Reinterpreting $pp \to W^+W^-$ searches for charginos

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The hallmark way to search for electroweakinos in natural supersymmetry at the LHC involves the trilepton plus missing energy ($\not{E}_T$) final state. This approach assumes an electroweakino mass hierarchy that allows for cascade decays leading to a final state of $W^\pm Z^0$ plus $\not{E}_T$. There are, however, situations when that decay pattern may not exist, such as when a chargino is the lightest electroweakino and the lightest supersymmetric particle is the gravitino. In regions of the parameter space where this ordering occurs, the production of any combination of neutralino/chargino leads to a $W^+W^- + \not{E}_T + X$ final state, where X could be additional jets or leptons. If X is soft, then all neutralino/chargino production modes fall into the same experimental final state, $\ell^+\ell^- + \not{E}_T$. ATLAS and CMS have $W^+(\ell^+\nu)W^-(\ell^-\bar{\nu}) + \not{E}_T$ searches, but their interpretation assumes a spectrum consisting of an isolated charged state. In this paper, we identify the circumstances under which natural supersymmetry models can avoid $W^\pm Z^0 + \not{E}_T$ bounds. For scenarios that escape $W^\pm Z^0 + \not{E}_T$, we then recast the latest ATLAS $W^+W^- + \not{E}_T$ search, taking into account all the states that contribute to the same signal. Assuming the lightest supersymmetric particle is massless, we find a bound of 460 GeV for a Higgsino-like degenerate doublet. Finally, we extend our arguments to a nonsupersymmetric simplified model containing new electroweak-scale $SU(2)_w$ doublets and singlets.

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I. INTRODUCTION

The LHC has several searches for physics beyond the standard model (BSM) that involve large missing transverse energy ($\not{E}_T$). Supersymmetry is one of the prime motivations for these searches, as the lightest supersymmetric particle (LSP) is stable (assuming R-parity), and has to be neutral for cosmological reasons. Motivated by arguments of naturalness and dark matter abundance, we are pushed to a spectrum where electroweakinos (admixtures of electroweak gauginos and Higgsinos) have masses in the range of hundreds of GeV while other supersymmetric particles are much heavier. As electroweakinos cannot decay to squarks/sleptons in this setup, one way to hunt for them is to look in diboson plus missing energy final states. Electroweakinos can decay $\chi \to V + \text{LSP}$, where V is any electroweak boson (including the Higgs), but decays involving $W^\pm$ and Z^0 (typically) dominate in natural setups.[1] Among all possible combinations of electroweakino production and decay mode, $pp \to \chi_2^0\chi_1^+ \to Z^0W^\pm\chi_1^0\chi_1^0$—associated production of a heavier (non-LSP) neutralino with a chargino followed by their decays to $Z^0/W^\pm$ plus LSP is the most attractive. Assuming leptonic decays of both the $W^\pm$ and Z^0, the final state is very clean, yet it has a largish production cross section (compared to, e.g., $Z^0(\ell^+\ell^-)Z^0(\ell^+\ell^-)$ from a pair of neutralinos) and sufficient handles to suppress the background. Specifically, the SM $W^\pm(\ell^\pm\nu)Z^0(\ell^+\ell^-)$ background has only one source of missing energy, unlike $W^+(\ell^+\nu)W^-(\ell^-\bar{\nu})$, the background for chargino pair production. In the wide parameter space, where this so-called "trilepton" search is applicable, the bound is quite strong, $m_{\chi^\pm} \sim m_{\chi_2} \gtrsim 600$ GeV [1,2] for a massless LSP.

The prevalence of the trilepton bound in natural supersymmetry leads us to an obvious question: what are the circumstances under which $W^\pm Z^0 + \not{E}_T$ fails as an electroweakino detection mode? Part of the power of the $W^\pm Z^0 + \not{E}_T$ search is its insensitivity to most of the supersymmetry spectrum—it only cares about the mass hierarchy and decays of the electroweakinos. One easy way to disrupt the $W^\pm Z^0 + \not{E}_T$ is to introduce some other BSM state(s) for the electroweakinos to decay to. While an interesting possibility, this necessarily involves adding new light states, taking us away from minimal natural supersymmetry, so we will not pursue this possibility here. The only additional light state we will permit is the gravitino $\tilde{G}$, a nonelectroweakino neutral state that falls out as the LSP

[1]Decays to the Higgs required a large hierarchy of masses among the different neutralinos and decays involving the photon are radiative.

whenever the scale of supersymmetry breaking is low [3].[2] We will permit additional heavy states, including larger electroweakino sectors, provided all electroweakinos predominantly decay to $W^{\pm}/Z^0 + \mathrm{LSP}$. Second, to narrow our scope further, we will look for scenarios where a different final state $W^+W^- + \not{E}_T$ takes over as the dominant discovery channel. With these caveats, we can rephrase our focus as allowing for the possibility of a gravitino LSP, an arbitrary hierarchy of electroweakino soft masses (and μ term), and additional electroweakinos, what are the criteria for $W^{\pm}Z^0 + \not{E}_T$ to fail in electroweakino detection while $W^+W^- + \not{E}_T$ succeeds? And in these scenarios, what are the additional experimental consequences?

As we will show, it is possible to avoid $W^{\pm}Z^0 + \not{E}_T$, even within the minimal supersymmetric standard model (MSSM), and in these parameter regions, $pp \to W^+(\ell^+\nu)W^-(\ell^-\bar{\nu}) + \not{E}_T$ is automatically the most sensitive electroweakino detection channel. However, an unavoidable consequence in these scenarios is that the $W^+W^- + \not{E}_T$ final state is populated (at least, at the level of detected, reconstructed objects) by multiple electroweakino production channels ($\chi_1^+\chi_1^-$, $\chi_1^{\pm}\chi_2$, $\chi_1^0\chi_2^0$, etc.). We revisit the $W^+(\ell^+\nu)W^-(\ell^-\bar{\nu}) + \not{E}_T$ results from ATLAS [5] and CMS [6] to update the bounds including all production channels. In extensions of the MSSM with additional electroweakinos, the realm of possibilities is larger. However, we will show that the dominance of $W^+W^- + \not{E}_T$ over $W^{\pm}Z^0 + \not{E}_T$ is a common outcome in R-symmetric extensions of the MSSM [7,8].

