

Probing the Goldstone equivalence theorem in Heavy Weak Doublet Decays

Bhaskar Dutta,¹ Yu Gao,¹ David Sanford,² and Joel W. Walker³

¹*George P. and Cynthia W. Mitchell Institute for Fundamental Physics and Astronomy,
Texas A&M University, College Station, TX 77843, USA*

²*Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125, USA*

³*Department of Physics, Sam Houston State University, Huntsville, TX 77341, USA*

This paper investigates the decays from heavy higgsino-like weak-doublets into Z, h bosons and missing particles. When pair-produced at the LHC, the subsequent $Z, h \rightarrow \ell\ell, b\bar{b}$ decays in the doublet decay cascade can yield $4\ell, 2\ell 2b$ and $4b + \cancel{E}_T + j(s)$ final states. Mutual observation of any two of these channels would provide information on the the associated doublets' decay branching fractions into a Z or h , thereby probing the Goldstone equivalence relation, shedding additional light on the Higgs sector of beyond the Standard Model theories, and facilitating the discrimination of various contending models, in turn. We compare the Z/h decay ratio expected in the Minimal Supersymmetric model, the Next-to Minimal Supersymmetric model and a minimal singlet-doublet dark matter model. Additionally, we conduct a full Monte Carlo analysis of the prospects for detecting the targeted final states during 14 TeV running of the LHC in the context of a representative NMSSM benchmark model.

PACS numbers: 12.60.Jv, 13.85.Hd, 14.80.Ly, 14.60.Fg

I. INTRODUCTION

The Higgs mechanism plays a central role in the electroweak symmetry breaking and many beyond the Standard Model (BSM) frameworks have been proposed to generate the correct weak-scale Higgs mass as well as to protect it from the ultraviolet(UV) divergence. In any such spontaneously symmetry breaking scenario, there are massless spin-0 (Goldstone) excitations along flat directions of the potential that realize the underlying symmetry of the Lagrangian. If the symmetry is gauged, these degrees of freedom are absorbed in the longitudinal modes of the newly massive vectors, and the Goldstone equivalence theorem mandates that amplitudes for longitudinal vector bosons will be equivalent to those of the associated Goldstone at large collision energies. In particular, for both the Standard Model (SM) and BSM cases, given that the Z mass arises from the Higgs vacuum expectation value (VEV) v , the Z longitudinal modes and the Higgs boson share common couplings, and a (near) unit ratio of Z/h production is generically expected. While there are no heavy electroweak states in the SM to decay directly to Z and h bosons, new states with a non-zero electroweak charge exist in many BSM theories, and their decay branching fraction into Z and h may be applied as a very useful probe of the Higgs sector in such models.

Supersymmetry (SUSY) has been widely accepted as a viable mechanism for alleviating large UV fermion-loop corrections to the Higgs mass. In R -parity enforcing SUSY models, the lightest (LSP) and the next-to lightest supersymmetric particle (NLSP) may be neutralinos. The NLSP may decay into the LSP along with a Z or h . This channel is particularly favorable when there are no other particles in the spectrum, e.g., sfermions, appearing between the lightest two neutralinos that may reduce the branching fraction into Z and h . In the mini-

mal supersymmetric standard model (MSSM), scenarios with a bino-like LSP and higgsino-like NLSPs are quite common, since lighter higgsinos are preferred in order to realize a smaller value of the SUSY-preserving higgsino mixing term μ . Moreover, since anomaly cancellation requires distinct $SU(2)_L$ Higgs doublets (H_u, H_d) to provide up- and down-like masses, there are two higgsino NLSPs in this case. The Z, h decay branching fractions of each depend sensitively on the individual neutralino mixing of H_u, H_d , although the ratio of the decay branching ratios into Z and h is of order unity when both contributions are added, as predicted by the Goldstone equivalence theorem. Nevertheless, the specific ratio may feature some weak residual dependence upon the specific model parameters, particularly the ratio $\tan\beta$ of VEVs acquired by the up and down type MSSM Higgs fields.

It is interesting to consider alternative scenarios that can impact the Z/h branching ratio. For example, testable deviation from the MSSM could be predicted if the Higgs mixes with other fundamental scalars that couple outside of the $SU(2)_L$ gauge structure, such as the the singlet field S in the Next-to Minimal Supersymmetric Model (NMSSM) [1–3]. This extension is independently well-motivated as a solution to the naturalness problem, providing an explanation for why the μ term might be light, of electroweak order, counter-balancing similarly sized contributions to the Z mass that emerge explicitly from the soft SUSY-breaking sector. Specifically, the μ term arises dynamically in this context, as the VEV of a new singlet chiral supermultiplet containing a pair of charge-parity (CP) even/odd scalars, as well as a fifth “singlino” neutralino. One or both of the (pseudo)scalars may take masses above or around the 125 GeV scale, and potentially confuse the interpretation of fermion pair mass measurements at colliders. Since S is a singlet, and does not participate in the Higgs mechanism, its mixing into the observed Higgs scalar can reduce the Higgs cou-

pling to the doublet NLSPs. Similarly, if a singlet pseudoscalar around 125 GeV emerges in decays, it can significantly suppress the observed branching fraction into Z by enhancing the observed Higgs-like fraction.

An alternative, explicitly non-supersymmetric, spectral modification that we will entertain for the sake of comparison and contrast involves extension of the SM using singlet-doublet fermionic (SDF) dark matter [4]. This type of model introduces a singlet fermion S that couples to the SM Higgs field via two heavier doublets D_1, D_2 , allowing for cascade decays into the same final states as the previously described NMSSM scenario. However this scenario can potentially be distinguished from the NMSSM by measuring the Z/h ratio, since the new fermions do not alter the Higgs sector or modify the Higgs mass.

At the LHC, the counts of $b\bar{b}$ and opposite-sign (OS) like-flavor (LF) light lepton pairs that reconstruct h or Z masses in a $2Z/h + \cancel{E}_T + \text{jet}(s)$ final state can potentially be utilized in order to measure the summed doublet higgsino (or analogous heavy electroweak state) decay branching fractions when such states are discovered. Observation of the Z/h branching fraction ratio, and quantification of its compatibility with unity, would probe the extent to which the Goldstone equivalence theorem can offer interesting constraints on models of new physics. The searches of interest are inherently difficult, since direct production of the higgsino-like second lightest neutralino in the NMSSM and of the heavier neutral fermion in the singlet-doublet extension are not generically expected to exhibit very large cross sections. The additional jet(s) are useful for building more missing energy into the targeted event topology, since tagging of the leptons and $b\bar{b}$ require visible decays of Z, h . This may exhaust the mass difference between the LSP and NLSP, especially when the LSP is not massless, limiting the available missing energy.

In Section II, we present sample MSSM and NMSSM higgsino scenarios that are of observational interest at the LHC, as well as a third example of a simplified fermion singlet-doublet dark matter model [4] that leaves the SM Higgs sector (and associated implications for the Goldstone equivalence manifest in the doublets' decay branchings) intact. Section III elaborates on experimental issues relevant to discrimination of the Z/h decay ratio. In order to ascertain the potential sensitivity of such an analysis of new heavy weak doublets at the LHC, the collider events in both signal and background channels are generated by Monte Carlo, and Section IV describes the simulation setup and assumptions. Sections V, VI detail the classification and selection optimization applicable to the various final states. We conclude in Section VII.

II. BENCHMARK SCENARIOS

The first benchmark scenario to be described is an MSSM construction. To be general, we choose a 70 GeV LSP mass, above $M_Z/2$, so that the tight invisible Z de-

cay constraints may be evaded without requiring a pure bino state. A 70 GeV LSP also evades existing LHC constraints on Higgsino pair production searches [5, 6]. We take the NLSPs to be higgsinos that are relatively light, but that can still decay into the LSP and the Z, h bosons. Due to its higgsino mixing, the LSP mass has to satisfy constraints arising from direct detection experiments, e.g. LUX [7]. We thus choose $\mu < 0$ to help suppress the LSP coupling to the Higgs, as shown in Table I.

MSSM	M_1	μ	$\tan\beta$	$M_{\tilde{\chi}_1^0}$	$M_{\tilde{\chi}_2^0}$	$M_{\tilde{\chi}_3^0}$	ξ^{Zh}
Point I	71	-190	10	70	198	202	3.6

TABLE I: A sample MSSM scenario with light higgsinos. The mass spectrum and decay branchings are evaluated with Suspect2 [8] and the MSSM calculator as part of the MadGraph [9] package.

For point I, we assume all sfermions are heavy and decouple at leading order. The wino is also assumed heavy. When $\tilde{\chi}_2^0, \tilde{\chi}_3^0$ are produced at the LHC, it is useful to consider a ratio of the decay branching into Z over that into h , as defined in Ref. [10],

$$\xi^{Zh} \equiv \frac{f_{\tilde{\chi}_2^0} BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z) + f_{\tilde{\chi}_3^0} BR(\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 Z)}{f_{\tilde{\chi}_2^0} BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h^*) + f_{\tilde{\chi}_3^0} BR(\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 h^*)}, \quad (1)$$

where f is the number fraction of a specific neutralino in the signal events, and h^* denotes any (pseudo)scalar at the Higgs mass. For instance, in the NMSSM h^* can be either the Higgs scalar or the singlet pseudoscalar a_1 . At all our benchmark points, the s-channel $Z^* \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_3^0$ process dominates pair production rates and $f_{\tilde{\chi}_2^0} \approx f_{\tilde{\chi}_3^0}$, due to a suppression in the $Z\tilde{\chi}_i^0 \tilde{\chi}_j^0$ coupling for $i = j$ when $\tilde{\chi}_2^0, \tilde{\chi}_3^0$ are dominantly higgsinos.

From the Goldstone theorem, $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 h \approx \tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 Z$ in the longitudinal Z polarization. As Z also has transverse polarization that couple to $\tilde{\chi}^0$, summing up the decay branchings of $\tilde{\chi}_2^0, \tilde{\chi}_3^0$ would result in comparable yet higher decay branching into Z , i.e. $\xi^{Z/h} > 1$ for $f_{\tilde{\chi}_2^0} = f_{\tilde{\chi}_3^0}$. It is worth noticing that a large $\xi^{Z/h}$ ratio can arise from a kinematic suppression when the mass gap separating the neutralinos is relatively small, as the decay into Z has a larger phase space. If Point I is modified to feature a very light bino, $\xi^{Z/h}$ is modified to around 2.

