\hat{r} \equiv \frac{m_{\tilde{h}} r}{E_Z}, \qquad (26)$$

where r is the measured length of the displaced vertex, and E_Z is the energy of the Z boson as reconstructed from the
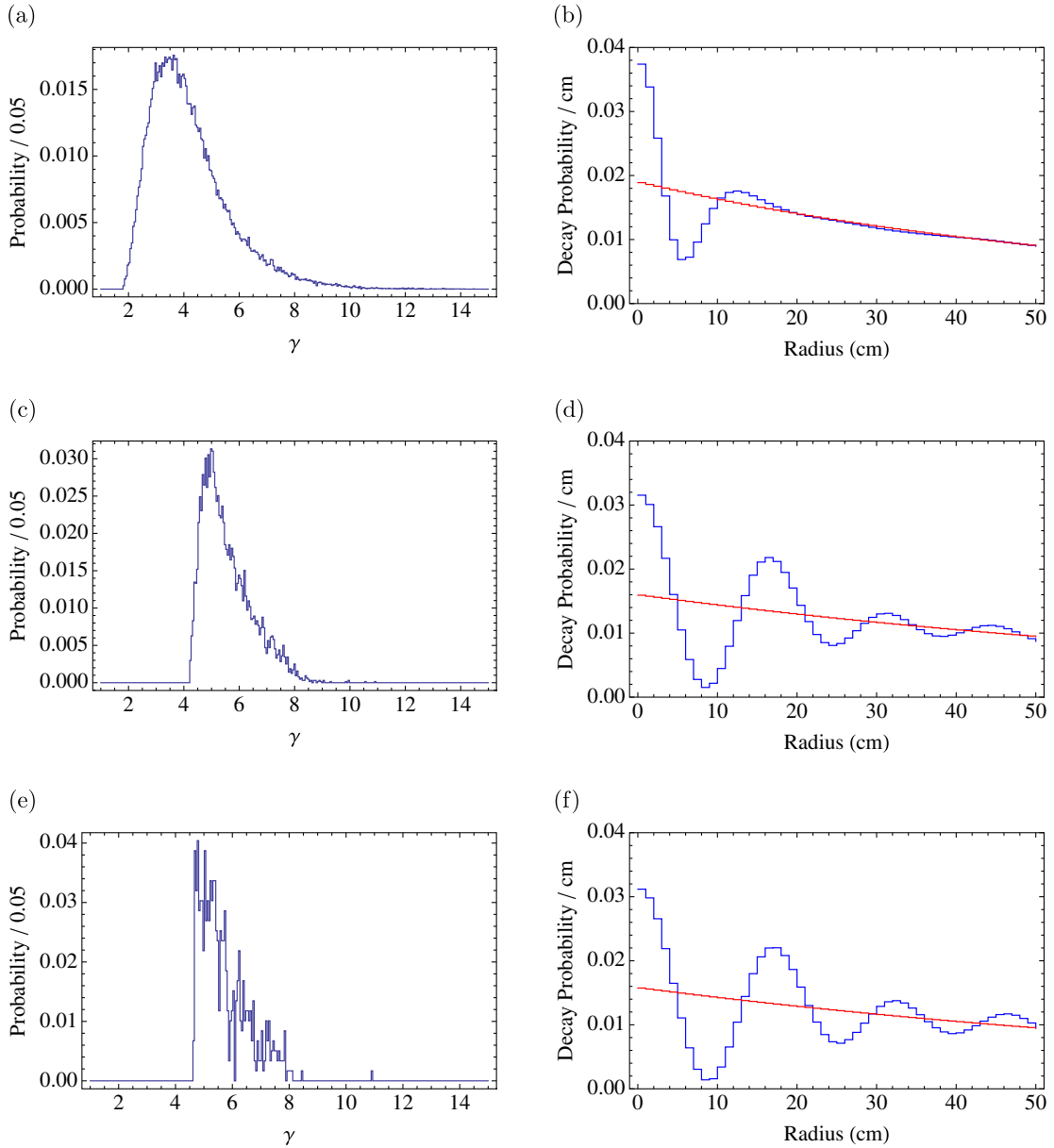
FIG. 1 (color online). Distributions of boost factors and the corresponding distributions of displaced vertex lengths under different lepton energy cuts. The case of decay without oscillation, which falls exponentially, is shown in red. Parton-level events are generated using MadGraph 5 with the cuts and mass spectrum as defined in the text. From top to bottom, the fraction of events that survive the energy cuts are about 100%, 11%, and 1%. (a) Lepton pair $200 < E < 2000$ GeV, (b) Lepton pair $200 < E < 2000$ GeV, (c) Lepton pair $500 < E < 600$ GeV, (d) Lepton pair $500 < E < 600$ GeV, (e) Lepton pair $550 < E < 560$ GeV, (f) Lepton pair $550 < E < 560$ GeV.

