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A Razor Search for Bino Dark Matter at 100 TeV

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Abstract: Abstract...

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1 Introduction

The existence of dark matter is unambiguous evidence of the need for new physics beyond the standard model. Indeed, given that there is far more dark matter in the universe than there is baryonic matter, determining its precise nature is one of the most exciting challenges in physics today. It is widely believed that dark matter is comprised of stable weakly interacting massive particles (WIMPs). These particles arise naturally in many extensions of the Standard Model (SM). Of these extensions, one of the most studied is the Minimal Supersymmetric Standard Model (MSSM) [1]. In the MSSM, the lightest supersymmetric partner (LSP) is predicted to be absolutely stable, making it a good candidate for dark matter. The identity of the LSP is determined by the mass hierarchy of the superpartners, which in turn depends on how supersymmetry is broken. However, taking into account experimental constraints and phenomenological considerations, the lightest neutralino emerges as the most attractive candidate for the LSP [2].

Despite the attractive simplicity of the MSSM, it is under siege from recent data from the Large Hadron Collider (LHC). A compelling alternative theory comes in the form of split supersymmetry [3–5]. In this scenario, the lightest superpartners are the fermionic ones (gauginos and higgsinos), while the scalar superpartners can be much heavier. In exchange for accepting some level of fine-tuning, we obtain numerous benefits, including the suppression of flavor-changing neutral currents and greater compatibility with data from CP-violation experiments.

The most interesting regions of the split SUSY parameter space lies beyond the reach of the LHC. In particular, pure wino and higgsino dark matter is required to be extremely

[1] For a detailed review, see [1]

heavy (3.1 and 1 TeV respectively) to be consistent with the observed relic density of dark matter in the universe.

In this paper, we describe a search strategy for pair-produced Higgsinos that decay to binos via intermediate Z and h bosons. It is well known that pure bino LSPs result in an overabundance of dark matter in the universe, in conflict with experimental observations. However, if the bino is nearly mass-degenerate with another particle, such as the gluino, stau, or squarks, it can coannihilate with it, thereby reducing the dark matter abundance to acceptable levels. Since scalars in split SUSY are heavy, the bino must be on the order of a few TeV as well, making it a ripe target for a 100 TeV collider.

The rest of the paper is structured as follows. In section 2, we describe our model and search channel in more detail, and list the existing experimental constraints on it. In section 3, we describe our analysis strategies for both the traditional cut-and-count analysis and the analysis performed with boosted decision trees. In section 4, we provide the results of both analyses and the reach in the split SUSY parameter space. Finally, in section 5, we conclude with the implications.

2 Model and experimental constraints

In the MSSM (and by extension, split SUSY), the neutralino sector consists of four mass eigenstates $(\tilde{N}_1, \tilde{N}_2, \tilde{N}_3, \tilde{N}_4)$ that are mixtures of the following gauge eigenstates: the neutral higgsinos $(\tilde{H}_u^0, \tilde{H}_d^0)$, the bino $(\tilde{B})$, and the neutral wino $(\tilde{W}^0)$. In the basis of these gauge eigenstates, the mass matrix of the neutralino can be written as

$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix},$$

where $s_\beta = \sin\beta, c_\beta = \cos\beta, s_W = \sin\theta_W$, and $c_W = \cos\theta_W$. The angle β is a central parameter of the theory - it parameterizes the mixing between the two Higgs doublets, $\tilde{H}_u$ and $\tilde{H}_d$. M_1 and M_2 are the coefficients of the soft supersymmetry breaking Lagrangian, and μ comes from the higgsino mass terms. In the limit of $m_Z \ll |\mu \pm M_1|, |\mu \pm M_2|$, the mass eigenstates are, to good approximation, a nearly pure bino, $\tilde{B}$, with mass M_1, a nearly pure wino, $\tilde{W}^0$, with mass M_2, and nearly pure higgsinos $\tilde{H}_{1,2}^0 = (\tilde{H}_u^0 \pm \tilde{H}_d^0)/\sqrt{2}$, with mass $|\mu|$[2]. The optimal search strategy for finding electroweakinos is highly dependent on the mass difference between them. Phenomenological collider studies on finding electroweakinos separated by about 0.1 - 50 GeV at a 100 TeV collider can be found in [6–9], while well-separated spectra have been studied in [10, 11].