Finally, our conclusions regarding the relative sensitivity of $W^{\pm}(\ell^+\nu)Z^0(\ell^+\ell^-)$ and $W^+W^- + \not{E}_T$ (or $\ell^+\ell^- + \not{E}_T$) are not restricted to supersymmetric extensions of the SM. They can be applied to any model with new electroweak multiplets, and we give a simple straw-man example in Sec. II.

The structure of the rest of the paper is as follows. In Sec. II, we describe the spectra probed by the different channels and the three different examples where the $W^+W^- + \not{E}_T$ channel is the most sensitive. In Sec. III, we present the details of the ATLAS search and our simulation work. Finally, Sec. IV contains our conclusions. Some technical details are presented in Appendix.

II. SPECTRA AND MODELS

We begin by considering the typical electroweakino spectrum where $W^{\pm}Z^0 + \not{E}_T$ is applicable. The lightest state, assumed to be neutral for cosmological reasons, sits at the bottom. The next lightest state particle (NLSP) is neutral, followed (increasing in mass) by the first chargino and other neutralinos. We will use LSP for the lightest state throughout this paper, even in circumstances where the LSP is the lightest neutralino (χ_1^0). We will call the next heaviest neutralino χ_2^0, while $\chi_1^{\pm}$ denotes the lightest chargino. The heavier chargino and heavier neutralinos χ_3^0, χ_4^0 will play no role in what follows. A cartoon depicting an example spectrum is shown below in Fig. 1, where we have taken the LSP to be the lightest neutralino. The fact that the NLSP is a neutralino is important, as its only open decay channel is to the LSP plus something neutral. With all squarks and sleptons decoupled and neglecting loop-level decays to photons, $Z^0 + \mathrm{LSP}$ is the only option.[3] The chargino is free to decay to either the NLSP or the LSP by emitting a $W^{\pm}$, though in scenarios where $m_{\chi_1^{\pm}} \sim m_{\chi_2}$, phase space considerations mean the decay $\chi_1^{\pm} \to W^{\pm} + \mathrm{LSP}$ dominates.

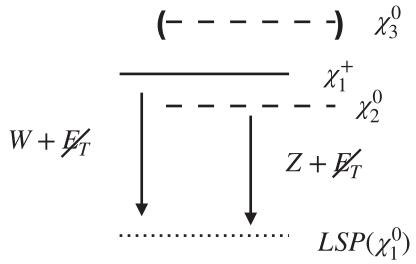

FIG. 1. Schematic spectrum that will have $W^{\pm}Z^0 + \not{E}_T$ as discovery channel. The number of neutralinos depends on the nature (wino or higgino-like) of $\chi_{2,3}^0$.

In order to suppress $W^{\pm}Z^0 + \not{E}_T$ while keeping $W^+W^- + \not{E}_T$ as a useful search channel for electroweakinos, the simplest possibility is to remove the neutralino—χ_2^0 in Fig. 1—by making it heavy. However, at least within the context of supersymmetry, removing the second neutralino is not feasible. Electroweakinos are part of $SU(2)_w$ multiplets that mix after electroweak symmetry is broken. As a result, the mass difference between the neutral and charged components of the multiplet goes as $\sim m_W^2/M$, where M is the overall mass of the multiplet. One cannot just remove the neutralino from the spectrum without violating $SU(2)_w$ invariance. More generally, in any model where the charged particle belongs to a nontrivial $SU(2)_w$ multiplet, electroweak invariance prevents splitting the different components by arbitrarily large values—and any term that distinguishes among the different members of the multiplet have to be proportional to the vacuum expectation value of the Higgs.

However, as we will review below, it is possible to reverse the mass order of the lightest chargino and the lightest neutralino. With no further additions, this mass ordering is not acceptable cosmologically, as the lightest electroweakino is now charged, but if we embed the scenario in the context of gauge mediated supersymmetry breaking (or another setup with supersymmetry breaking at

[2]Another possibility leading to the same conclusion would be the siniglino of the NMSSM [4].

[3]As we are ultimately interested in leptonic final states, we will ignore the possibility of neutralinos decaying to Higgs + LSP.

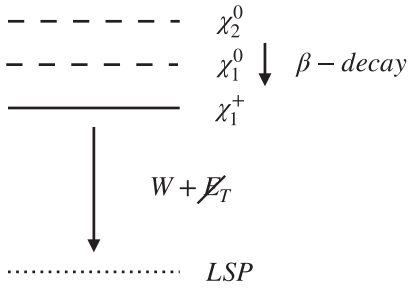

FIG. 2. Schematic spectrum that will have $W^+W^- + \not{E}_T$ as discovery channel. The mass splitting between the neutralinos and the chargino is small so the products from β-decay are very soft. The number of neutralinos is model dependent but it does not affect the conclusion. In this case, the LSP is the gravitino.

a low scale), then the gravitino is the LSP and there is no immediate issue.[4]

With the gravitino as LSP, an NLSP chargino will decay to $W^\pm + \text{LSP}$. The lightest neutralino can decay directly to $Z^0 + \text{LSP}$; however, it now also has the possibility to decay to $W^\mp + \chi_1^\pm$ (beta decay). If the latter dominates sufficiently, Z^0 decays are eliminated and the trilepton signal is stifled.