The second scenario that we discuss is a singlino LSP, higgsino NLSP case in the NMSSM [11], whose superpotential has the following structure,

$$W_{\text{Higgs}} \supset \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3. \quad (2)$$

An effective $\mu = \lambda \langle \hat{S} \rangle$ term is generated when the singlet field takes a VEV, and naturalness suggest that the combination is of the order of M_Z . Note that the trilinear singlet term simultaneously generates a mass proportional to $\kappa \langle \hat{S} \rangle \equiv \kappa \mu / \lambda$. The somewhat heavy observed Higgs

mass at 125 GeV receives tree level contribution from the singlet field, which argues for a larger singlet coupling λ in order to help reduce dependence on multi-TeV stops and the associated fine tuning. Interestingly, the NMSSM allows one of the scalars (and one pseudoscalar) to be very light, if it is mainly a singlet. This extra scalar, which decays into $(b\bar{b}, \tau\bar{\tau})$ at an invariant mass outside the 125 GeV window, will be a strong indication of this model. However, if we stay in the picture that the Higgs is the lightest of the NMSSM scalars and contains no more than 50% singlet, the singlet cubic coupling κ would be non-vanishing. The correlations between a large λ , a small μ , a non-zero κ , and a mass gap from the LSP greater than the Higgs mass force the higgsino dominated $\tilde{\chi}_2^0, \tilde{\chi}_3^0$ to be at least ~ 270 GeV. We take the first (A) and third (C) benchmarks from Ref. [10], summarized as Points II and II' in the present Table II.

NMSSM	λ	κ	μ	$\tan\beta$	m_{a_1}	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$\xi^{Z/h}$
Point II	0.8	0.25	220	2.9	161	143	270	270	2.1
Point II'	0.8	0.25	230	2.9	119	150	279	279	0.7

TABLE II: A pair light higgsino NMSSM benchmark points, exhibiting over (II) and under (II') production of the Z relative to the h .

We are interested in focusing on the parameter space region where the singlet (pseudo)scalars are somewhat heavier than, or comparable in mass to, the Higgs, and not kinematically distinguishable. For benchmark point II, the singlet-dominated pseudoscalar a_1 is a fair bit heavier than the Higgs, at 161 GeV. This kinematically prohibits decays of the NLSP into a_1 , and the ratio $\xi^{Z/h} > 1$ thus falls within the same range as it does in the MSSM. For benchmark point II', a_1 is slightly lighter at 119 GeV, which is very close to the h mass and can fake the Higgs boson. The total decay fraction into h and a_1 will exceed the Z fraction in this case, leading to a ratio $\xi^{Z/h} < 1$ that is distinguishable from the MSSM.

The third scenario we consider is a non-SUSY BSM example with an unmodified Higgs sector, specifically the singlet-doublet fermionic (SDF) dark matter model [4]. This model extends the SM with a singlet fermion S that couples to the SM Higgs field via two heavier weak doublets D_1, D_2 , which have $U(1)_Y$ charges of $\frac{1}{2}$ and $-\frac{1}{2}$, respectively,

$$-\mathcal{L}_{SDF} = y_{D_1} S H D_1 + y_{D_2} S H^\dagger D_2 + \frac{1}{2} M_S S^2 + M_D D_1 D_2. \quad (3)$$

The new fermions S, D_1, D_2 mix via a symmetric mass matrix,

$$\mathcal{M} = \begin{pmatrix} M_S & \frac{1}{\sqrt{2}} y_{D_1} v & \frac{1}{\sqrt{2}} y_{D_2} v \\ \frac{1}{\sqrt{2}} y_{D_1} v & 0 & M_D \\ \frac{1}{\sqrt{2}} y_{D_2} v & M_D & 0 \end{pmatrix}. \quad (4)$$

In general, the spectrum of neutral mass eigenstates $\{\chi_i^0\}$ consists of one lighter singlet-dominated state and

two heavier doublet-dominated states that behave analogously to the pair of higgsinos in supersymmetric models, though larger couplings allow for more mixing than is typically possible in the neutralino sector of the MSSM. We will focus on the parameter state where the DM χ_1^0 is light and singlet-dominated, while the two doublet-like states $\chi_{2,3}^0$ are heavier, in order to allow for the desired decays. For visual distinction, these fermions do not have a tilde (\sim) positioned above their symbols. The mixing angle $\tan\theta \equiv y_{D_1}/y_{D_2}$ indicates the relative size of the D_1, D_2 couplings, and $y \equiv \sqrt{y_{D_1}^2 + y_{D_2}^2}$.

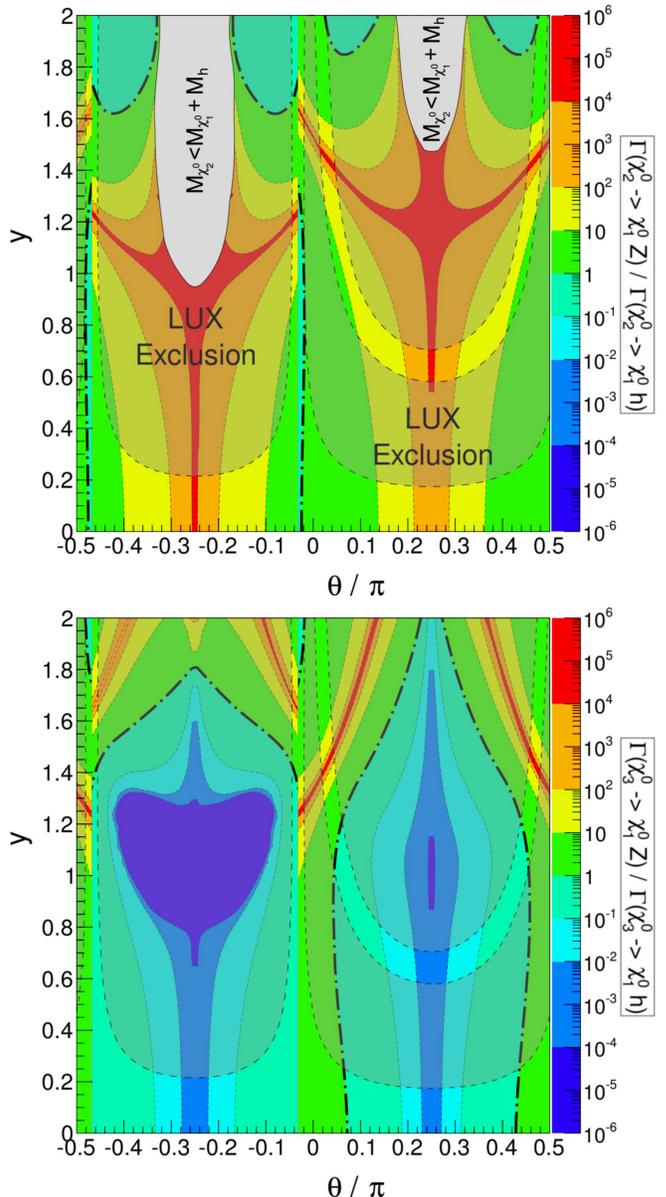


FIG. 1: Near symmetric branching ratio of $\chi_{2,3}^0$ decays in the SDF dark matter model. $M_S = 50$ GeV and $M_D = 200$ GeV throughout.

Neglecting any potential loop-order correction to the

SDF	y	θ	M_S	M_D	$M_{\chi_1^0}$	$M_{\chi_2^0}$	$M_{\chi_3^0}$	$\xi^{Z/h}$
Point III	0.4	-0.05π	72	189	70	201	203	3.0

TABLE III: Benchmark SDF dark matter point.

Higgs mass, the terms in Eq. 4 leave the SM Higgs sector unchanged, and the Goldstone equivalence theorem predicts similar branching fractions in the $\chi_{2,3}^0 \rightarrow \chi_1^0, Z/h$ decays. Fig. 1 show the Z/h ratios associated with $\chi_{2,3}^0$ decays are approximately symmetric, up to corrections from the kinematic and mixing differences. The $ySHD$ term plays a central role in providing the NLSPs comparable decay width into Z, h (see Appendix A for details). The discontinuity at $\theta \approx -0.03\pi$ occurs because the pair of doublet-like states become Dirac once more at that point, resulting in a phase shift in the rotation matrix across the transition. We refer to Ref. [4] for other phenomenological studies of this model.

Table III provides an SDF benchmark (Point III). The mixing angle is chosen to be $\theta = -0.05\pi$, where the LSP-nucleon scattering is suppressed and the coupling y can take relatively large values. Similar to the MSSM, the Point III also gives rise to a higher decay branching into Z , as predicted by the Goldstone equivalence theorem. This shows that, in the simplified picture of weak doublet fermion decays, the unaltered Higgs sector also yields a ratio $\xi^{Z/h} > 1$; this stands in contrast to the situation where a new field masking the Higgs is additionally present, as in the case of NMSSM. However, similar final states and a similar ξ ratio make this model difficult to distinguish from other constructions like the MSSM, underscoring a need for caution in the interpretation of results that may be mutually associable with a degeneracy of underlying structures. In this case, more knowledge about the model's particle spectrum will be needed.

III. EXPERIMENTAL CONSIDERATIONS

Pair production of the various heavy weak doublet candidates identified with the aforementioned scenarios constitutes a potentially viable search channel at the LHC. The decay of these doublets and the subsequent decay of the associated Z/h boson products lead to final states that contain leptons and b -tagged jets, plus some amount of missing transverse energy \cancel{E}_T , and (optionally) additional jets.

The Z boson will decay dominantly to hadrons (70%), including a 15% share to just the $b\bar{b}$ final state. Invisible decays account for 20% of the branching, and the final 10% is shared among the three lepton pair production modes $\ell\ell$. There is no intrinsic preference for or against τ production in this mode, but we will focus on the selection only of light lepton (e, μ) flavors because they have a much higher detection efficiency, and a lower fake rate. The Higgs boson h will be reconstructed from its decay into $b\bar{b}$, at a large branching which is under correction from the size of $\tan\beta$ in supersymmetric models.

If a ~ 125 GeV NMSSM singlet pseudoscalar emerges, it dominantly decays into $b\bar{b}$ with a branching near 100%.