So far, the well-separated spectra have been studied using multi-lepton channels, since the large mass difference between the electroweakinos can lead to energetic leptons that can be easily identified. Among the multi-lepton searches, the trilepton searches (with W and Z as the intermediate dibosons) have the best reach, due to the high production

[2]This limit is well-motivated, since we are considering heavy electroweakinos that are out of the reach of the LHC - the minimum mass of the higgsinos considered is 500 GeV, and the wino is decoupled to 3 TeV.

Stage	$N_{2,3}C_2$	N_2N_3
Pair production cross section	60 fb	16 fb
Intermediate diboson contribution	(WZ) 30 fb	(Zh) 8 fb
Applying $BR(W \to l\nu)$, $BR(Z \to ll)$ & $BR(h \to bb)$	0.42 fb	0.32 fb

Table 1. Comparison of cross-sections for $(N_{2,3}C_2)$ and (N_2N_3), for $|\mu| \approx 1$ TeV, at a 100 TeV pp collider. The branching ratios are taken to be the same as the SM ones listed in the PDG.

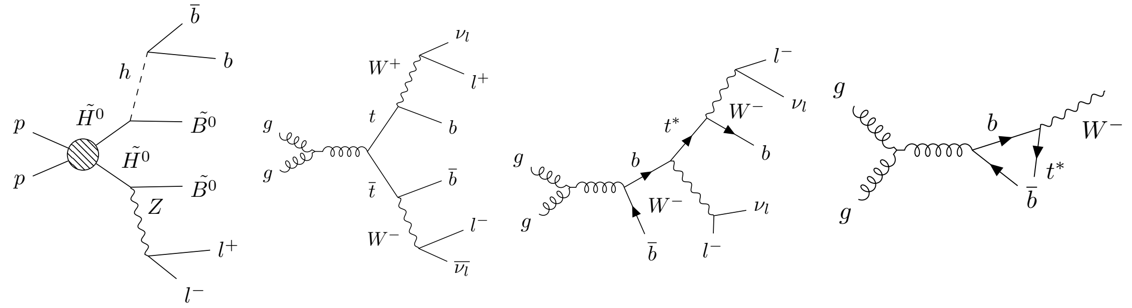

Figure 1. From left to right, the representative Feynman diagrams of the signal process (upper left), the dominant tt background (upper right), tbW without a top quark in the s-channel (lower left), and $bbWW$ without a top quark in the s-channel (lower right). (Generated using [12].)

cross-section of chargino-neutralino pairs combined with the large reduction in $t\bar{t}$ and QCD backgrounds obtained by requiring three leptons. Multilepton searches with Zh and ZZ as the intermediate dibosons are unlikely to be as powerful, due to the lower pair-production cross-section of neutral higgsinos, combined with the low branching ratio of Z to leptons. However, if we move beyond multilepton searches, the channel with Zh as the intermediate dibosons emerges as a possible competitor to the WZ channel. If the Z decays leptonically and h decays to a pair of bs, then after applying the relevant branching ratios, the signal cross sections become comparable (for details, see table 1). It should be noted that at a 100 TeV collider, we can take advantage of the Goldstone equivalence theorem to simplify the calculation of the branching ratios involving Higgsinos. For a Higgsino NLSP and Bino LSP, we have

$$BR(N_{NLSP} \to N_{LSP}Z) \approx BR(N_{NLSP} \to N_{LSP}h) \approx 0.5.$$

In this paper, We study the process:

$$pp \to \tilde{H}_1^0 \tilde{H}_2^0 \to (Z\tilde{B}^0)(h\tilde{B}^0) \to ((l^+l^-)\tilde{B}^0)((b\bar{b})\tilde{B}^0).$$

Although this combination of NLSP and LSP has been studied previously in [10], this particular decay topology has not, and so can be combined with other searches to obtain a greater significance. The main backgrounds for this process are: $t\bar{t}$, tbW with the b and W not coming from a t, and $bbWW$ with no intermediate s-channel top quarks. We also decouple the wino mass, setting at 3 TeV. We obtain the Higgsino pair production cross sections from Prospino2. From the Goldstone equivalence theorem, the Higgsinos go into Z and h each with a probability of 50%, and we set $B(Z \to l^+l^-) = 6.7\%$ and $B(h \to bb) = 56\%$[3]., consistent with the Standard Model.