Finally, even if beta decay of neutralinos dominates, neutralino production followed by beta decay and $\chi_1^\pm \to W^\pm + \text{LSP}$ can still lead to a trilepton signal, i.e., $pp \to \chi_2\chi_1^\pm \to W^\pm\chi_1^+\chi_1^- \to 3\ell + \not{E}_T$. This contribution can be suppressed as well if χ_2^0 and $\chi_1^\pm$ have similar mass. In this case, the lepton from the beta decay is too soft to pass the detector id requirements.

While this set of requirements removes (or at least strongly suppresses) the trilepton signal, there are now several channels ($\chi_1^+\chi_1^-$, $\chi_1^\pm\chi_2$, $\chi_1\chi_2$, etc.) contributing to the $\ell^+\ell^- + \not{E}_T$ final state and must be considered when interpreting the W^+W^- channel bound. In Fig. 2, we summarize the necessary criteria for $W^+W^- + \not{E}_T$ to be the most sensitive channel.

To better illustrate how these requirements work and what they demand of the spectrum, we now introduce three benchmark scenarios. In the context of supersymmetry, the electroweakino sector has been vastly studied in the literature. In particular, Ref. [8] precisely analyzed the conditions for the chargino to be the lightest of the electroweakinos in two different supersymmetric models. We now proceed to summarize what was found in Ref. [8] and to quote the results relevant to our paper.

Starting within the MSSM, and in the limit when one assumes the electroweak breaking effects are small, the masses of neutralinos can be written as [10]

$$
\begin{aligned}
m_{\chi_B^0} &= M_1 - \frac{m_Z^2 s_W^2 (M_1 + \mu \sin 2\beta)}{\mu^2 - M_1^2} \\
m_{\chi_W^0} &= M_2 - \frac{m_W^2 (M_2 + \mu \sin 2\beta)}{\mu^2 - M_2^2} \\
m_{\chi_{H1}^0} &= |\mu| + \frac{m_Z^2 (I - \sin 2\beta)(\mu + M_1 c_W^2 + M_2 s_W^2)}{2(\mu + M_1)(\mu + M_2)} \\
m_{\chi_{H2}^0} &= |\mu| + \frac{m_Z^2 (I + \sin 2\beta)(\mu - M_1 c_W^2 - M_2 s_W^2)}{2(\mu - M_1)(\mu - M_2)},
\end{aligned} \tag{1}
$$

where M_1 and M_2 are assumed to be real and positive and I is equal to ± 1 depending on the sign of μ. Here we are using B, W, H to label different eigenstates according to their nature (mostly bino, wino, or Higgsino) and 1,2,3,4 to label their mass from light to heavy. There are similar expressions for the chargino masses,

$$
\begin{aligned}
m_{\chi_W^\pm} &= M_2 - \frac{m_W^2 (M_2 + \mu \sin 2\beta)}{\mu^2 - M_2^2} \\
m_{\chi_H^\pm} &= |\mu| + \frac{I m_W^2 (\mu + M_2 \sin 2\beta)}{\mu^2 - M_2^2}.
\end{aligned} \tag{2}
$$

If we assume that the lightest chargino is winolike, then $M_2 \ll |\mu|$ so that $m_{\chi_W^\pm}$ corresponds to $m_{\chi_1^+}$. In this limit, we see that $m_{\chi_W^0}$ is actually equal to $m_{\chi_1^\pm}$ (they will be split by QED corrections), and thus production of the lightest chargino in association with this winolike neutralino is roughly the same size (at least from a kinematics perspective) as chargino pair production. If we further take $M_1 \ll M_2, |\mu|$ such that the bino is the LSP, charginos will decay $\chi_1^\pm \to W^\pm + \text{LSP}$, neutralinos as $\chi_2^0 \to Z^0 + \text{LSP}$, exactly the type of scenario where (for all values of M_1, M_2) $W^\pm Z^0 + \not{E}_T$ searches are relevant. The same situation will happen if M_1 is larger than M_2 but another neutral state like the gravitino in gauge mediation supersymmetry breaking (GMSB) or the singlino in the NMSSM is the LSP.

If we instead assume that Higgsinos are lighter than the wino, corresponding to $|\mu| \ll M_2$, then the exact ordering among the charginos and neutralinos depends on the value of M_1. If M_1 is smaller than $|\mu|$ and M_2, then $m_{\chi_B^0}$ corresponds to the LSP and one can easily see that $m_{\chi_{H1}^0}$ and $m_{\chi_{H2}^0}$ are of the same size as $m_{\chi_H^\pm}$, and that one of the two is lighter than $m_{\chi_H^\pm}$ and the other heavier. The spectrum again matches Fig. 2, so $W^\pm Z^0 + \not{E}_T$ will set the strongest bound.

However, if $M_1 > M_2 > |\mu|$ with positive μ and $\tan\beta$ close to one, we find the following mass hierarchy for the lightest electroweakinos:

$$
m_{\chi^\pm} = \mu - \frac{m_W^2}{M_2} \qquad m_{\chi_1^0} = \mu - \frac{m_W^2}{2M_2} \qquad m_{\chi_2^0} = \mu, \tag{3}
$$

[4]The gravitino as DM candidate has some challenges from the model building point of view [9], but any discussion in this direction is beyond the scope of this paper since the solutions do not involve the electroweakino spectrum.

with the other electroweakinos heavier. In this situation, the lightest of the three eigenstates is the charged one. Note that, although one gets a spectrum where the chargino is lighter than any neutralino, the mass difference between $\chi^{\pm}$ and $\chi^0_{1,2}$ is small. The LSP in this case has to be another neutral state like the gravitino (in GMSB) or the singlino in the NMSSM. We are going to focus on the first possibility as an example where the LSP is not an electroweakino. The NMSSM adds an extra singlet superfield and modifies the neutralino mass matrix adding more parameters. Nonetheless, in situations where the LSP is mostly singlino and a chargino is the NLSP, one can realize a spectrum leading to the same signal [11].

