Probing Light Higgsinos in Natural SUSY from Monojet Signals at the LHC (Postprint)

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Abstract

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Full Text

Preamble

Probing Light Higgsinos in Natural SUSY from Monojet Signals at the LHC

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Abstract

We investigate a strategy to search for light, nearly degenerate higgsinos within the natural MSSM at the LHC. We demonstrate that the higgsino mass range µ in 100 − 150 GeV, which is preferred by naturalness, can be probed at 2 significance through the monojet search at 14 TeV HL-LHC with 3000 fb ^{1} luminosity. The proposed method can also probe certain regions in the parameter space for the lightest neutralino with high higgsino purity that cannot be reached by planned direct detection experiments at XENON-1T(2017).

I. INTRODUCTION

One of the key theoretical motivations for low-energy supersymmetry (SUSY) is that it provides a framework for a light Higgs boson without invoking unnatural fine-tuning of theory parameters. However, the recent discovery of a Standard Model (SM) Higgs-like particle with mass around 125 GeV [1, 2], in conjunction with the non-observation of supersymmetric particles, has largely excluded the most studied parameter ranges within the minimal supersymmetric Standard Model (MSSM) for which the naturalness criterion is satisfied. If the observed resonance is to be identified with the lightest CP-even Higgs boson of the MSSM, heavy multi-TeV stops and/or large Higgs-stop trilinear soft-breaking coupling are required to achieve sufficient enhancement of the predicted Higgs mass [3, 4]. Furthermore, null results on gluino searches at the LHC so far have pushed the lower limit on gluino mass above the TeV scale [5]. All these developments significantly jeopardize the naturalness of the MSSM with a standard sparticle spectrum. Therefore, it is imperative to consider possibly hidden parameter spaces where the theory maintains naturalness, and to look for other strategies for verifying such natural SUSY models at the LHC [6]. In this work, we investigate the possibility of monojet signals induced by light higgsinos at 14 TeV high-luminosity LHC (HL-LHC) as a probe of natural SUSY.

The justification for light, nearly degenerate higgsinos within the natural MSSM comes from the following consideration. In the MSSM, the minimization of the tree-level Higgs potential leads to the relation [7]:

= $-\mu^2$ + Hu $\tan^2$ $\tan^2$ − 1 (cid:39) $-\mu^2 - m^2$ and m^2 where m^2 Hu represent the weak scale soft SUSY breaking masses of the Higgs fields, and μ is the higgsino mass parameter. A moderate/large tan (cid:38) 10 is assumed in the last approximate equation. In order to avoid large fine-tuning in Eq.(1), μ and mHu must be of the order of 100 − 200 GeV, which implies light higgsinos. At the same time, the electroweak gaugino mass parameters M , are preferred to be of similar order as the heavy gluino mass parameter M , and large Higgs-stop trilinear coupling A is needed [8].

Hence, generically we have μ (cid:28) M , and the mass splittings between the lightest chargino and the lightest two neutralinos at leading order are determined by [13]:

m ˜ ± − m ˜ 0 m ˜ 0 − m ˜ 0 (cid:18) (cid:18) 1 − sin 2 − (cid:19) $\tan^2$ W (1 + sin 2), 1 − sin 2 + (cid:19) $\tan^2$ W (1 − sin 2) .

This in turn implies that light electroweak gauginos in the natural MSSM are nearly degenerate higgsino-like states with mass differences of about 3 − 10 GeV (for M = M 0.5 − 2 TeV). Therefore, a direct search for light higgsinos may serve as a sensitive probe of the natural MSSM. For such light higgsinos, the electroweak production rates for Z → ˜ ˜ and Z/ ∗ → ˜ ˜ are expected to be reasonably large, reaching pb-level at the LHC. However, since the light higgsinos are nearly degenerate, the products of their subsequent decays, ˜ →

Z ˜ , ˜ → W ˜ , and ˜ → W *˜ , will carry small energies and, hence, the currently adopted search strategy for electroweak gauginos through their direct pair production is not applicable to this case [9, 10]. Recently, a new search channel based on wino pair production with a same-sign diboson plus missing transverse energy (E_T) final state has been proposed for the 14 TeV LHC in [11]. Also, it has been pointed out that for (m˜ ± − m˜) (cid:46) 1 GeV, the wino may have a long lifetime and such long-lived charged particles are already excluded by LHC data [12].

II. CALCULATIONS AND DISCUSSIONS

We study the detection of light higgsinos via monojet searches at the LHC in the following processes (see Fig. 1 for the corresponding Feynman diagrams):

pp → ˜ ± ˜ j, ˜ ˜ j, ˜ ± ˜ , j.

In these processes, a hard jet radiated from initial partons recoils against the invisible missing transverse energy from soft decay products and can be used as a handle to tag the higgsino pair production. Because of the small mass splitting (m 3 − 10 GeV) between ˜ and ˜ , all three channels (j˜ ˜ , j˜ ˜ , and j˜ ± ˜ ,) share the same topology in the detector. As a result, the monojet production rates within the natural MSSM are greatly enhanced.