Light leptons will not be produced directly at any appreciable rate by the decays of the Higgs, although there may be leptonic decays arising from its direct decay products, with light opposite-sign mixed-flavor pairs (along with the associated missing neutrinos) represented in the final state at a typical branching of about 1% each (for a SM Higgs) via the WW^* and $\tau\tau$ channels. These rates may be further discriminated from the direct decays of the Z by demanding same flavor combinations with kinematic reconstruction of the parent mass.

From the decay of mixed Z/h pairs, the targeted final states will therefore correspond to 4 leptons $\ell\ell\ell\ell$, 4 b -tags $b\bar{b}b\bar{b}$, or a mixed state $\ell\bar{b}b\bar{b}$. The lepton production channels will be associated with Z boson decays, and the b -tag production channels will be dominantly associable with decays of the Higgs (and Higgs-like states). Channels involving b -tags will have substantial disadvantages with regards to detection efficiency and fake rate.

Two out of the three described signals must be measured in order to ascertain the parent doublets' total decay branching ratio into Z and h . The four lepton signal must contend with SM $VV + \cancel{E}_T$ production, where the vector boson, especially the Z , decay leptonically and jet mismeasurement provides a source of missing energy. A selection of a least four leptons together with a \cancel{E}_T cut can be effective against this background. Profitable selection alternatives will be discussed in Section V.

The four b signal must compete with SM $t\bar{t}$ production, where the two natural b quarks from top decay combine with two additional jet-faked b 's; due to a crowded final state, the fake b jets are non-negligible and make this background quite severe, even after a $b\bar{b}$ invariant mass window cut is imposed. The mixed $\ell\bar{b}b\bar{b}$ signal is affected by both backgrounds. If the LSP is massless, Run I of the LHC sets limits in the $4b$ channel, but there are no existing limits for a massive LSP scenario.

When the mass gap between the decaying doublets and the LSP is close to (or less than) 125 GeV, the decay into h may become kinematically suppressed, leading to Z dominated final states with the observable consequence that $\xi^{Z/h} > 1$. Additionally, even when decay into h is allowed, it can still be very difficult in this regime to boost an appreciable quantity of \cancel{E}_T . It is helpful then to tag on initial state radiation (ISR) jets in order to boost the overall \cancel{E}_T of the visible system, but 2 ISR jets are observed in simulation (for the Point II benchmark specifically) to cost a half magnitude order in production cross section.

Further details regarding the mode of simulation, the specific mechanisms available for controlling various backgrounds, and the expected visibility of the three targeted final state signal topologies at the $\sqrt{s} = 14$ TeV LHC are provided in the following sections. We will not attempt a detailed extraction of the $\xi^{Z/h}$ ratio from simulated collider data in this work, but will instead direct attention toward the preliminary task of establishing the

signal. We will reference NMSSM benchmark II for concreteness, and comment on the extrapolation of results to other benchmark scenarios.

IV. EVENT GENERATION AND SELECTION

Signal and the standard model (SM) background Monte Carlo event samples, including parton showering and fast detector simulation, are generated via the standard MADGRAPH5/MADEVENT [9], PYTHIA [12], PGS4 [13] chain. MADEVENT is configured, in conjunction with PYTHIA, to use MLM matching with kt jets in the “Shower kT” scheme, setting (`ickkw` \Rightarrow 1), (`xqcut` \Rightarrow 80), (`drjj` \Rightarrow 0), (`auto_ptj_mjj` \Rightarrow T), (`QCUT` \Rightarrow 80), and (`SHOWERKT` \Rightarrow T). The PGS4 detector simulation employs a standard LHC-appropriate parameter card, with jet clustering performed using the anti-kt algorithm. Hadronic tau reconstruction employs a customized treatment that directly references the explicit decay chain at the PYTHIA level, applying a flat efficiency of 60% and a flat fake rate of 1% [14, 15]. The algorithms for tagging of heavy flavor jets have also been customized for a higher efficiency, on the order of 75% [15, 16]. Selection cuts are implemented on the detector-level event simulation within AEACUS 3.15 [17, 18], using the instructions demonstrated in Card A. Wide jets are accepted with a transverse momentum $P_T > 30$ GeV, up to a pseudorapidity magnitude of $|\eta| < 5.0$, while b-jets are accepted with the same P_T limits inside $|\eta| < 2.5$ (although PGS4 reduces this effectively to 2.0). Leptons, including hadronic taus, are accepted with $P_T > 10$ GeV and $|\eta| < 2.5$. Light leptons (e, μ) are required to maintain a mutual isolation of $\Delta R > 0.3$ radians.

TABLE IV: Matched production and residual effective cross section (fb) at the LHC14 are tabulated for the three targeted final state event topologies, reported individually for the $t\bar{t}$ +Jets and VV +Jets backgrounds, as well as the benchmark Point II NMSSM signal.

Selection	$t\bar{t}$ +Jets	VV +Jets	Signal
Matched Production	613,000	1,330	53
Cat I ($4^+ e/\mu, 0^+ B$'s)	0.043	0.092	0.062
Cat II ($2-3 e/\mu, 2^+ B$'s)	4080	0.176	0.137
Cat III ($0-1 e/\mu, 4^+ B$'s)	949	0.097	0.058

Background candidates simulated here are the inclusive production of $t\bar{t}$ with 0-2 jets, the inclusive production of two vector bosons with 0,1, or 2 Jets, as well as single W - or Z -boson production including 0-4 initial state Jets. The single vector channels exhibit very large production cross sections, around two orders larger than the corresponding $t\bar{t}$ background, and the approximately 3.5 and 10 million events considered for each case remain a substantial under-sampling. Approximately 120 and 1,500 fb^{-1} of integrated luminosity are simulated for

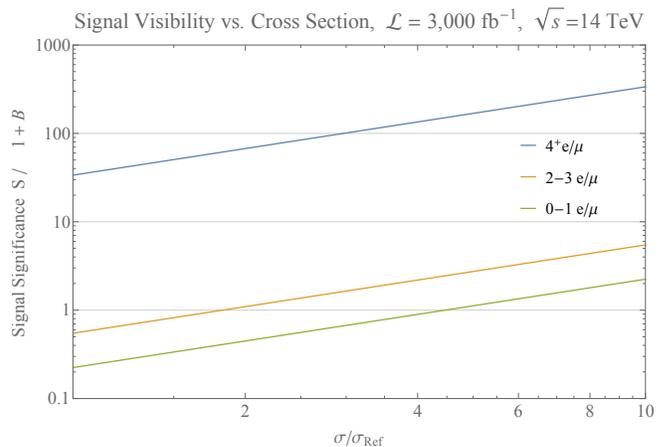


FIG. 2: The signal significance metric $S/\sqrt{1+B}$ is projected for each of the targeted final state topologies at a luminosity of $3,000 \text{ fb}^{-1}$ at the $\sqrt{s} = 14$ TeV LHC. Collider modeling is based on NMSSM benchmark II, which features 270 GeV higgsinos and a Z/h ratio of $\xi^{Z/h} = 2.1$. The horizontal axis represents numerical scaling of the production cross section relative to this benchmark. The optimized event selections employed are provided in the right-hand panel of Fig. (5) and in Figs. (13), and in the surrounding text. There is no cut employed on missing transverse energy. Notice that the scaling of the post-cut σ depends on both the higgsino production cross-section and the neutralino decay branching into the specific final state categories.

the $t\bar{t}$ and VV backgrounds, respectively. For signals, we simulate the NMSSM benchmark II point, likewise inclusively considering 0-2 Jets, over-sampled to an integrated luminosity approaching one million events per femtobarn.

Signal events are pre-classified into three non-overlapping categories based on the count of light leptons (e, μ), along with a complementary threshold for the count of heavy-flavor (b-tagged) jets, as stipulated at the bottom of the Card A instructions. Category I contains at least 4 leptons, but has no b-tagging requirement. Category II contains either 2 or 3 leptons, and at least 2 b-jets. Category III contains either 0 or 1 leptons, and at least 4 b-jets. There is significant attenuation of both signal and background by these preliminary topological cuts, as demonstrated in Table IV. Category I is intrinsically low-background, and the signal already competes well here, being of the same magnitude order as the isolated $t\bar{t}$ +Jets and VV +Jets components. Categories II and III are dominated by the $t\bar{t}$ +Jets background, which shall prove quite difficult to reduce while retaining any appreciable portion of the already meager signal.

It should be emphasized before proceeding that the baseline NMSSM matched production cross section (~ 50 fb) provided in Table IV is for the particular neutralino mass $M_{\tilde{\chi}_{2,3}} \sim 270$ GeV associated with benchmark II, which has been selected as the default scenario for our

collider study. The cross section can be a quite a bit larger when the associated doublets are lighter, as can occur in the MSSM and in the SDF models. If the relevant mass scale, e.g. for the higgsino-type MSSM neutralino or for the SDF doublet, is reduced from 270 GeV to around 200 GeV, an increase in the higgsino pair-production cross section by a factor of order five can generically be expected [19, 20]. In Fig. (2) we preemptively summarize the optimized visibility of each signal region at a luminosity of $3,000 \text{ fb}^{-1}$ as a rescaled function of the post-cut cross section. Kinematic cut efficiencies are expected to be less affected by scaling when the mass gaps between the LSP and NLSP(s) remain as represented by the benchmarks. The scaling is affected by both the higgsino production rate and the ratio $\xi^{Z/h}$ that determines the neutralinos' branching into each final state category. Benchmark II, with $\xi^{Z/h} = 2.1$, thus inherits a greater share of leptonic final states. For a model with a low $\xi^{Z/h}$, like benchmark I', a higher branching ratio into $b\bar{b}$ would then enhance the $bbll$ significance (relative to $4l$). The 4-lepton (Category I) signal region is found to be highly visible, whereas the mixed lepton plus b-jet signal region (Category II) is conditionally visible, and the 4 b-jet signal region (Category III) projects low visibility. The applicable event selection strategies in each event category are developed in detail in the subsequent sections.