- ATLAS - [13]
- CMS [14]
- relic density

3 Analysis Details

3.1 Simulation

We simulated parton-level events using MadGraph 5 v2.3.2.2 and MadEvent [15], then passed those events to Pythia 6 [16] for showering and hadronization. Finally, we used Delphes 3 [17] to perform a fast, parametrized detector simulation, with the FCC Delphes card devised by the FCC-hh working group[4]. For the backgrounds, we allowed up to one additional jet in the final state, to approximate NLO QCD effects, and performed MLM matching with the `xqcut` parameter set to 40 GeV.

One of the challenges we faced while performing this analysis was dealing with the sheer number of background events to generate and analyze. At a 100 TeV collider, the background cross-sections grow very large compared to their 14 TeV counterparts. For example, the cross section for the inclusive production of top quark pairs increases from ~ 975 pb (N^{3}LO) to ~ 32000 pb (NLO), that is, increasing the collision energy by about seven times increases the number of events by a factor of more than 30! Multiplying this by 3 ab^{-1} (the expected integrated luminosity from the first 10 years of running the FCC), gives us 96 billion top pair production events. Simulating this many events would require enormous amounts of computing time as well as huge amounts of storage. To alleviate the first problem, we generated events on the University of Arizona cluster, leveraging the power of many nodes to perform event generation simultaneously. But this alone would not be enough. Since we expect our signal process to have a dilepton resonance from an on-shell Z boson, we restricted the phase space for event generation for backgrounds to the region where the invariant mass of dilepton pairs lies between 80 and 100 GeV. Additionally, the bino dark matter that escapes the detector would result in a large amount of missing transverse energy (MET), so we required a minimum MET of 100 GeV at the parton level.

At the reconstructed level, we relaxed the lepton isolation criterion in the Delphes detector card from ΔR_{min} from 0.4 to 0.05. This is motivated by the fact that due to the large mass difference between the higgsino NLSP and the bino LSP in our search channel, the intermediate Z bosons will be highly boosted, and the leptons to which they decay will be highly collimated. The value of 0.05 is consistent with what is suggested in previous 100 TeV studies ([10, 11, 18]) and will allow for easier comparison between strategies.

3.2 Event selection for the cut-and-count method

The event selection was done with the help of the MadAnalysis 5 package [19].

[3] https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR
[4] https://github.com/HEP-FCC/FCCSW/tree/master/Sim/SimDelphesInterface/data

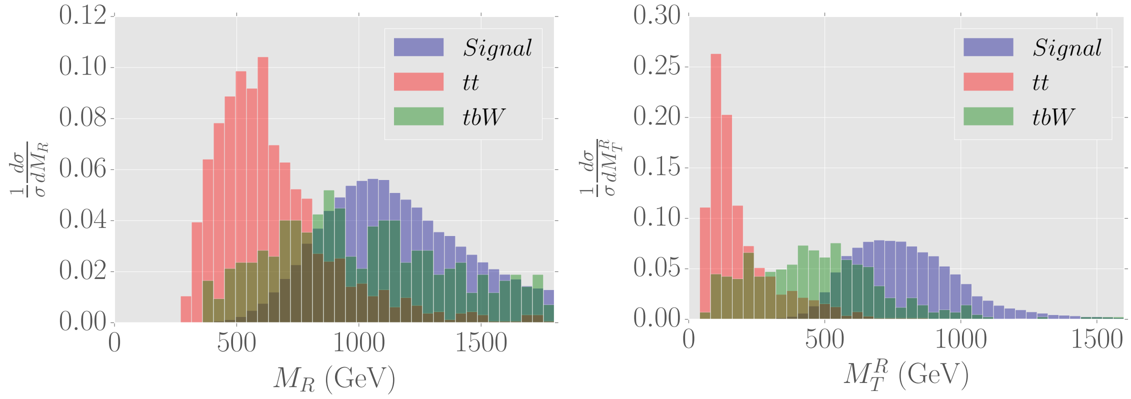

Figure 2. Normalized distributions of the razor kinematical variables M_R (left) and M_T^R (right) for a 1 TeV Higgsino NLSP and 25 GeV Bino LSP. We can see that M_R is peaked around 1 TeV for the signal, which is what we would expect, since it corresponds to the mass difference between the NLSP and LSP.