In addition, when µ (cid:28) M , , these processes are largely insensitive to other SUSY parameters except the higgsino mass µ. Therefore, we do not consider the production of stops and gluinos in this paper, which contribute to fine-tuning in more complicated and model-dependent ways [8]. The current constraints on the mass limits of stops and gluinos in natural SUSY have been discussed in [14, 15]. The sleptons and first two generation squarks are irrelevant for our analysis and we assume them to be heavy.

Since monojets have a distinctive topology of events with a single high-pT hadronic jet and large missing E_T, their relevance to searches for pair production of weakly-interacting particles has been exploited at the LHC [20]. The SM backgrounds to the above monojet signature are dominated by the following four processes: (i) pp → Z(→ ¯) + j, which is the main irreducible background with the same topology as our signals; (ii) pp → W(→) + j, which fakes the signal only when the charged lepton is outside the acceptance of the detector or close to the jet; (iii) pp → W(→) + j, which may fake the signal since a secondary jet from hadronic tau decays tends to localize on the side of E_T; (iv) pp → t̄t, which may resemble the signal but also contains extra jets and leptons. This allows us to highly suppress the t̄t background by applying b-jet, lepton, and light jet vetoes.

For the QCD background, misreconstruction of jet energy in the calorimeters can cause an ordinary di-jet event with large missing energy to mimic the signal. An estimation of the QCD background based on full detector simulation can be found in [16]. By fitting the jet energy response function (JERF) using the method in [17], the authors of [18] found that the multijet background in supersymmetric monojet analyses at 14 TeV LHC can be reduced to a negligible level by requiring a large E_T cut, such as E_T > 200 GeV. Since other dominant backgrounds have E_T > 200 GeV, we set E_T > 500 GeV as in [19], where the cuts for monojet events are optimized for 14 TeV LHC, thus we can safely neglect the QCD background in our calculation. (The pile-up effects at 14 TeV HL-LHC have not been considered in this work due to lack of exact detector configurations.) The diboson backgrounds and single top background are not considered in our calculations due to their small cross sections compared to other backgrounds.

In our calculations, we assume M = M = 1 TeV and use Suspect [21] and SUSY-HIT [22] to calculate masses, couplings, and branching ratios of the relevant sparticles. The parton-level signal and background events are generated with MadGraph5 [23]. We perform parton shower and fast detector simulations with PYTHIA [24] and Delphes [25]. We cluster jets using the anti-k algorithm with a cone radius R = 0.7 [26]. In order to obtain reasonable statistics, a generator-level event filter was applied which imposed a parton-level cut of pT > 120 GeV on the leading jet for signals and W/Z + j backgrounds. It should be noted that jet veto cuts can significantly affect the QCD corrections to the backgrounds [27]. To include QCD effects, we generate parton-level events of Z/W + j with up to two jets that are matched to the parton shower using the MLM-scheme with merging scale Q = 60 GeV [28]. Due to the t̄t events containing a large number of jets, we need not generate events with extra hard partons, which will be strongly rejected by the jet veto [19]. Although additional jets may come from the decays of ˜ ± or ˜ , they are too soft to pass our strict pT cut on the leading jet adopted in the following analysis. Therefore, there is no need to generate higgsino pairs without an additional parton in the final state. Besides, our signal simulation is exclusively based on Eq.(4) so that double counting will not arise in our calculation.

In Fig. 2, we display the cross section of pp → ˜ ± ˜ j, ˜ ˜ j, ˜ ± ˜ , j as a function of higgsino mass µ after requiring the parton-level cut pT(j) > 120 GeV at 14 TeV LHC. Since ug initial states have large parton distribution functions, the largest contribution to the cross section of our signals comes from ˜ ˜ j. The degenerate spectrum of ˜ ± and ˜ , implies that signals with the same initial states have approximately the same cross sections. Therefore, the total production rate is amplified and can reach nearly pb-level.

In Fig. 3, we show the normalized distributions of the reconstructed leading jet pT(j) and E_T for signals and backgrounds. From the upper panel, one can see that for pT(j) > 200 GeV, the signals have a harder pT(j) spectrum than the backgrounds. A greater value of µ corresponds to an increase in the average pT of the jet. The difference in peaks of the signals (120 GeV) and t̄t background (m /2) is caused by the parton-level cut pT(j) > 120 GeV. From the lower panel, one observes that the signals have larger E_T than the backgrounds. Thus, a hard cut on E_T will be effective in reducing the backgrounds.

According to the above analysis, events are selected to satisfy the following criteria for monojet searches [20], and the cuts for E_T and pT(j) are optimized for 14 TeV LHC [19]: (i) We require large missing transverse energy E_T $>$ 500 GeV; (ii) The leading jet is required to have pT(j) $>$ 500 GeV and | | $<$ 2; events with more than two jets with pT above 30 GeV in the region | | $<$ 4.5 are rejected; (iii) We veto the second leading jet with pT(j) $>$ 100 GeV and | | $<$ 2; (iv) A veto on events with an identified lepton (= e, µ,) or b-jet is imposed to reduce the background from W + j and t̄t. We use the b-jet tagging efficiency parametrization given in [29] and include a misidentification rate of 10% and 1% for c-jets and light jets, respectively. We also assume the tagging efficiency is 40% and include mis-tags of QCD jets using Delphes.