V. REFINING THE 4 LEPTON SIGNAL

The natural final state to target for models similar to the NMSSM benchmark under consideration is clearly the Category I 4-lepton topology. It is possible to substantially improve the resolution of signal from background by making a few additional event selections, as shall be investigated in the present section. To begin, a sequence of plots is shown that compare the normalized event shape distributions of the signal and background for several observables, with the goal of isolating points of leverage for improved signal discrimination. All plots have been generated with the RHADAMANTHUS 1.2 [18] software package. The single vector backgrounds have been integrated with the di-boson production channel. Moderate bin smoothing is employed.

In Figs. (3), the signal is differentiated from the relevant backgrounds as less likely to feature a hadronic tau (left panel) and more likely to feature precisely one candidate Z -boson, defined as an OS-LF dilepton pair with an invariant mass of $92 \pm 5 \text{ GeV}$ (right panel). More specifically, the $t\bar{t}$ background generally has no suitable candidates, whereas the unified vector backgrounds are more likely, by almost nine times, to contain two pair rather than one. The signal is observed to contain (0,1,2) reconstructible Z -bosons in approximately (10,50,40) percent of events, respectively. In Figs. (4), the signal is differentiated from the relevant backgrounds as less likely to feature more than one jet (left panel) and less likely to

feature any b-jets (right panel). It is noted that the signal production cross section for 2 jets is smaller by about a factor of almost four than the matched inclusive cross section with 0-2 jets; the lower count values are additionally easier to distinguish from the highly jetty background.

Based upon these observations, supplementary event selections are performed, corresponding to a hadronic tau veto, a requirement of precisely one OS-LF di-lepton invariant mass reconstructed within 5 GeV of the Z boson, a veto on b-jets, and a veto on events with more than one jet of any type. In Figs. (5), the absolute event counts attributable to the signal and background components are compared as a function of the missing transverse energy \cancel{E}_T cut threshold for an integrated luminosity of 300 fb^{-1} ; the left-hand panel corresponds to the raw category I pre-selection, whereas the described secondary event selections are enacted in the right-hand panel. The suggested \cancel{E}_T cut is moderate, no more than about 100 GeV. Depending on this threshold, a signal count of about 4-7 events is expected, over a deeply suppressed background. If both single and double dilepton pair reconstructions are accepted, then a signal count of around 8-12 events over a background of 3-6 events is expected, again varying with the selection of a mild missing transverse energy threshold, which is no greater than 100 GeV. The projected signal significance is relatively stable to these adjustments, in the range of 4-6.

VI. REFINING THE 2-3 LEPTON PLUS 2^+ B-JETS AND 4^+ B-JET SIGNALS

The Category II event classification with 2-3 leptons and 2 or more b-jets has the disadvantage of a final state topology that is readily mimicked by the dual leptonic decay of W bosons from $t\bar{t}$ production. With a moderate fake rate for b-jets, the background is likewise heavily represented in the Category III 0-1 lepton with 4 or more b-jets event topology. Moreover, the light SUSY electroweak sector considered for the signal benchmarks does not typically yield a quantity of missing energy that is sufficiently large to substantially distinguish it from the background. See Figs. (9,12), left-hand panels, for a comparison of the raw event residuals as a function of missing transverse energy cut threshold at a luminosity of 300 fb^{-1} . The signal is observed to be dwarfed in both cases by around four magnitude orders. A large variety of kinematic discriminants and specialized discovery variables have been tested in an effort to identify handles effective for the isolation of signal events.

Considering first category II, it is apparent in Figs. (6) that the signal is emphasized by vetoing hadronic taus and by insisting that an available pair of light OS-LF leptons kinematically reconstruct the mass of a Z -boson. Figs. (7) show a similar preference for hadronic (b-jet) reconstruction of a particle in the Z /Higgs mass window, with a narrow constituent separation in ΔR ; a cut $\Delta R < 2.5$ will be selected. Figs. (8) exhibit some benefit

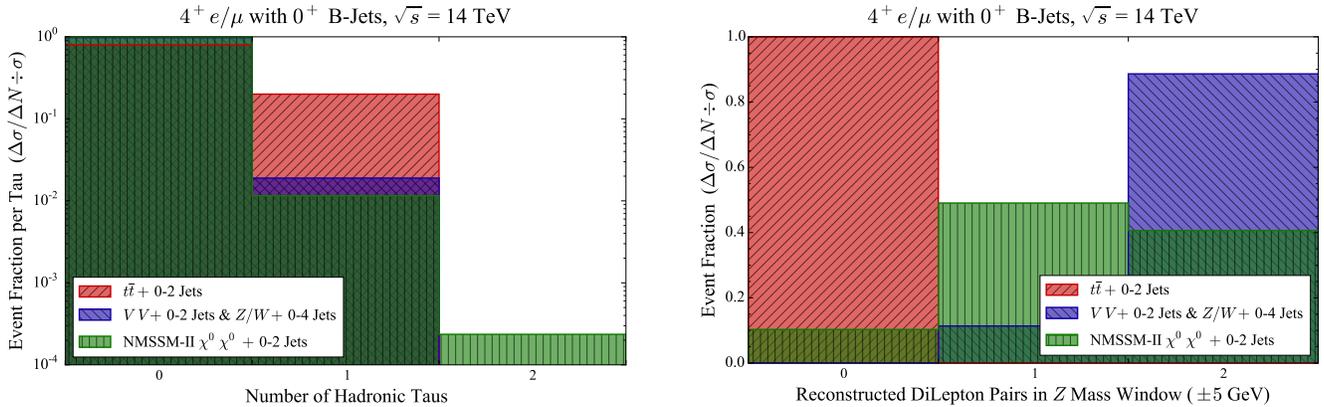


FIG. 3: Signal and background event shapes are compared for the final state topology with 4^+ light leptons (category I). Left: The signal generally contains no hadronic taus, whereas there is a substantially elevated likelihood for the $t\bar{t}$ background component to contain one. Right: Over 90% of the signal features a reconstructed OS-LF dilepton in the Z -boson mass window (92 ± 5) GeV, whereas the same holds true for virtually none of the $t\bar{t}$ background component. About half of the signal reconstructs precisely a single Z , whereas almost 90% of the unified vector backgrounds are actually observed to reconstruct two pair.

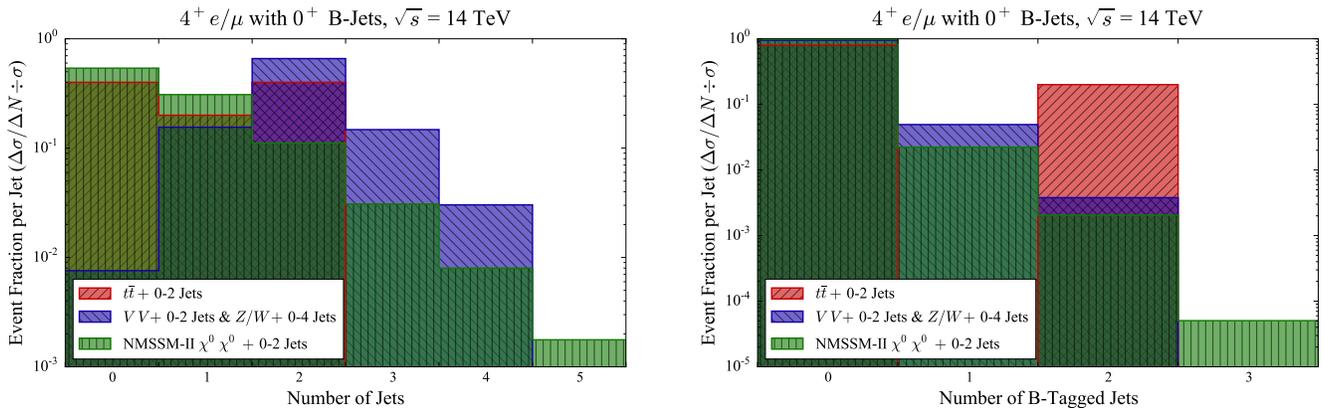


FIG. 4: Signal and background event shapes are compared for the final state topology with 4^+ light leptons (category I). Left: Approximately 80% of the signal features no more than 1 Jet, whereas the $t\bar{t}$ and di-boson backgrounds have a substantially elevated likelihood of feature more jets. Right: Only about 2% of the signal includes the presence of a b-jet, whereas the backgrounds, especially the $t\bar{t}$ component are substantially more likely to contain up to two such objects.

from vetoing single track jets, and placing a lower bound on the (dimensionful) missing transverse energy significance, which we shall select as $\cancel{E}_T/\sqrt{H_T} > 2.0$ [$\text{GeV}^{1/2}$]. Figs. (9) compare the signal and background event residuals before (left) and after (right) these secondary selections. The background is reduced by around two magnitude orders, while the signal is reduced only by a factor close to two. However, the ratio still heavily favors the $t\bar{t}$ +Jets background component, by 2-3 orders of magnitude (less at higher \cancel{E}_T cut thresholds). Potential discriminants tested and found to be ineffective in this case include M_{T2} (the “s-transverse mass”) [21, 22], M_{T2}^W [23], the jet and dilepton- Z transverse energy balance ΔE_T [24], the razor variables [25, 26], the α_T ratio [27, 28], the \cancel{E}_T -jet angular difference $\Delta\phi$ [29], the

“biased” azimuthal difference $\Delta\phi^*$ [30], the lepton W -projection L_P [31, 32], and various transverse thrust and event shape statistics [33–36].