lepton pair energy. Figure 2 shows the improvement with using this quantity $\hat{r}$ instead of the measured length of the displaced vertex, where the improvement in reconstructing the oscillation without throwing away a significant number of events is evident.

3. Uncertainty in vertex reconstruction

There are also uncertainties regarding the reconstruction of the position of the displaced vertex arising from

uncertainties in the measured energies and angles at the detector. We use the uncertainties as listed in [15]. The largest uncertainty comes from the measurement of θ_{dir}, the angle of the direction of the lepton relative to the beam as measured in the ECAL; it leads to an uncertainty of ~2 cm in the position of the displaced vertex. We include this uncertainty by smearing the displaced vertex length distribution with a Gaussian of width 2 cm (the uncertainty in the reconstruction of the primary interaction vertex is
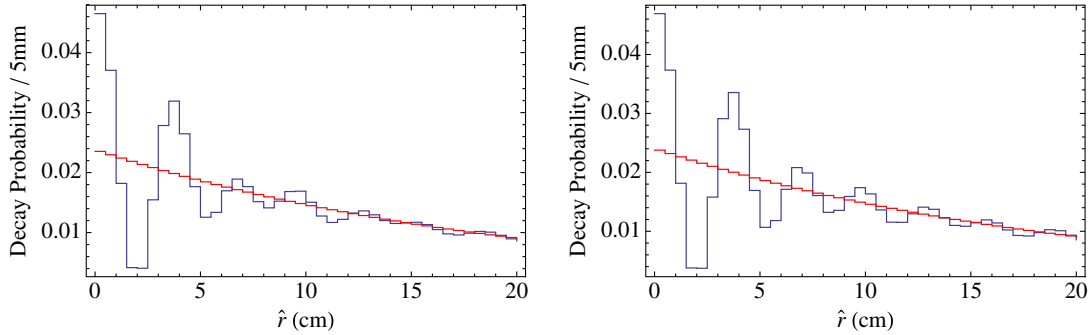
FIG. 2 (color online). Event distribution as a function of $\hat{r}$, for lepton pair energies $200 < E < 2000$ GeV (left) and $500 < E < 2000$ GeV (right).

smaller [15] and can be ignored for this purpose). The distribution of displaced vertex distances before and after the smearing is shown in Fig. 3. As we can see, the effect gets slightly washed out but still persists. The oscillation feature can therefore be reconstructed despite measurement uncertainties at the detector.