Focusing on this mass ordering within the context of GMSB, the $\chi^0_{1,2}$ neutralinos can either beta decay to $\chi^{\pm}_1$ or directly to the gravitino emitting a photon or a Z^0. As explained earlier, for $W^{\pm}Z^0 + \not{E}_T$ to be suppressed, beta decay of the neutralino must dominate. Reference [8] introduced the following ratio to distinguish which decay dominates:

$$R_\Gamma \equiv \frac{\Gamma(\chi^0_{1,2} \to \chi^{\pm}_1 \bar{f} f')}{\Gamma(\chi^0_{1,2} \to \tilde{G} X)}. \tag{4}$$

The decay of the neutralino to the gravitino is given by [3]

$$\Gamma(\chi^0_{1,2} \to \tilde{G} X) = \kappa_{\tilde{G}X} \frac{m^5_{\chi^0}}{96\pi M^{*2}_P m^2_{3/2}} \left[1 - \frac{M^2_X}{m^2_{\chi^0}}\right]^4, \tag{5}$$

where $\kappa_{\tilde{G}X}$ encodes the $O(1)$ coupling of the neutralino to the gravitino and X (which introduce a small model dependence into R_Γ) and $m_{3/2}$ is the gravitino mass. The three-body decay of the neutralino to the chargino and soft leptons is beta decay which makes R_Γ proportional to $m^2_{3/2}(\Delta m/m_{\chi^{\pm}_1})^5$, where Δm is the mass difference between the (lightest) neutralino and the (NLSP) chargino.

The condition for $W^+W^- + \not{E}_T$ to give a stronger bound than $W^{\pm}Z^0 + \not{E}_T$ is

$$\begin{aligned}&\sigma(pp \to \chi^+_1\chi^-_1) + \sigma(pp \to \chi^{\pm}_1\chi^0_{1,2})\mathrm{BR}(\chi^0_{1,2} \to \chi^{\pm}_1 \bar{f} f') \\ &\quad > \sigma(pp \to \chi^{\pm}_1\chi^0_{1,2})\mathrm{BR}(\chi^0_{1,2} \to \tilde{G} X),\end{aligned} \tag{6}$$

where we assume both channels to have similar analysis efficiencies and neglect terms that go quadratically with the branching ratios. The inequality six is satisfied when $R_\Gamma > \frac{\sigma(pp\to\chi^{\pm}_1\chi^0_{1,2}) - \sigma(pp\to\chi^+_1\chi^-_1)}{\sigma(pp\to\chi^{\pm}_1\chi^0_{1,2}) + \sigma(pp\to\chi^+_1\chi^-_1)}$, which is roughly equal to $1/2$ for the values of masses that we are considering. This is a rather simple assumption that does not take into account the specifics of the different final states, such as efficiencies or SM backgrounds, but the important point is that there will always be a region where $W^+W^- + \not{E}_T$ will dominate.

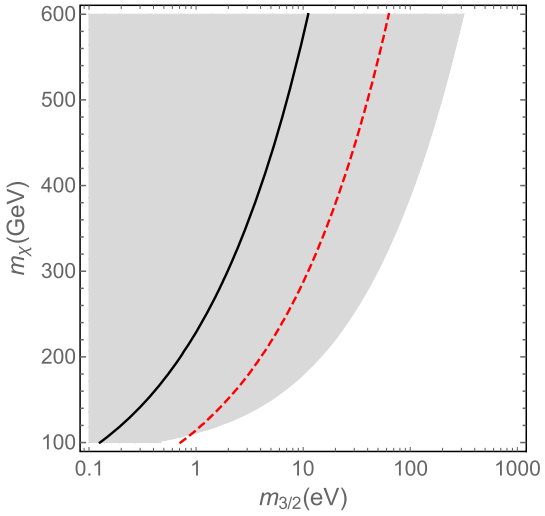

FIG. 3. Line of $R_\Gamma = 1/2$ for $\Delta m = 5$ GeV (dashed) and $\Delta m = 10$ GeV (solid) in the chargino mass versus gravitino mass plane. The shaded region corresponds to a prompt decay of the chargino. The region right of the lines while in the shaded region is the parameter space where $W^+W^- + \not{E}_T$ will give the strongest bound in this model.

In Fig. 3, we have plotted the line of $R_\Gamma = 1/2$ (larger values for R_Γ will be to the right of the one plotted) in the plane ($m_{3/2}$, m_χ) for $\Delta m = 5$ GeV (dashed) and 10 GeV (solid). As can be seen from the figure, the relevant parameter space corresponds to chargino masses of few hundreds of GeV and gravitinos in the tens of eV. The smaller we take Δm, the smaller $m_{3/2}$ must be to maintain $R_\Gamma > 1/2$. The gravitino mass sets the overall chargino lifetime, and for sufficiently small $m_{3/2}$, the charginos become long-lived. As our focus is on the $W^+(\ell^+\nu)$ $W^-(\ell^-\bar{\nu}) + \not{E}_T$ search, which assumes a promptly decaying signal, we will not consider long-lived electroweakinos in this paper. Long-lived electroweakinos are an interesting possibility, but require completely different search strategies; see [12–14]. To fix the parameter space, we will designate decay lengths smaller than 0.5 mm as prompt, corresponding to the shaded region of Fig. 3.

Since the mass splitting Δm controls the energy of remnants from χ^0_2 beta decay (which may include additional leptons), if we try to push the parameter space to larger Δm, we cannot ignore the $W^{\pm}Z^0 + \not{E}_T$ channel—the lepton p_T requirement in the ATLAS trilepton searches [2] is set to 10 GeV. While the turn on of the $W^{\pm}Z^0 + \not{E}_T$ sensitivity will not be immediate at $\Delta m = 10$ GeV, we will focus on Δm between 5 (smaller values will lead to a long-lived chargino for the values of $m_{3/2}$ we are considering) and 10 GeV. Since $m_{3/2} < 100$ eV when translating experimental constraints into this scenario, we must be careful to use interpretations that also assume a massless LSP.