Category III presents similarly in many regards, and faces the same central obstacle that the hadronic event shape is excessively similar to the background. A similar preference is observed for vetoing the hadronic tau, vetoing single track jets, and enforcing a missing energy significance of $\cancel{E}_T/\sqrt{H_T} > 2.0$ [$\text{GeV}^{1/2}$]. Distinctions are observed in Figs. (11), which argues for trimming the total number of jets to no more than 5 with the leading pair tagged, and in Figs. (10), which argues for vetoing light leptons and insisting on two hadronic (b-tagged jet) kinematic reconstructions in the Z /Higgs window. Combinatoric backgrounds reduce the efficacy of a cut

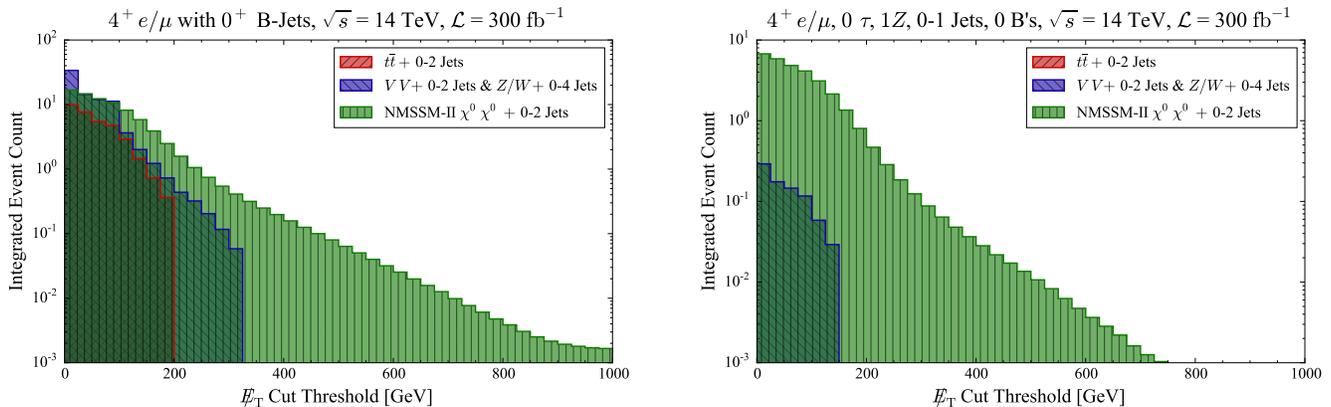


FIG. 5: Signal and background integrated event counts are compared for the final state topology with 4^+ light leptons (category I) at a luminosity of 300 events per femtobarn as a function of the missing transverse energy \cancel{E}_T cut threshold. Left: The raw event categorization is intrinsically low background, with order parity among the signal and two background components, as well as a slight preference for signal at larger missing energies. Right: Enacting the secondary event selections (0 τ , 1Z, 0 B's, 0-1 Jets) suggested by Figs. (3,4) preferentially suppresses the background, rendering the signal dominant. There is no preference for large missing energy, although neither is a modest cut in the vicinity of $\cancel{E}_T > 100$ GeV strongly disfavored.

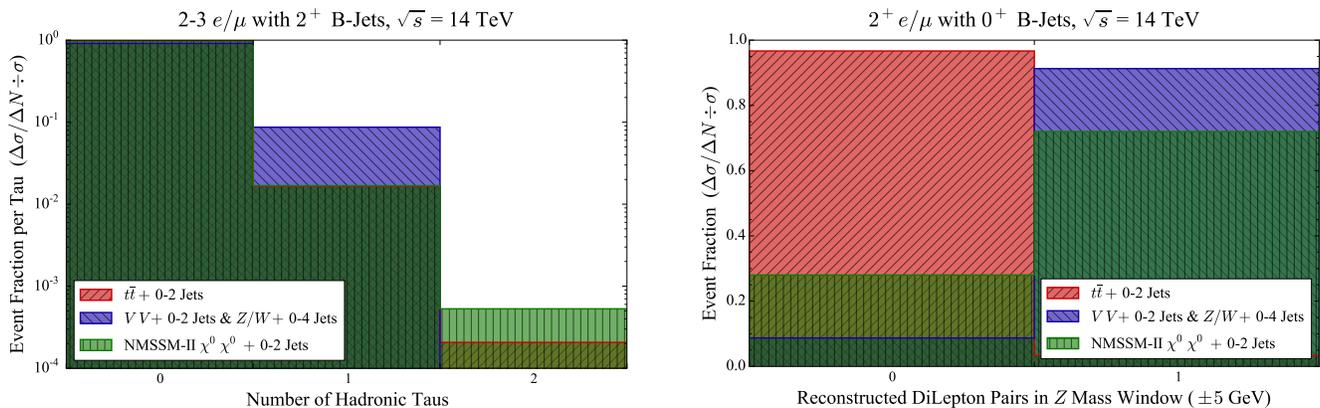


FIG. 6: Signal and background event shapes are compared for the final state topology with 2 – 3 light leptons and 2^+ b-jets (category II). Left: The signal generally contains no hadronic taus, whereas there is a marginally elevated likelihood for the vector background component to contain one. Right: Around 70% of the signal features an OS-LF dilepton pair with an invariant mass of 92 ± 5 GeV, whereas the same holds true for less than 5% of the $t\bar{t}$ background component.

on angular separation for the best mass reconstruction in this case. Figs. (12) compares the signal and background event residuals before (left) and after (right) these secondary selections. The background is again reduced by around two magnitude orders, while the signal is reduced by a factor close to three. However, the ratio still heavily favors the background

Figs. (13) evaluates signal to background event significances, using the metric $S/\sqrt{1+B}$, as a function of the missing transverse energy cut threshold for the category II (Left) and III (Right) final state topologies, applying the described optimizations at luminosities of 300 fb^{-1} and $3,000 \text{ fb}^{-1}$, for the baseline cross section of the benchmark II model and also for a hypothetical spectrum that is sufficiently more light to engender a one magnitude or-

der increase in the production cross section. When both scale factors are invoked it appears possible to resolve a significant signal for the category II final state topology, providing a crucial second data point, in conjunction with the highly visible first category, for reconstruction of the model. Even granting both factors, the category III final state topology remains difficult to substantially disentangle from the background.

VII. DISCUSSION AND CONCLUSIONS

In this paper we investigated decays from heavy higgsino-like weak-doublets into Z, h bosons and (small) missing energy. As examples, we considered the MSSM,

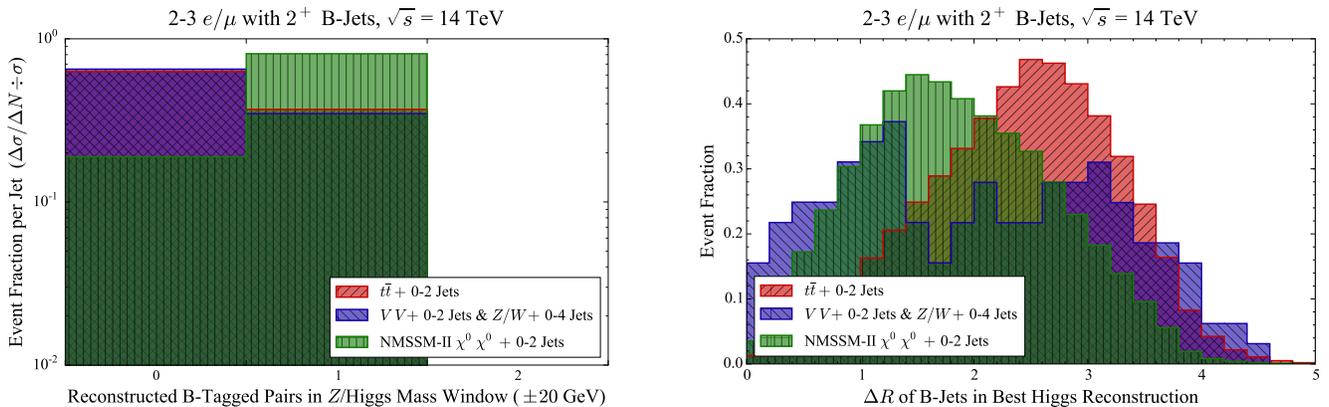


FIG. 7: Signal and background event shapes are compared for the final state topology with 2 – 3 light leptons and 2^+ b-jets (category II). Left: Over 80% of the signal features a reconstructed b-jet pair in the Z/H -boson mass window (92 – 20 GeV to 126 + 20 GeV), whereas the same holds true for just around 35% of the unified background components. Right: The angular separation ΔR of the pair of jets that come closest by invariant mass to reconstructing a Higgs is systematically smaller for the signal than the $t\bar{t}$ background component.

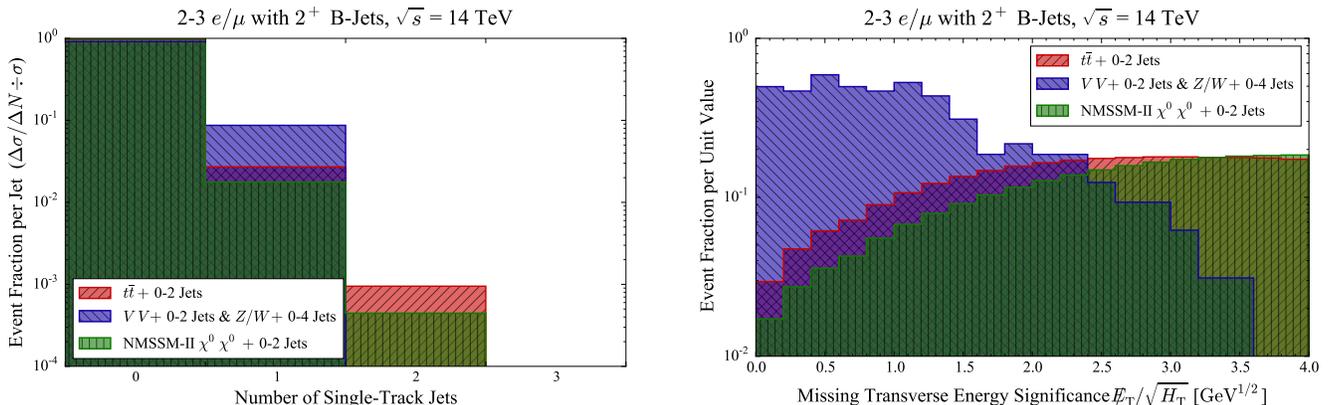


FIG. 8: Signal and background event shapes are compared for the final state topology with 2 – 3 light leptons and 2^+ b-jets (category II). Left: The signal generally contains no single-track jets, whereas approximately 10% of the vector background component does have such a jet. Right: The relative (dimensionful) significance of the missing transverse energy as a numerical ratio of E_T to the square-root of the event scale M_T (both in GeV) is substantially larger for the signal (as well as for $t\bar{t}$) than the vector background components.

NMSSM and a singlet-doublet extension of the SM featuring a DM candidate that is capable of explaining the observed relic density after satisfying direct detection constraints. The NMSSM is well motivated by its natural accommodation of the 125 GeV Higgs and a weak scale value of μ .