C. Estimate of data size and parameter space

We now estimate the amount of data required to observe the oscillation in the scenario discussed in this section. For the parameters and mass spectrum specified earlier, and with lepton energy cut $400 < E < 500$ GeV, we estimate that about 2% of all $Z \to l^+ l^-$ events are reconstructed and pass all the cuts (this is similar to the efficiency in [15]). To distinguish the oscillation feature from the case of a pure exponential decay, we require that a fit with the former provide a 3σ or better fit to the data than a fit with the latter. For this purpose, we only use events with displaced vertex lengths larger than 3 cm, which should have negligible background contamination from prompt events. With these requirements, we estimate the required amount of data to be

$$\mathcal{L} \sim 300 \text{ fb}^{-1}. \tag{27}$$

This corresponds to ~ 20 displaced vertex events that pass all the cuts. This particular scenario, at least, is therefore within reach of the LHC within a few years of running. We stress, however, that this is an extremely rough estimate and should be interpreted accordingly and can change significantly for a different choice of parameters and cuts. In Fig. 4, we show the estimated reach for 14 TeV LHC with higher stop masses.

Next, we explore the regions of parameter space that can give oscillations observable at the LHC. Due to the various experimental constraints discussed in the previous subsection, oscillations cannot be visible for all values of the SUSY-breaking scale (F) and the Higgsino mass ($m_{\tilde{h}}$). In particular, we place the following requirements:

(i) The oscillation wavelength ($2\pi\Delta m_{\tilde{h}}^{-1}$) must be longer than the precision of the displaced vertex measurement to prevent the feature from being smeared out. Here we require the wavelength to be larger than 2 cm.

(ii) The oscillation wavelength must be shorter than 150 cm in order to see at least one complete oscillation within the ECAL.
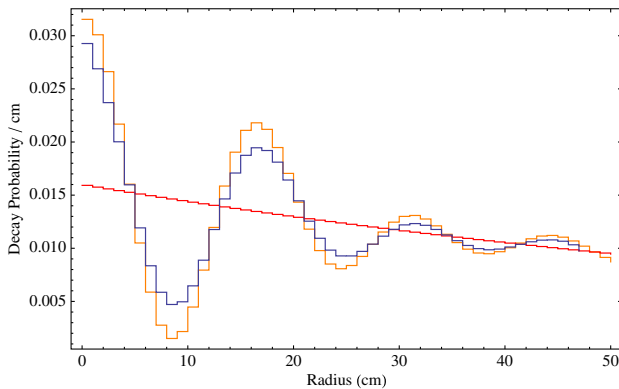

FIG. 3 (color online). The distribution of displaced vertex lengths with preselection and lepton energy cut $400 < E < 500$ GeV. The larger (smaller) distributions correspond to before (after) smearing by a Gaussian of width $\sigma_r = 2$ cm and are shown in orange (blue).
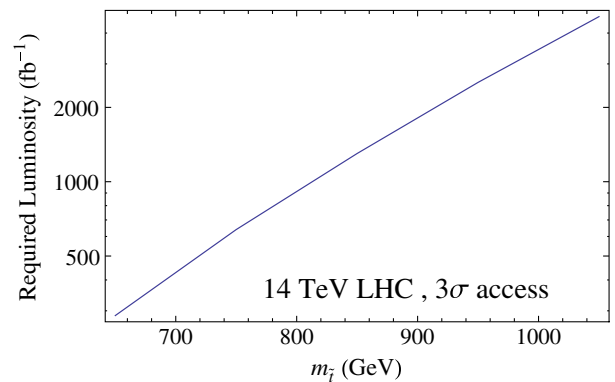