One additional feature of this scenario that is worth mentioning is that the neutralinos are predominantly

Higgsino-like and are therefore pseudo-Dirac [15]. As a result, the production of same-sign charginos—coming from neutralino decays and leading to a final state of same sign leptons plus $\not{E}_T$ (i.e., $pp \to \chi_1\chi_2 \to \chi_1^+\chi_1^+\tilde{G}\,\tilde{G} \to W^+(\ell^+\nu)W^+(\ell^+\nu) + \not{E}_T$)—is very suppressed. The origin of the suppression is an approximate charge conjugation symmetry only broken by the small splitting between the two neutralinos [15].

While it is possible to arrange for $m_{\chi_1^\pm} < m_{\chi_1^0}$ in the MSSM, the parameter space is quite limited. However, in extensions of the MSSM with Dirac gaugino masses, $m_{\chi_1^\pm} < m_{\chi_1^0}$ is far more common. Some scenarios that contain Dirac gauginos include extradimensional supersymmetry models [16–19] or four-dimensional models where the $U(1)_R$ symmetry present in the supersymmetric kinetic term is imposed on the rest of the theory [7,20–23]. In these so-called R-symmetric models, there are actually four charginos: the two states from the MSSM, one from the $SU(2)_w$ adjoint Dirac partner of the wino, and one from an additional $SU(2)_w$ doublet (an R-Higgs) whose presence is required to impose exact R-symmetry on the Higgs terms in the superpotential. For reference, the superpotential for this setup is shown in Appendix. These four states can be further classified by their R-charge (± 1), so the chargino mass matrix splits into two 2×2 blocks. In the limit of large tan β and a vanishing $SU(2)_w$ adjoint vev, the 2×2 block containing the lightest eigenvalue simplifies to

$$M_{\chi^\pm} = \begin{pmatrix} M_{D2} & O(gv/\sqrt{2}) \\ O(\lambda v/\sqrt{2}) & \mu \end{pmatrix}, \tag{7}$$

where M_{D2} is the $SU(2)_w$ gaugino Dirac mass, g is the $SU(2)_w$ coupling, and λ is the coupling for trilinear superpotential interaction containing the $SU(2)_w$ adjoint, a MSSM Higgs, and its R-Higgs partner (see Appendix).

The neutralinos in this setup form four Dirac fermions.[5] In the large tan β, small $SU(2)_w$ adjoint vev approximation used above,[6] their mass matrix has the form

$$M_{\chi^0} = \begin{pmatrix} M_{D1} & 0 & 0 & O(gv/2) \\ 0 & M_{D2} & 0 & O(gv/2) \\ 0 & 0 & \mu & 0 \\ O(\lambda v/\sqrt{2}) & O(\lambda v/2) & 0 & \mu \end{pmatrix}, \tag{8}$$

where the new parameter M_{D1} is the $U(1)_Y$ Dirac gaugino mass. Let us decouple M_{D1}, analogous to what we did in the MSSM case, reducing the neutralino mass matrix to 3×3. Comparing the lower right 3×3 block of Eq. (8) with Eq. (7), we see the mass matrices have the same structure, but that the off-diagonal entries are larger for the charginos by a factor of $\sqrt{2}$. Diagonalizing the larger off-diagonal entries translate to larger splitting among eigenvalues, and thus the lightest eigenvalue of $M_{\chi^\pm}$ will be lighter than the lightest of M_{χ^0}. This result is not restricted to the simplifying limits we have taken here and persists throughout large regions of parameter space, as explored thoroughly in Ref. [8].

As in the MSSM case, $m_{\chi_1^\pm} < m_{\chi_{1,2}^0}$ is only viable cosmologically in the context of low-energy supersymmetry, where the chargino plays the role of the lightest of the electroweakinos and the gravitino is the LSP. While the R-symmetric model has more parameters and states, we have not introduced any additional light particles (compared to the MSSM in GMSB), so the relevant parameters and kinematics of electroweakino decay are unchanged from our MSSM discussion. As such, Eq. (4) continues to hold in the R-symmetric case, with the viable parameter space described by Fig. 3. Of course, while the mass parameters ($\Delta m, m_\chi$, etc.) are the same, their description in terms of UV parameters is different in R-symmetric models than in the MSSM. Finally, as all electroweakinos are Dirac in this model, there is no possibility for a same sign dilepton signal because there is an exact charge conjugation symmetry [15].

While supersymmetry was useful for providing context for the previous two scenarios, our arguments regarding the validity of $W^+W^- + \not{E}_T$ versus $W^\pm Z^0 + \not{E}_T$ are essentially just statements about the mass ordering of states in new $SU(2)_w$ multiplets and do not require full supersymmety structure. To illustrate this, consider a simple SM extension consisting of a vectorlike fermion $SU(2)_w$ doublet with $Y = -1/2$, Σ, and a neutral pseudoscalar ϕ. Adding interactions among Σ, ϕ, and the SM, we have

$$\mathcal{L} = M_\Sigma \bar{\Sigma}\Sigma + \frac{m^2}{2}\phi^2 + \frac{c_\phi}{\Lambda}\partial^\mu\phi\bar{\Sigma}\gamma_\mu\gamma_5 L + \frac{c_h}{\Lambda}(H\Sigma)^2 + \ldots, \tag{9}$$

where L is a SM lepton doublet (either e or μ), and for simplicity we have suppressed a possible interaction between $\bar{\Sigma}$, E, and the Higgs. This can be justified either by taking the coupling to be very small, or by imposing a discrete symmetry that distinguishes ϕ and the Higgs.[7] The mass splitting between the states in Σ is controlled by the last term and is $\sim v^2/\Lambda$. For the appropriate sign of c_h, the neutral state (Σ^0) will be heavier than the charged one ($\Sigma^\pm$), and it can either decay $\Sigma^0 \to \phi\nu$ via the nonrenormalizable operator or it can beta decay to the charged

[5]The wino, bino, and two Higgsinos of the MSSM (4 Weyl fermions) plus their R-symmetric partners (four more Weyl states).