Signals from the MSSM, NMSSM and the singlet-doublet extension will be similar, i.e., we will expect to find decays into Z, h plus missing energy that cascading into final states with $4\ell, 2\ell 2b$ and $4b$ plus missing energy. Leptonic products will be dominantly associated with decays of the Z , whereas decays of the Higgs will be associated dominantly with heavy flavor jets. Establishing two of the prior three final states would potentially provide a mechanism for quantifying the Z to h ratio, which may in turn assist in discriminating between specific models

exhibiting the described spectral features. In particular, observation of this ratio will clarify the manner in which the Goldstone Equivalence Theorem is manifest within and places constraint upon new physics. The ratio of Z to h production in higgsino-like decays would be somewhat greater than 1 in the case of the MSSM and the singlet-doublet extension, since the net Z rate includes also the contribution of transverse polarizations. By contrast, in the NMSSM the lighter neutralinos can decay into another state a , which can naturally be close to the light Higgs mass, that masquerades as the Higgs in decays and gives rise to a Z/h ratio that is smaller than 1 by its.

We explored the visibility of the $4\ell, 2\ell 2b$ and $4b$ final states, which are useful to establishing the Z/h ratio, at the 14 TeV LHC. If heavy colored particles are

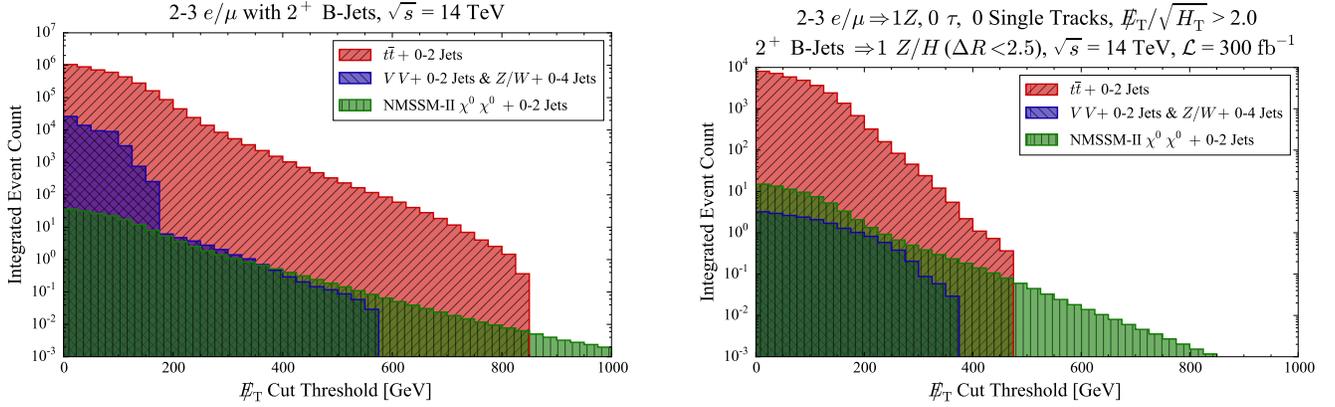


FIG. 9: Signal and background integrated event counts are compared for the final state topology with 2 – 3 light leptons and 2⁺ b-jets (category II) at a luminosity of 300 events per femtobarn as a function of the missing transverse energy \cancel{E}_T cut threshold. Left: The raw event categorization reveals daunting background domination by $t\bar{t}$ +Jets, with no substantive improvement in the signal to background ratio at large values of the missing energy. Right: Enacting the secondary event selections (0 τ , 1 leptonic Z, 0 single track jets, 1 hadronic Z/H with $\Delta R < 2.5$, and $\cancel{E}_T/\sqrt{H_T} > 2.0$), the signal to background ratio is improved by one or two magnitude orders (more at larger \cancel{E}_T cuts), although it remains apparently intractable at the studied luminosity and signal cross section.

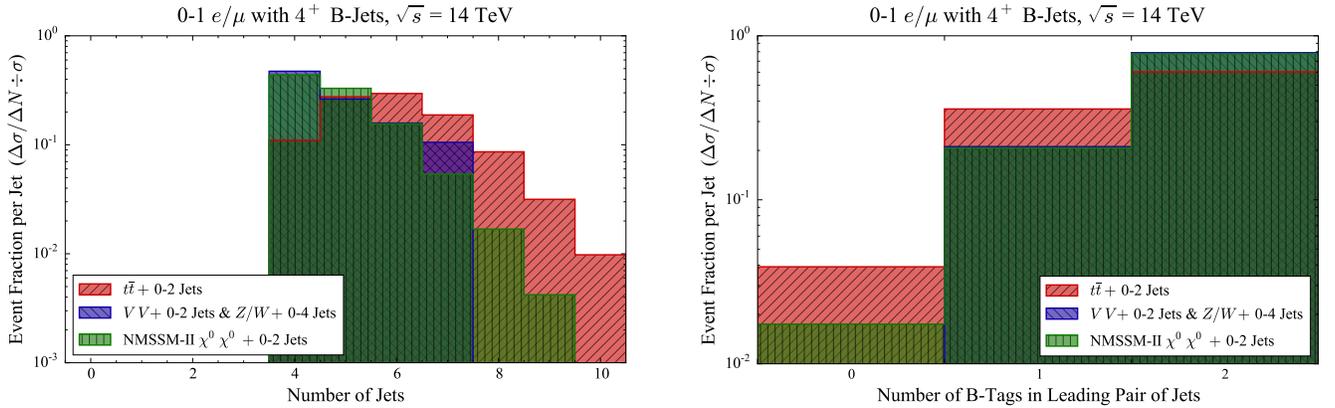


FIG. 10: Signal and background event shapes are compared for the final state topology with 0 – 1 light leptons and 4⁺ b-jets (category III). Left: The $t\bar{t}$ background is generally jettier than the signal, with a larger fraction of events at six or more jets. Right: The leading pair of signal jets is somewhat more likely to be b-tagged than the leading pair of jets in the $t\bar{t}$ background, one or more of which are likely to be initial state radiation.

to be probed at the LHC, then the lighter MSSM and NMSSM neutralinos and charginos (or their new fermion counterparts) will likewise be within reach for direct production. However, the reach for these neutralinos and new fermions is not very high, and existing bounds vanish rapidly for scenarios with a massive lightest neutralino/fermion. We selected a representative NMSSM benchmark within this class of models for detailed collider simulation, with higgsino next-to-lightest neutralinos around 270 GeV, a singlino lightest supersymmetric particle around 140 GeV, and a light pseudoscalar around 160 GeV. Leading backgrounds were also simulated, and various event selection scenarios were tested in an effort to optimize the targeted signals. The inclusion of 1-2 initial state jets can be helpful in providing some addi-

tional boost to the visible system, although low signal rates, lightness of the invisible final state, and narrowness of the mass hierarchy were found to limit the efficacy of hard cuts on missing energy. The four-lepton signal region is highly visible, with just 300 fb⁻¹ of integrated luminosity proving sufficient for a 5 σ level discovery of the benchmark model. For the same masses, the $2\ell 2b$ and $4b$ final states contend with standard model backgrounds that prove difficult to reduce. Discovery is possible in the $2\ell 2b$ topology if the benchmark cross section is elevated by a factor of around ten, in conjunction with an elevation of the luminosity to the order of 3000 fb⁻¹. Visibility of the $4b$ topology would seem to require a new collider environment, with substantially upgraded luminosity and/or center-of-mass energy.

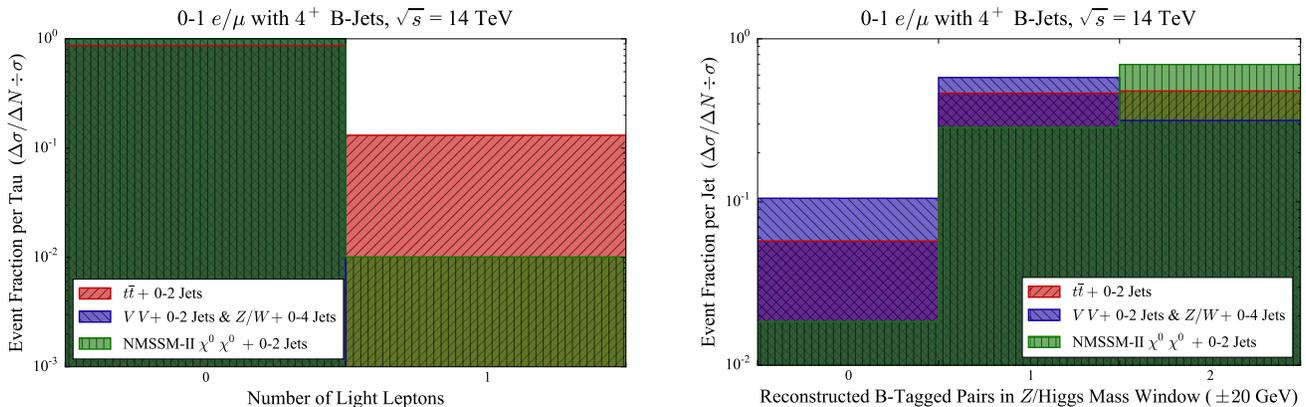


FIG. 11: Signal and background event shapes are compared for the final state topology with 0 – 1 light leptons and 4⁺ b-jets (category III). Left: The $t\bar{t}$ background is substantially more likely to retain a single lepton than the signal. Right: Around 70% of the signal features two reconstructed b-jet pairs in the Z/H -boson mass window (92 – 20 GeV to 126 + 20 GeV), whereas the same holds true for just around a half (third) of the $t\bar{t}$ (vector) background components.