FIG. 4 (color online). Estimated minimal required luminosity for the oscillation to be seen at a 3σ level at the 14 TeV LHC, as a function of stop masses (other masses are as given in Table I, and the cuts and efficiencies are as discussed in Sec. IV C).
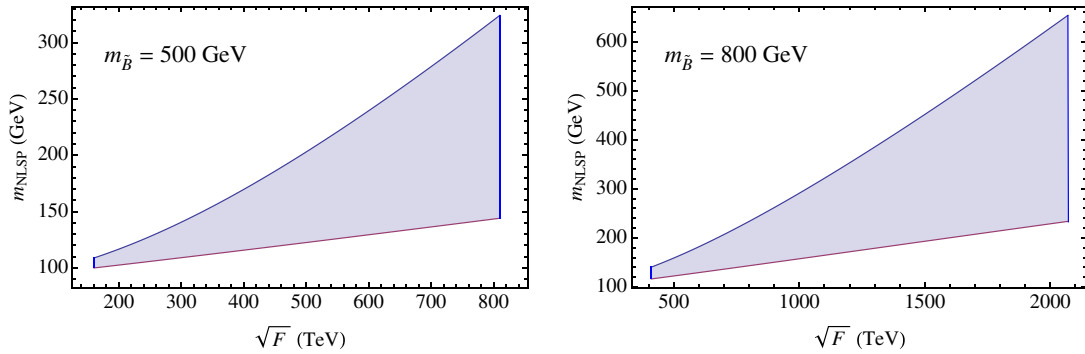
FIG. 5 (color online).   Combinations of SUSY-breaking scale, $\sqrt{F}$, and Higgsino mass, $m_{\tilde{h}}$, for which the oscillation is observable at the LHC with the four constraints discussed in the text, for two different bino masses.

(iii) The decay length ($c\tau$) must be longer than the oscillation wavelength.

(iv) The decay length must be shorter than $\sim 4 \times 150$ cm in order to have at least 20% of the decays appear in the measurable region.

Figure 5 shows the parameter space that gives oscillations observable at the LHC based on the criteria listed above. We have set $\gamma = 6$ to make these plots. The first two constraints set upper and lower bounds on the SUSY-breaking scale $\sqrt{F}$, which are reflected in the limits in the plots. For a given $\sqrt{F}$ and bino mass, the other two constraints set upper and lower bounds on the Higgsino mass. Since the Higgsino production rate is not very sensitive to its mass, the observation limit does not depend strongly on $m_{\tilde{h}}$. Improvements in the vertex measurement precision or more stringent energy cuts can easily open up more parameter space.

V. DISCUSSION AND CONCLUSIONS

Although we have focused exclusively on a single benchmark scenario so far, the oscillation phenomenon is more general and can be realized in many other scenarios. We now turn to a broader discussion of this phenomenon.

Broadly speaking, the following criteria must be satisfied for the possibility of oscillations at the LHC:

(1) Two approximately degenerate mass eigenstates separated by a tiny mass splitting that can be produced in a coherent superposition.

(2) Different interaction behavior (e.g. different decay widths) for the two components that the state oscillates between, in order for the oscillation to be observable.

(3) Decay inside the detector for the signal to be detected.

Any setup that satisfies these requirements can give an interesting oscillation signal at the LHC with the right parameters.

For instance, Dirac gauginos are not necessary for oscillations in the neutralino sector. The neutralino sector

of the minimal supersymmetric Standard Model already contains Majorana masses for the bino and neutral wino and Dirac masses for the Higgsinos. If the gauginos are several orders of magnitude heavier than the Higgsinos, the two lightest neutralino mass eigenstates are combinations of $\tilde{H}_u$ and $\tilde{H}_d$, degenerate at Higgsino mass μ, separated by a tiny splitting due to different mixing with the gauginos. The mass splitting in this case is $\mathcal{O}(\mu^2/m_{\tilde{g}})$, which requires the gauginos to be at the grand unified theory scale to get oscillations observable at the LHC. A pure $\tilde{H}_u$ produced in an interaction at the LHC, for instance, will then evolve as a coherent superposition of these two mass eigenstates, oscillating between $\tilde{H}_u$ and $\tilde{H}_d$ as it travels through the detector. If $\tilde{H}_u$ and $\tilde{H}_d$ decay into different Standard Model final states, the oscillation of the neutralino will manifest itself as variations in the final states produced at different distances from the interaction point.