[TABLE:I]: Cut flow of the signal events for µ = 100, 200 GeV at 14 TeV LHC with L = 100 fb ^{1}. The cross section of t̄t is normalized to the approximately next-to-next-to-leading order value ¯ = 920 pb [30].

In Table I, the resulting cut flow for signal and background events is presented for a center-of-mass energy of 14 TeV and an integrated luminosity of 100 fb ^{1}. After the cuts pT(j) $>$ 500 GeV and E_T $>$ 500 GeV, the Z + j and W + j backgrounds are reduced by O(10), while the signals are only reduced by O(10 ^{2}). The lepton and light jet veto suppresses Wj backgrounds by an additional two orders of magnitude. For the t̄t background, we have not included the hadronic channels due to its large jet multiplicity and small E_T. We impose the third jet veto as required by the ATLAS collaboration [20], which was not used in [19]. We also checked that our results are consistent with those obtained in Ref. [31] by setting the same values of cuts and collider energy. The Z(¯) process remains the dominant background after all cuts.

In Fig. 4, we display the dependence of the signal significance S/√B on the higgsino mass µ at 14 TeV HL-LHC for various luminosities, L = 3000 fb ^{1}. The overall background B, including systematic errors, is calculated through the formula B = Σ B + Σ (0.01B)^{2}, (i = Z + j, t̄t, W(→) + j, W(→) + j), where we assume the systematic error to be 1%. With increasing µ, the significance drops rapidly due to the reduction in signal cross sections. At L = 3000 fb ^{1}, the range µ 100 − 150 GeV, favored by naturalness, can be probed at 2 significance. However, it should be mentioned that since realistic detector performances of the HL-LHC are still not available, we can expect our analysis to be improved by optimizing signal extraction strategies and better understanding background uncertainties through dedicated analyses by the experimental collaborations at HL-LHC.

[Figure 5: see original paper]: Scatter plot of samples surviving the constraints from (1)-(6) in the text. The horizontal lines show the 90% C.L. bound from XENON100 [44], future sensitivities at LUX [45] and XENON1T [46], respectively. The vertical dashed line is the sensitivity of monojet signals at 2 significance at 14 TeV LHC with L = 3000 fb ^{1}.

As a complementary search for light higgsinos, we also investigate the probing ability of dark matter direct detection experiments. We compute dark matter observables using the package MicrOmega [32] and scan the following parameter space: 100 GeV µ 200 GeV, 1 TeV M , M 2 TeV, −3 TeV A = A_b 3 TeV, 1 tan 60, m˜_R = m_ƀ_R 2 TeV. Other irrelevant mass parameters are taken as 2 TeV. The above parameters are further constrained by: (1) Measurements of B → X and B → processes at 2 level [33]; (2) Higgs mass in the range 123-127 GeV [34]; (3) LHC searches for H/A → [35]; (4) Direct search results of stop/sbottom pair productions at the LHC [15]; (5) LEP data [37]; and (6) Electroweak precision measurements [36].

We note that in the natural MSSM, the thermal relic density of the light higgsino-like neutralino dark matter is typically low due to the large annihilation rate in the early universe. This makes the standard thermally produced WIMP dark matter inadequate in the natural MSSM. In order to provide the required relic density, several alternative mechanisms have been proposed [38–40], such as choosing the axion-higgsino admixture as the dark matter [41]. In this case, the spin-independent neutralino-proton scattering cross section ^SI must be re-scaled by a factor Ω_˜ h²/Ω_PLh² [41], where Ω_PLh² is the relic density measured by the Planck satellite [42]. However, it should be mentioned that if the naturalness requirement is relaxed, a heavy higgsino-like neutralino with mass about 1 TeV can solely produce the correct relic density in the MSSM [43]. Of course, all these analyses are performed assuming a standard ΛCDM model.

The results for the spin-independent higgsino-proton scattering cross section are shown in Fig. 5 and compared with current limits from XENON-100, LUX [44, 45] and future reach projections of XENON-1T [46]. We also present the 2 probing sensitivity of the higgsino mass µ by our proposed monojet strategy at the LHC with L = 3000 fb ¹. From Fig. 5, we can see that even with the scale factor Ω_˜ h²/Ω_PLh², most of the samples can be probed by XENON-1T(2017). Only those samples corresponding to a neutralino with high higgsino purity cannot be covered by XENON-1T(2017). In this case, our proposed monojet searches may be used to probe such a light higgsino-dominant neutralino with mass up to 150 GeV at 14 TeV LHC for L = 3000 fb ¹.

III. CONCLUSION

In this paper, we studied a strategy for searching for light, nearly degenerate higgsinos in the natural MSSM. Our results showed that for L = 3000 fb ¹, the higgsino mass range µ 100 − 150 GeV favored by naturalness may be probed at 2 significance through monojet searches at 14 TeV LHC. Additionally, this method can probe certain regions in the parameter space for the lightest neutralino with high higgsino purity that cannot be reached by planned direct detection experiments at XENON-1T(2017).

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Note: Figure translations are in progress. See original paper for figures.