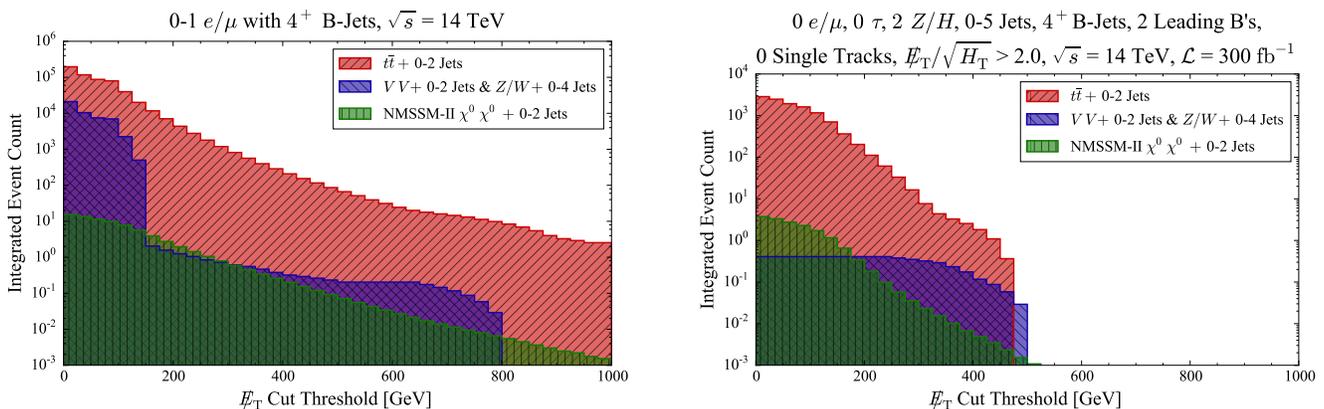


FIG. 12: Signal and background integrated event counts are compared for the final state topology with 0 – 1 light leptons and 4⁺ b-jets (category II) at a luminosity of 300 events per femtobarn as a function of the missing transverse energy \cancel{E}_T cut threshold. Left: The raw event categorization reveals daunting background domination by $t\bar{t}$ +Jets, with no substantive improvement in the signal to background ratio at large values of the missing energy. Right: Enacting the secondary event selections (0 e/μ , 0 τ , 0-5 total jets, 2 leading b-jets, 0 single track jets, 2 hadronic Z/H , and $\cancel{E}_T/\sqrt{H_T} > 2.0$), the signal to background ratio is improved by around two magnitude orders, although it remains apparently intractable at the studied luminosity and signal cross section.

It appears that it will be possible for the LHC to establish (in the 4ℓ channel) the studied class of models, where only lighter weak fermions exist around the electroweak scale, where the mass gap separating the dark matter candidate from the next to lightest states is not much larger than ~ 125 . For the lightest of these scenarios, and utilizing high luminosities, it seems further possible that the LHC will be able to also confront the $2\ell 2b$ channel, allowing for direct discrimination of the Z to h ratio in decays of a higgsino-like state. These observations would function as a probe of the manner in which the new physics manifests the Goldstone equivalence theorem, and would provide the opportunity to distinguish between the NMSSM and models such as MSSM or the singlet-doublet extension of the SM.

VIII. ACKNOWLEDGMENTS

We would like to thank Teruki Kamon, Nikolay Kolev and Keith Ulmer for helpful discussions. This work is supported in part by DOE Grant No. DE-FG02-13ER42020, and NSF Award PHY-1206044. JWW acknowledges support from the SHSU Enhancement Research Grant program, the SHSU Department of Physics, and the Mitchell Institute for Fundamental Physics and Astronomy. DS acknowledges support from DOE grant DEFG0292ER40701, and the Gordon and Betty Moore Foundation, through Grant No. 776 to the Caltech Moore Center for Theoretical Cosmology and Physics.

```

1 ***** cut_card.dat v3.13 ***
2 * Classify Objects with No Cuts
3 *** Object Reconstruction ****
4 # ALL Jets
5 OBJ_JET_000 = PTM:30, PRM:[0.0,5.0], CUT:0
6 # LEAD Jet
7 OBJ_JET_001 = SRC:+000, PRM:[0.0,2.5],
8 CUT:[1,UNDEF,-1], OUT:PTM_001, ANY:0
9 # SECOND Jet
10 OBJ_JET_002 = SRC:[+000,-001], PRM:[0.0,2.5],
11 CUT:[1,UNDEF,-1], OUT:PTM_002, ANY:0
12 # B-Tagged Jets
13 OBJ_JET_003 = SRC:+000, PRM:[0.0,2.5], HFT:0.5, CUT:0
14 # Non-B Jets
15 OBJ_JET_004 = SRC:[+000,-003], PRM:[0.0,2.5], CUT:0
16 # B-TAGS in Jets 1,2
17 OBJ_JET_005 = SRC:[+001,+002], HFT:0.5, CUT:0
18 # Non-B Sub-Leading Jets
19 OBJ_JET_006 = SRC:[+000,-001,-002,-003],
20 PRM:[0.0,2.5], CUT:0
21 # 1 B-Tags in Z/Higgs Window
22 OBJ_JET_007 = SRC:+003, EFF:[WIN,92,20,126,20,1], CUT:0
23 # 2 B-Tags in Z/Higgs Window
24 OBJ_JET_008 = SRC:+003, EFF:[WIN,92,20,126,20,2], CUT:0
25 # 2 B-Tags in Higgs Window
26 OBJ_JET_009 = SRC:+003, EFF:[WIN,126,20,2], CUT:0
27 # Single Track Jets
28 OBJ_JET_010 = SRC:+000, TRK:[1,1], CUT:0
29 # Leading or B-Tagged Jets (No Output)
30 OBJ_JET_011 = SRC:[+001,+002,+003]
31 # Nearest B-Tag Object Pair to Higgs Window
32 OBJ_JET_012 = SRC:+003, EFF:[OIM,126,UNDEF,-1]
33 # Further B-Tag Object Pair from Higgs Window
34 OBJ_JET_013 = SRC:[+003,-012], EFF:[OIM,126,UNDEF,-1]
35 # ALL Leptons
36 OBJ_LEP_000 = PTM:10, PRM:[0.0,2.5]
37 # Light Soft Leptons
38 OBJ_LEP_001 = SRC:+000, EMT:-3, SDR:[0.3,UNDEF,1], CUT:0
39 # Soft Taus
40 OBJ_LEP_002 = SRC:+000, EMT:+3, CUT:0
41 # DiLepton Pairs in Z Window
42 OBJ_DIL_001 = LEP:001, DLS:-1, DLF:1, WIN:[92,5], CUT:0
43 OBJ_DIL_002 = LEP:001, DLS:-1, DLF:1, WIN:[92,10], CUT:0
44 ***** Event Selection *****
45 # Full Event Missing Transverse Energy
46 EVT_MET_000 = OUT:1
47 # MET-Jet Delta Phi (Leading+B-Tags)
48 EVT_MDP_001 = MET:000, JET:011, OUT:1
49 # MET Significance MET / sqrt( HT )
50 EVT_RHR_001 = NUM:000, DEN:000, OUT:1
51 # Invariant Mass of Nearest Higgs Window Pair
52 EVT_OIM_001 = JET:012, OUT:1
53 # Invariant Mass of Further Higgs Window Pair
54 EVT_OIM_002 = JET:013, OUT:1
55 # Delta-R Separation of Nearest Higgs Window Pair
56 EVT_ODR_001 = JET:012, OUT:1
57 # Delta-R Separation of Further Higgs Window Pair
58 EVT_ODR_002 = JET:013, OUT:1
59 ***** Event Filtering *****
60 # Category I: 4 Leptons, 0+ B-Jets
61 CUT_ESC_001 = KEY:LEP_001, CUT:4
62 CUT_ESC_002 = KEY:JET_003, CUT:0
63 CUT_CHN_001 = ESC:[+001,+002]
64 # Category II: 2-3 Leptons, 2+ B-Jets
65 CUT_ESC_003 = KEY:LEP_001, CUT:[2,3]
66 CUT_ESC_004 = KEY:JET_003, CUT:2
67 CUT_CHN_002 = ESC:[+003,+004]
68 # Category III: 0-1 Leptons, 4+ B-Jets
69 CUT_ESC_005 = KEY:LEP_001, CUT:[0,1]
70 CUT_ESC_006 = KEY:JET_003, CUT:4
71 CUT_CHN_003 = ESC:[+005,+006]
72 *****

```

Card A: AEACuS instruction card for computation of relevant event statistics. Pre-filtering into event topology categories I-III is performed in the final lines.

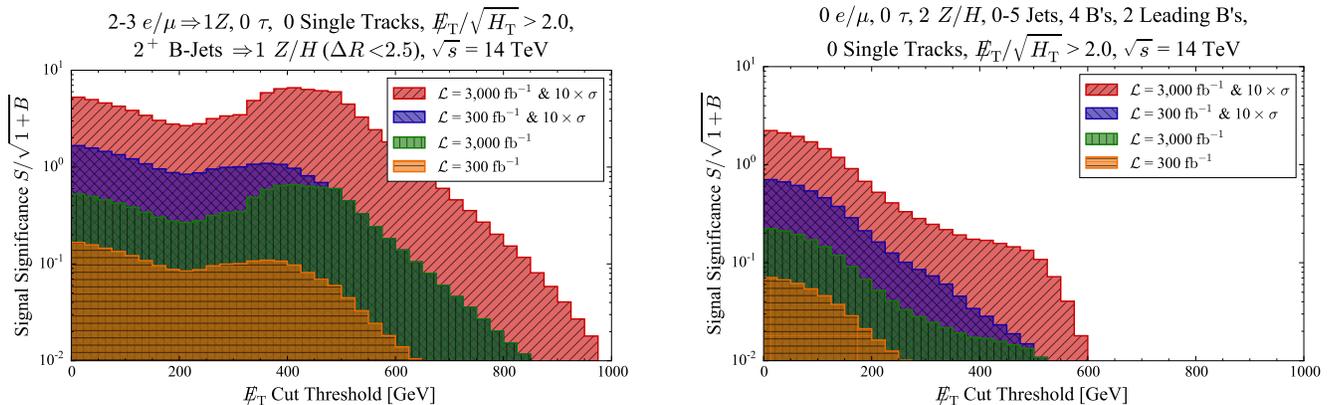


FIG. 13: The signal to background significance metric $S/\sqrt{1+B}$ is evaluated as a function of the missing transverse energy cut threshold for the category II (Left) and III (Right) final state topologies, applying the optimizations described in the right-hand panels of Figs. (9,12). Four contours are shown, corresponding to luminosities of 300 fb^{-1} and $3,000 \text{ fb}^{-1}$, for the baseline cross section of the benchmark model and also for a hypothetical spectrum that is sufficiently more light to engender a one magnitude order increase in the production cross section. Only by conspiracy of both factors may a significant excess be observed, and then only for category II. Similarities in the signal and background missing transverse energy shapes render a substantive \cancel{E}_T cut ineffective.