Likewise, the existence of a gravitino LSP is also not necessary. Neutralinos can decay with detector-scale displaced vertices in models with R-parity violation (see e.g. [25], where R parity is broken by bilinear terms $\mu_L L H_u$ in the superpotential, and the decays are suppressed due to naturally small coefficients and Yukawa couplings, leading to displaced vertices). If the neutralino sector contains both Dirac and Majorana mass terms, an oscillation signal as described in this paper is possible. Similarly, one can also look for oscillations in displaced vertices involving the Higgs or a photon (see e.g. [26]) instead of the Z boson, provided the vertex can be reconstructed sufficiently accurately.

Moreover, oscillations are not confined to the neutralino sector. In the MRSSM, all gauginos have Dirac masses, and anomaly mediation generates Majorana masses for all gauginos. This implies that the charginos and the gluino can also oscillate into the corresponding Dirac partners. If the lightest chargino (NLSP) is almost degenerate with the lightest neutralino (LSP), the chargino must decay into a three-body final state (e.g. LSP+ virtual W, W into two fermions) and can be long-lived due to phase space

suppression; e.g., [27] has postulated charginos with life-times $\sim 10^{-11}$ s. Likewise, the gluino can be long-lived in split-SUSY-like scenarios [28], where the squarks are heavy and suppress the decay of the gluino. Displaced vertices are therefore possible. The problem with observing oscillations with gluinos and charginos is that they interact via strong and electromagnetic forces. Long-lived gluinos in split SUSY are expected to get stopped in the detector. Likewise, ATLAS has looked for long-lived charginos by searching for disappearing tracks in the tracking volume of the detector, where a chargino lighter than 90 GeV with a lifetime between 0.2 and 90 ns has been excluded [29,30]. Unfortunately, such interactions cause the state to decohere into a single mass eigenstate, thereby destroying the oscillation feature. Oscillations with cm-scale displaced vertices extending into the body of the detector are therefore possible only with neutralinos, which interact weakly, but not with gluinos or charginos.

It can nevertheless be possible to uncover evidence of the oscillation even in the absence of displaced vertices in some scenarios. Consider a scenario where the decay length is comparable to the oscillation length, so that the state completes only a fraction of an oscillation before it decays, but the scale is too small to give rise to displaced vertices so that the decay is prompt. If the two components that the state oscillates between decay to different Standard Model final states, the time integrated decay fractions into these different states in the presence of an oscillation are different from the fractions that would be expected in its absence. Although not as spectacular as the direct observation of oscillations in the distribution of displaced vertices, observing this deviation in decay fractions would be a hint of an oscillation in effect.

The observation of oscillations not only provides spectacular signals but can also be useful for extracting valuable information about fundamental parameters in the underlying theory. In the scenario presented in Sec. IV, for instance, the oscillation scale is tied to the fundamental scale of supersymmetry breaking $\sqrt{F}$; if other parameters of the theory have been measured from other processes, the oscillation signal can be used to calculate the SUSY-breaking scale. The observation of the oscillation in the distribution of displaced vertices as discussed in this paper can also be a strong hint of the Dirac nature of gauginos, complementing other signatures of Dirac gauginos and R-symmetric models (see e.g. [31,32]).

Improvements on the experimental front can also improve the chances of observing and refining these oscillation signals. The proposed International Linear Collider can provide significant improvement, in particular by eliminating the uncertainty from proton PDFs, which is a significant contribution to the smearing of the signal. Improvements in timing techniques at the LHC itself can also significantly improve on measurement uncertainties and corrections for boost factors.

In summary, in this paper we have drawn attention to the possibility of a neutralino oscillation signal that can be observed at the LHC. Such a signal can be naturally realized in R-symmetric models, where gauginos are Dirac particles but anomaly mediation necessarily generates very small Majorana masses for a low SUSY-breaking scale. The oscillation and decay lengths can be at the right scales for the oscillation to be observable at the LHC. More detailed studies regarding specific model-building issues and detector-level specifics will be required if hints of such a feature actually emerge in the data. For the moment, the possibility of such a spectacular signal at the LHC, which is reasonably well motivated yet has remained hitherto unexplored, is a tantalizing prospect by itself.

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