[6]In addition, we have set the two superpotential Higgs masses to be the same, $\mu_u = \mu_d = \mu$. See Appendix for more details.

[7]For example, Z_2 symmetry under which Σ and ϕ are odd and the rest of the fields even.

component, $\Sigma^0 \to \Sigma^\pm \ell^\mp \overset{(-)}{\nu}$. If $\Sigma^0 \to \phi\nu$ dominates, then Σ^0 production will lead to a purely invisible final state. However, if beta decay dominates, then we will be in a situation, as earlier, where the whole Σ doublet contributes to the $\ell^+\ell^- + \not{E}_T$ final state and can be picked up by ATLAS/CMS $W^+W^- + \not{E}_T$ searches.[8] By construction, there is no possibility of a same sign dilepton signal in this model.

Taking ϕ to be massless, the partial decay width of $\Sigma^0 \to \phi\nu$ (denoted as Γ_ϕ) and the partial width of $\Sigma^0 \to \Sigma^+ f f'$ (denoted as Γ_β) are equal to

$$\Gamma_\phi = \frac{c_\phi^2}{8\pi}\frac{M_\Sigma^3}{\Lambda^2}$$
$$\Gamma_\beta = \frac{2}{15\pi^3}\frac{c_h^5}{\Lambda^5} v^6, \tag{10}$$

where v is the vev of the Higgs. We can now investigate the region of the parameter space where beta decay dominates. In Fig. 4, we show the line $\Gamma_\beta = \Gamma_\phi$ in the Λ versus M_Σ plane for $c_h = 1$ and $c_\phi = 10^{-4}$. To the left of the black line is the viable region, where $\Gamma_\beta > \Gamma_\phi$. The white region corresponds to the prompt decay of $\Sigma^\pm$. The splitting between the neutral and the charged component of Σ is less than few GeV in the whole plot (and we are still taking the mass of ϕ to be negligible to make sure all decays are prompt). Varying c_ϕ and c_h will just move the position of the black line and the region where the decay is prompt but the conclusion will be the same—there are regions where the whole doublet contributes to the $pp \to \ell^+\ell^- + \not{E}_T$ final state.

Amusingly, our experience with this toy model allows us to craft a scenario with an isolated charged state—the type of signal the ATLAS/CMS analysis assumes. Instead of the $SU(2)_w$ doublet Σ, we could introduce a vectorlike singlet with $Y = -1$ (Δ) that decays to the right-handed leptons plus ϕ via the following higher dimensional operator $\partial^\mu\phi\bar{\Delta}\gamma_\mu\gamma_5 e_R$.

Summarizing this section, we have shown that in scenarios where $W^\pm Z^0 + \not{E}_T$ will not give any bound due to the suppression of decays Z^0's the $W^+W^- + \not{E}_T$ search will set the strongest bounds. We have also shown that, in these scenarios, there are several states contributing to the same final state and therefore the experimental bound calculation is more complex than the naive experimental interpretation. For example, in the MSSM suppressing the $W^\pm Z^0 + \not{E}_T$ implies that the whole Higgsino doublet will be the lightest of the electroweakinos and will have neutral states contributing to the same final state (plus soft objects) in the decays to the gravitino LSP. The question that remains is how those extra states affect and modify the ATLAS/CMS interpretation.

[8] Σ production does not generate any on-shell $W^\pm$'s, but this is irrelevant as the analysis only looks for sufficiently energetic, opposite sign leptons and missing energy.

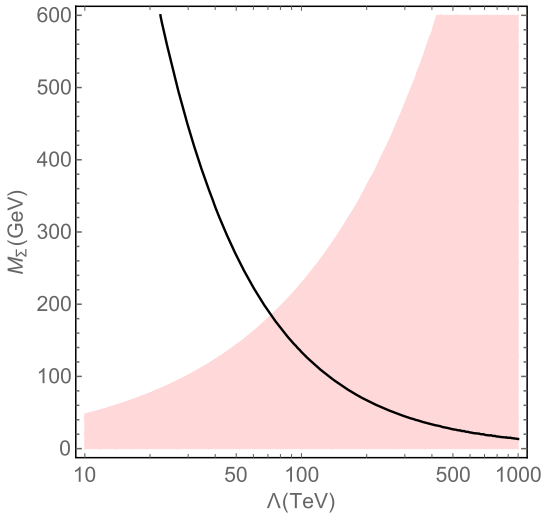

FIG. 4. The black line indicates where $\Gamma_\beta = \Gamma_\phi$ for $c_h = 1$ and $c_\phi = 10^{-4}$ as a function of the mass of Σ (M_Σ) and Λ. The white region corresponds to a prompt decay of the charged component, whereas the shaded region corresponds to a long-lived charged particle. The viable region is the white one to the left of the black line.

III. WW + $\not{E}_T$ SEARCH AND SIMULATION

Both ATLAS [5] and CMS [6] have searches for two opposite sign (OS) leptons and missing energy that they interpret as a bound on chargino pair production,[9] where the charginos decay to a leptonic $W^\pm$ and a neutralino LSP ($pp \to \chi^+\chi^- \to W^+(\ell^+\nu)W^-(\ell^-\nu)\chi_1^0\chi_1^0$). The CMS search uses 36 fb^{-1} and excludes chargino masses between 160 and 200 GeV for a massless LSP, while the ATLAS variation uses the full Run II luminosity at 13 TeV, 138 fb^{-1}. For a purely winolike (i.e., charged components of an $SU(2)$ triplet, where the other components are taken to have no role in the bound) and decaying 100% of the time to $W^\pm$ plus massless neutralino LSP, the bound is $m_{\chi^\pm} > 410$ GeV. The bound gets weaker when the LSP increases in mass since the decay products of the chargino get softer. As ATLAS has updated the analysis with the full dataset we will base our discussion on that analysis, although our conclusions will apply to any search with similar requirements.