1. **Trigger**: Events were selected if they had at least one lepton with $p_T > 100$ GeV.
2. **Identification:**
   - We required that events contain exactly two leptons of the same flavor and with opposite charges, with $p_T > 15$ GeV, and $|\eta| < 2.5$.
   - We required that events contain at least two b-tagged jets with $p_T > 30$ GeV and $|\eta| < 2.5$.
3. **Invariant mass of Z-candidate:** We required that the invariant mass of the two leptons, $m_{l^+l^-}$, lie between 85 and 95 GeV.
4. **Invariant mass of h-candidate**, We combine the two b-tagged jets with the highest p_T to form a h candidate and require that its invariant mass, m_{bb}, lies between 75 and 150 GeV.
5. **Missing Tranverse Energy:** We required events to have MET $>$ 400 GeV.
6. **Razor variables**: Razor variables [20] were designed for searches involving two massive (and nearly mass-degenerate) pair produced particles. This analysis is useful here because of the nearly mass-degenerate pair-produced Higgsinos. The first razor variable, M_R, inherits the knowledge of the mass difference between the parent particle (the Higgsino), and the invisible particle (the Bino). The second razor variable, M_T^R, can be thought of as a longitudinally-invariant analogue of the transverse mass. We scanned across a range of minimum values of these variables to find the ones that yielded the greatest significance.

3.3 Optimizing using gradient boosted decision trees

Description of the AdaBoost algorithm [21].

	σ_{signal}	σ_{tt}	σ_{tbW}	$\sigma_{tot,BG}$	S/B	$S/\sqrt{B}$
Original	0.33	3.60e+04	151000.00	5.61e+08	1.79e-06	0.04
Trigger	0.28	5.30e+03	43029.55	1.45e+08	5.83e-06	0.07
SFOS leptons	0.23	1.76e+03	5384.37	2.14e+07	3.19e-05	0.15
2 b jets	0.04	2.56e+02	620.43	2.63e+06	4.13e-05	0.07
MET $>$ 400 GeV	0.03	4.29e+00	25.40	8.91e+04	8.60e-04	0.26
$85GeV < m_{ll} < 95$ (GeV)	0.02	1.64e+00	0.48	6.38e+03	9.97e-03	0.80
$75 < m_{bb} < 150$ (GeV)	0.02	4.97e-01	0.18	2.03e+03	2.80e-02	1.26
$m_R > 800GeV$	0.02	2.38e-02	0.18	6.12e+02	8.19e-02	2.03
$m_T^R > 400GeV$	0.02	7.93e-03	0.18	5.64e+02	8.84e-02	2.10

Table 2. Representative cut flow table for a 1 TeV Higgsino NLSP and 25 GeV Bino LSP. All cross sections are given in femtobarns, and the significance, $S/\sqrt{B}$, is calculated for an integrated luminosity of 3000 fb^{-1}.

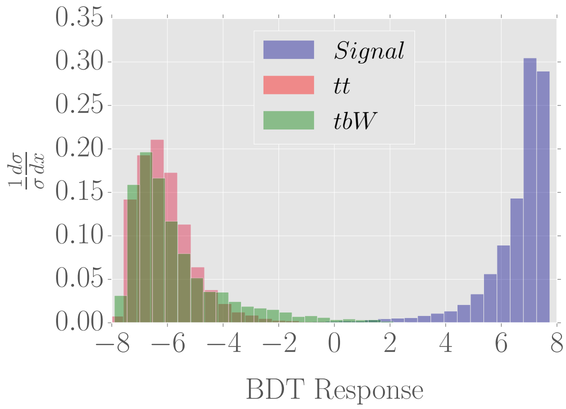

Figure 3. Distribution of the decision function of the gradient boosted decision tree classifier algorithm for our signal and backgrounds. We observe that there is an appreciable separation between the signal and background distribution, which is suggestive of the potential for machine learning to improve our searches.

4 Results

Our

5 Conclusion

Reach not as high due to difficulty in identifying b-jets. But still, a different topology that can be combined with other searches to boost the significance.

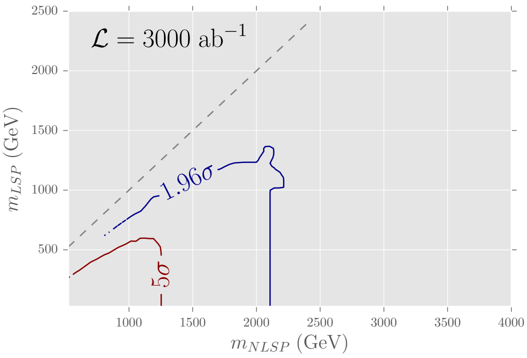

Figure 4. Reach in parameter space

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