- [1] J. R. Ellis, J. Gunion, H. E. Haber, L. Roszkowski, and F. Zwirner, “Higgs Bosons in a Nonminimal Supersymmetric Model,” *Phys.Rev.* **D39**, 844 (1989).
- [2] M. Drees, “Supersymmetric Models with Extended Higgs Sector,” *Int.J.Mod.Phys.* **A4**, 3635 (1989).
- [3] L. Durand and J. L. Lopez, “Upper Bounds on Higgs and Top Quark Masses in the Flipped $SU(5) \times U(1)$ Superstring Model,” *Phys.Lett.* **B217**, 463 (1989).
- [4] C. Cheung and D. Sanford, “Simplified Models of Mixed Dark Matter,” *JCAP* **1402**, 011 (2014), 1311.5896.
- [5] V. Khachatryan et al. (CMS), “Searches for electroweak neutralino and chargino production in channels with Higgs, Z, and W bosons in pp collisions at 8 TeV,” *Phys. Rev.* **D90**, 092007 (2014), 1409.3168.
- [6] V. Khachatryan et al. (CMS), “Searches for electroweak production of charginos, neutralinos, and sleptons decaying to leptons and W, Z, and Higgs bosons in pp collisions at 8 TeV,” *Eur. Phys. J.* **C74**, 3036 (2014), 1405.7570.
- [7] D. Akerib et al. (LUX Collaboration), “First results from the LUX dark matter experiment at the Sanford Underground Research Facility,” (2013), 1310.8214.
- [8] A. Djouadi, J.-L. Kneur, and G. Moultaka, “SuSpect: A Fortran code for the supersymmetric and Higgs particle spectrum in the MSSM,” *Comput. Phys. Commun.* **176**, 426 (2007), hep-ph/0211331.
- [9] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, “MadGraph 5 : Going Beyond,” *JHEP* **1106**, 128 (2011), 1106.0522.
- [10] B. Dutta, Y. Gao, and B. Shakya, “Light Higgsino Decays as a Probe of the NMSSM,” *Phys.Rev.* **D91**, 035016 (2015), 1412.2774.
- [11] U. Ellwanger, C. Hugonie, and A. M. Teixeira, “The Next-to-Minimal Supersymmetric Standard Model,” *Phys. Rept.* **496**, 1 (2010), 0910.1785.
- [12] T. Sjostrand, S. Mrenna, and P. Z. Skands, “PYTHIA 6.4 Physics and Manual,” *JHEP* **05**, 026 (2006), hep-ph/0603175.
- [13] J. Conway et al., “PGS4: Pretty Good (Detector) Simulation,” (2009), URL <http://www.physics.ucdavis.edu/~conway/research/>.
- [14] A. G. Delannoy, B. Dutta, A. Gurrola, W. Johns, T. Kamon, et al., “Probing Supersymmetric Dark Matter and the Electroweak Sector using Vector Boson Fusion Processes: A Snowmass Whitepaper,” (2013), 1308.0355.
- [15] B. Dutta, T. Li, J. A. Maxin, D. V. Nanopoulos, K. Sinha, et al., “Third Generation in Cascade Decays,” (2014), 1412.5986.
- [16] T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, “The Ultra-High Jet Multiplicity Signal of Stringy No-Scale \mathcal{F} - $SU(5)$ at the $\sqrt{s} = 7$ TeV LHC,” *Phys.Rev.* **D84**, 076003 (2011), 1103.4160.
- [17] J. W. Walker, “CutLHCO: A Consumer-Level Tool for Implementing Generic Collider Data Selection Cuts in the Search for New Physics,” (2012), 1207.3383.
- [18] J. W. Walker, “AEACuS 3.15,” (2015), URL <http://www.joelwalker.net/code/aeacus.tar.gz>.
- [19] C. Han, A. Kobakhidze, N. Liu, A. Saavedra, L. Wu, and J. M. Yang, “Probing Light Higgsinos in Natural SUSY from Monojet Signals at the LHC,” *JHEP* **02**, 049 (2014), 1310.4274.
- [20] A. G. Delannoy, B. Dutta, A. Gurrola, W. Johns, T. Kamon, et al., “Probing Dark Matter at the LHC using Vector Boson Fusion Processes,” *Phys.Rev.Lett.* **111**, 061801 (2013), 1304.7779.
- [21] “Search for Supersymmetry in hadronic Final states using M_{T2} with the CMS detector at $\sqrt{s} = 7$ TeV,” (2012), CMS PAS SUS-12-002.
- [22] C. Lester and D. Summers, “Measuring masses of semi-invisibly decaying particles pair produced at hadron colliders,” *Phys.Lett.* **B463**, 99 (1999), hep-ph/9906349.
- [23] Y. Bai, H.-C. Cheng, J. Gallicchio, and J. Gu, “Stop the Top Background of the Stop Search,” *JHEP* **1207**, 110

- (2012), 1203.4813.
- [24] S. Chatrchyan et al. (CMS Collaboration), “Search for physics beyond the standard model in events with a Z boson, jets, and missing transverse energy in pp collisions at $\sqrt{s} = 7$ TeV,” Phys. Lett. B **716**, 260 (2012), 1204.3774.
- [25] S. Chatrchyan et al. (CMS Collaboration), “Inclusive search for squarks and gluinos in pp collisions at $\sqrt{s} = 7$ TeV,” (2011), 1107.1279.
- [26] C. Rogan, “Kinematical variables towards new dynamics at the LHC,” (2010), 1006.2727.
- [27] “SUSY searches with dijet events,” (2008), CMS PAS SUS-08-005.
- [28] L. Randall and D. Tucker-Smith, “Dijet Searches for Supersymmetry at the LHC,” Phys.Rev.Lett. **101**, 221803 (2008), 0806.1049.
- [29] “Search for squarks and gluinos with the ATLAS detector using final states with jets and missing transverse momentum and 4.7 fb^{-1} of $\sqrt{s} = 7$ TeV proton-proton collision data,” (2012), ATLAS-CONF-2012-033, 1208.0949, URL <http://cdsweb.cern.ch>.
- [30] “Search strategy for exclusive multi-jet events from supersymmetry at CMS,” (2009), CMS PAS SUS-09-001, URL <http://cdsweb.cern.ch/record/1194509>.
- [31] S. Chatrchyan et al. (CMS Collaboration), “Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC,” Phys.Rev.Lett. **107**, 021802 (2011), 1104.3829.
- [32] “Search for supersymmetry in pp collisions at $\sqrt{s} = 7$ TeV in events with a single lepton, jets, and missing transverse momentum,” (2011), CMS PAS SUS-11-015.
- [33] G. Aad et al. (ATLAS Collaboration), “Measurement of event shapes at large momentum transfer with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV,” Eur.Phys.J. **C72**, 2211 (2012), 1206.2135.
- [34] V. Khachatryan et al. (CMS Collaboration), “First Measurement of Hadronic Event Shapes in pp Collisions at $\sqrt{s} = 7$ TeV,” Phys.Lett. **B699**, 48 (2011), 1102.0068.
- [35] A. Banfi, G. P. Salam, and G. Zanderighi, “Resummed event shapes at hadron-hadron colliders,” JHEP **0408**, 062 (2004), hep-ph/0407287.
- [36] M. Guchait and D. Sengupta, “Searches for Supersymmetry at the LHC with 7 TeV energy,” (2011), 1102.4785.

Appendix A: Doublet decay in the SDF model

Assuming $M_S < M_D$, and that the lightest $\tilde{\chi}_1^0$ is mostly the singlet S , the heavier $\tilde{\chi}_2^0, \tilde{\chi}_3^0$ are mixtures of

the doublets D_1, D_2 , and the squared matrix elements of their decay processes are

$$\begin{aligned} \mathcal{M}_{\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 Z}^2 &= \frac{y^2}{2} \left[(M_{\tilde{\chi}_i^0} + M_{\tilde{\chi}_j^0})^2 - M_Z^2 \right] \\ &\times \left[(N_{i2}N_{j1} + N_{i1}N_{j2})c_\theta + (N_{i3}N_{j1} + N_{i1}N_{j3})s_\theta \right]^2 \\ &+ \frac{g^2 + g'^2}{2} (N_{i2}N_{j2} - N_{i3}N_{j3})^2 \\ &\times \left(M_{\tilde{\chi}_i^0}^2 + M_{\tilde{\chi}_j^0}^2 + 4M_{\tilde{\chi}_i^0}M_{\tilde{\chi}_j^0} - M_Z^2 \right) \end{aligned} \quad (\text{A1})$$

$$\begin{aligned} \mathcal{M}_{\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 h}^2 &= \frac{y^2}{2} \left[(M_{\tilde{\chi}_i^0} + M_{\tilde{\chi}_j^0})^2 - M_h^2 \right] \\ &\times \left[(N_{i2}N_{j1} + N_{i1}N_{j2})c_\theta - (N_{i3}N_{j1} - N_{i1}N_{j3})s_\theta \right]^2, \end{aligned} \quad (\text{A2})$$

where s_θ, c_θ are short for $\sin\theta, \cos\theta$. N_{ij} are the elements of the mixing matrix that diagonalizes the mass matrix in Eq. 4. $\tilde{\chi}_{2,3}^0$ either decay into the singlet component of $\tilde{\chi}_1^0$ via the $ySHD$ terms, or into the small doublet component in $\tilde{\chi}_1^0$ via the gauge couplings.

Note that without the $ySHD$ term, i.e. in the limit $y \rightarrow 0$, the singlet would altogether decouple from the doublet, $\tilde{\chi}_1^0$ would have no mixing into D_1, D_2 , implying $N_{12} = N_{13} = 0$, and the prior decays would become forbidden. Turning on $y > 0$, with y still smaller than unity, the doublet mixings in $\tilde{\chi}_1^0$ grow linearly with y , implying $N_{12}, N_{13} \propto y$, giving a y^2 dependence also in the second term in Eq. A1. Thus, decay widths into both Z, h grow as y^2 when $y \ll 1$, and thereby maintain a comparable size. At large y , $y \cdot v_{ev} \sim M_S, M_D$ in the mass terms, which cause the D_1, D_2 mixings to become more complicated. Still, this property qualitatively holds, as is observed for the benchmark Point III in Table III.