The ATLAS search requires exactly two opposite sign leptons (e/μ) with $p_T > 25$ GeV and $|\eta| < 2.47(2.7)$ electrons (muons) and an invariant mass of the dilepton pair greater than 100 GeV. In addition, the missing transverse energy must be greater than 110 GeV. Up to one light flavor jet satisfying $p_T > 20$ GeV and $|\eta| < 2.4$ is allowed,

[9] For alternative interpretations, see, for example, [24].

while all events containing a b-tagged jet are vetoed. Surviving events are further classified according to whether the leptons have the same or different flavor and the number of light flavor (non-b quark or gluon) jets (0 or 1), then broken into several signal regions according to the kinematical variable $M_{T2} = \min_{\not{p}_{T1}+\not{p}_{T2}=\not{p}_T}\{\max[m_T(p_T^{\ell_1}, \not{p}_{T1}), m_T(p_T^{\ell_2}, \not{p}_{T2})]\}$, where $p_T^{\ell_{1,2}}$ are the transverse momenta of the leptons and $\not{p}_T$ is the missing transversed momentum. Not seeing any excesses from the SM background ATLAS derives the bound of 410 GeV for an isolated winolike chargino and a massless LSP.

We have shown in the previous section that whenever the chargino is the LSP there are other states close by in mass that will populate the same signal, so one has to reinterpret the previous bound in a more realistic situation. To study this in Monte Carlo, we use the MSSM model from Sec. II as a test case, working with a UFO model file that includes the Feynman rules of the MSSM in GMSB [25] (within the framework of MadGraph5_aMC@NLO [26]). We set the gravitino as the LSP, decouple all sparticles other than the electroweakinos, and (following Sec. II) choose electroweakino masses such that the Higgsino is the lightest multiplet with the chargino lighter than the lightest neutralino.

For a given chargino mass and fixed chargino-neutralino mass difference of $\Delta m = 10$ GeV, we simulate the production of all possible pairs of chargino/neutralino, $pp \to \chi_i\chi_j$ (where $i, j = 1, 2, \pm$), forcing the neutralinos $\chi_{1,2}$ to beta decay so that every event contains $W^+W^- + \not{E}_T +$ soft particles. The parton level events are then passed through PYTHIA8 [27] for the $W^\pm$ decays, showering, and hadronization, then through DELPHES [28] for detector simulation. We generate 50,000 events for every electroweakino mode ($\chi_1^+\chi_1^-$, $\chi_1\chi_2$, etc.).

The simulated events are then run through the ATLAS analysis [5] and separated into signal regions. We find that the total signal efficiency (summing over all signal regions) is between 1.4% and 1.5% for every electroweakino mode—i.e., $pp \to \chi_1^0\chi_2^0$, $pp \to \chi_1^0\chi_1^+$, etc. have the same analysis efficiency as $pp \to \chi_1^+\chi_1^-$. In addition, there are no appreciable differences in how different electroweakino modes populate the individual signal regions.

To determine the mass bound in our setup, we equate the cross section times efficiency for $pp \to \chi_i\chi_j$ ($i, j = 1, 2, \pm$, Higgsino-like hierarchy) to the cross section times efficiency for the model ATLAS uses, $pp \to \chi_1^+\chi_1^-$ (winolike). Not knowing the full details of how the different signal regions are combined and weighted in the statistical analysis, we use the total efficiency (summing all signal regions) to set bounds. The LSP is massless in our scenario[10]; therefore,

[10]The three models have a massless LSP (or ϕ in the nonsusy case).

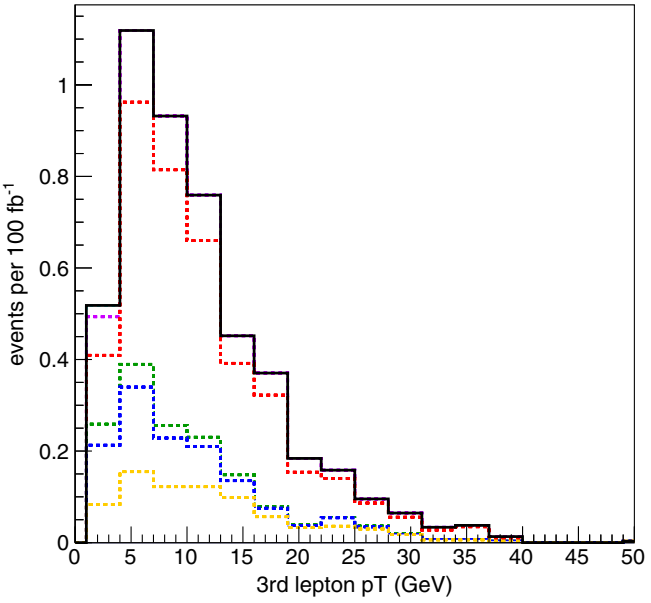

FIG. 5. The p_T of the third hardest lepton in simulated events that pass the ATLAS analysis. The dotted lines indicate the contributions from (starting from the bottom) $pp \to \chi_1^0\chi_2^0$ (yellow), $\chi_1^0\chi^+$ (blue), $\chi_1^0\chi^-$ (green), $\chi_2^0\chi^+$ (red), $\chi_2^0\chi^-$ (violet), and $\chi^-\chi^+$ (cyan). The black line shows the sum of all contributions.

the ATLAS number we want to compare to is $m_\chi = 410$ GeV. Because the analysis efficiency is the same for all production modes, it drops out of the equation and the bound is determined by cross sections alone,

$$\sum_{i,j}\sigma(pp \to \chi_i\chi_j)(m_\chi) = \sigma(pp \to \chi_1^+\chi_1^-)_{\text{wino}}(m_\chi = 410\ \text{GeV}). \quad (11)$$

Here, m_χ is included to remind us that it is the only parameter we dial (the mass splitting is fixed to 10 GeV, all branching fractions are ∼100%, and the only couplings involved are electroweak gauge couplings). Using the NLO-NLL cross sections from Ref. [29], the cross section for the ATLAS model is 48 fb, which translates into an exclusion bound (95% CL) on the Higgsino mass of 460 GeV. While we have calculated this bound using the MSSM model, it applies to the other scenarios we have presented since the three of them have an electroweak doublet decaying to two leptons plus missing energy (and soft objects).

Although we have calculated our bound using the dilepton signal, there are events with three leptons, with the third one coming from the leptonic beta decay of the neutralino. These leptons are too soft to be used to put a bound using the trilepton signal [1,2], as we have emphasized, but they are still present and are a potential handle to improve the search (or to dig out what model is causing a signal, should one be seen). Specifically, we could look for the presence of a third lepton off-line, where p_T thresholds

are typically lower. Finding a third lepton will indicate that there are several states with similar mass and not just an isolated charged state. In Fig. 5 below, we have plotted the p_T of the third lepton for events that have passed all other $W^+W^- + \not{E}_T$ cuts (originating from a spectrum with $\Delta m = 10$ GeV). There are about five events with $p_T > 5$ GeV per 100 fb^{-1}, while only ~2 events above 10 GeV. This is an idealized plot, achieved by fixing the lepton id for leptons with $2\text{ GeV} < p_T < 10\text{ GeV}$ to 100% in the DELPHES card (rather than the conservative default of 0% for leptons with $p_T < 10$ GeV), but it does give some idea of what sort of spectrum to expect and how the yield will depend on p_T. For smaller Δm, the p_T of the third lepton will be softer, making them more difficult to reconstruct.

IV. CONCLUSIONS

In this paper, we have investigated the circumstances under which electroweakinos in natural supersymmetry escape bounds coming from the $W^\pm Z^0 + \not{E}_T$ "trilepton" channel. We identify three criteria: (i) a compressed electroweakino spectrum, with a chargino as the lightest state and mass splittings to heavier neutralino state(s) $O(10\text{ GeV})$; (ii) the predominant neutralino decay mode is beta decay, to $\chi_1^\pm + W^\mp$; and (iii) a gravitino LSP (or other, neutral, nonelectroweakino state). One unavoidable consequence of these criteria is that all $\chi_i\chi_j$, $i = 1, 2, \pm$ modes lead to a $W^\pm W^\mp + \not{E}_T$ final state (plus additional, soft particles) and must be considered when interpreting experimental limits in that channel.

We provided three example models, two supersymmetric and one non, that realize the above features. Then, using a MSSM GMSB model with Higgsinos as the lightest electroweakinos, we recast the ATLAS $W^+W^- + \not{E}_T$ analysis, including all electroweakino modes. For mass splittings among all electroweakinos $\Delta m < 10$ GeV, we find all electroweakino modes have the same analysis efficiency. The resulting exclusion bound is $m_\chi > 460\,\text{GeV}$, compared to the ATLAS bound of 410 GeV (massless LSP).

In general, there are soft leptons coming from the (beta-) decay of the neutralino to the chargino that can potentially be used to distinguish between a model with an isolated charged state from a model with a doublet almost degenerated in mass.

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APPENDIX: R-SYMMETRIC SUPERPOTENTIAL

In the R-symmetric MSSM (MRSSM) [7,30,31], the $U(1)_R$ symmetry inherent in supersymmetric kinetic terms is imposed on the superpotential. The $U(1)_R$ charges of the gauge fields (and their superpartners) are fixed to one, but there is some flexibility in the matter sector. In order for EWSB to not spoil $U(1)_R$, we require $R_{H_u} = R_{H_d} = 0$. All other MSSM matter fields are given $R = 1$. As the superpotential must have $R = 2$, this charge assignment forbids the usual μ-term. Without this term, Higgsinos would be massless. To fix this issue, we introduce new superfields, R-Higgses, with the same SM quantum numbers as the Higgs but carrying R-charge $= 2$. We can then write gauge and $U(1)_R$ invariant mass terms connecting the MSSM Higgses to their R-partners. As there are two MSSM Higgses, we need two R-Higgses,

$$W \supset \mu_u R_u H_u + \mu_d R_d H_d. \tag{A1}$$

We assume the R-Higgses do not get vevs. Having added the R-Higgses, we need to assess whether there are other interactions we need to include. Trilinear interactions involving R-Higgses and two MSSM fields are forbidden by R-symmetry, but we can write down superpotential trilinear interactions between R-Higgses, MSSM Higgses, and the $SU(2)_w$ and $U(1)_B$ Dirac mass partners Φ_{W_a}, Φ_B (which carry R-charge -1),

$$\begin{aligned} W \supset\ & \lambda_u R_u \tau^a H_u \Phi_{W_a} + \lambda_d R_d \tau^a H_d \Phi_{W_a} \\ & + \lambda'_u R_u H_u \Phi_B + \lambda'_d R_d H_d \Phi_B, \end{aligned} \tag{A2}$$

where τ^a are $SU(2)_w$ generators. Once EWSB occurs, these λ interactions lead to mixing among the fermionic components in H_u, R_u, Φ_W, Φ_B, the full set of MRSSM electroweakinos. In Sec. II, we make the simplifying assumption that $\lambda_{u,d} \sim g$, $\lambda'_{u,d} \sim g'$, and $\mu_u = \mu_d$.

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