Simplified supersymmetry with sneutrino LSP at 8 TeV LHC

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ABSTRACT: The current searches of supersymmetry (SUSY) are based on the neutralino lightest sparticle (LSP). In this article we instead focus on SUSY with sneutrino LSP. It is well motivated in many contexts, especially in which sneutrino services as a dark matter candidate. We first develop a simplified model, which contains the stop, chargino/neutralino and sneutrino, to describe the LHC phenomenologies of a large class of models with sneutrino LSP. Then we investigate bounds on the model using the SUSY searches at the 8 TeV LHC. Strong exclusion limits are derived, e.g., masses of stop and chargino can be excluded up to about 900 GeV and 550 GeV, respectively. We also propose optimizations for some searches without turning to higher energy and luminosity.

KEYWORDS: Supersymmetry Phenomenology, Monte Carlo Simulations

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Natural X-ray lines from the low scale supersymmetry breaking

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ABSTRACT

In the supersymmetric models with low scale supersymmetry (SUSY) breaking where the gravitino mass is around keV, we show that the 3.5 keV X-ray lines can be explained naturally through several different mechanisms: (I) a keV scale dark gaugino plays the role of sterile neutrino in the presence of bilinear R-parity violation. Because the light dark gaugino obtains Majorana mass only via gravity mediation, it is a decaying warm dark matter (DM) candidate; (II) the compressed cold DM states, whose mass degeneracy is broken by gravity mediated SUSY breaking, emit such a line via the heavier one decay into the lighter one plus photon(s). A highly supersymmetric dark sector may readily provide such kind of system; (III) the light axino, whose mass again is around the gravitino mass, decays to neutrino plus gamma in the R-parity violating SUSY. Moreover, we comment on dark radiation from dark gaugino.

1. Introduction and motivations

Dark matter (DM) as a solid evidence for new physics beyond the standard model (SM) receives wide attention, both from the theoretical and experimental physics communities. The original focus is the weakly interacting massive particle (WIMP) DM candidate due to the WIMP miracle argument on the correct order of DM relic density. But the experimental results discouraged us despite several events which are far from confirmation. On the other hand, the keV scale warm DM (WDM) became more interesting since the progress on N-body simulation of DM structure formation indicates that WDM can give the correct abundance of DM galaxy substructures nevertheless cold DM can not [1].

If DM is in the keV region, the searching strategy will be quite different. For instance, it, which is non-relativistic in the present epoch, tends to leave null hints in the current underground DM detectors. (This seems to be consistent with the most stringent bounds from the XENON100 [2] and LUX [3] experiments.) On the top of that, its signatures from the sky should not locate at the high energy region, and we may have to rely on the observation of X-ray line, which has relatively clear astrophysical background. Recently, a tentative 3.5 keV gamma ray line through the observation of galaxy clusters and the Andromeda galaxy was discovered [4]. Although the origin of this line is controversial [5,6], it is still of interest to ascribe it to dark matter activities.

This possibility inspires a lot of works soon later. Refs. [7,8] attempt to understand it via the effective operator analyses. Specific candidates are also proposed, e.g., a keV sterile neutrino [9] which was motivated long ago, axion-like particles [10] (DM decays into axion which then converts into a pair of photons may fit data better [11]), axino [12], and millicharged dark matter [13]. All these particles have masses at the keV scale, producing the X-ray line via decaying or annihilating into gamma, among others. But the eXciting DM (eXDM) [14] takes a quite different approach which is beyond the WDM framework. There the X-ray line instead comes from the decay of the heavy DM exciting state, which is tinnily heavier than DM by an amount of about 3.5 keV, back into the DM plus photon with others.

We should seriously ponder on the natural origin of the keV scale, which is by no means a trivial question in model building since the SM has a characteristic scale of 100 GeV. In the keV WDM scenario, one may want to seek a theoretical reason for such a low mass scale. In the eXDM-like scenario, generating such a small mass splitting without incurring fine-tuning is of concern to us as well. It is well known that supersymmetry provides a natural solution to the gauge hierarchy problem. And in the supersym-

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Light doubly charged Higgs boson via the $WW^*$ channel at LHC

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Abstract The doubly charged Higgs bosons $H^{\pm\pm}$ searches at the large hadron collider (LHC) have been studied extensively and strong bound is available for $H^{\pm\pm}$ dominantly decaying into a pair of same-sign di-leptons. In this paper we point out that there is a large cavity in the light $H^{\pm\pm}$ mass region left unexcluded. In particular, $H^{\pm\pm}$ can dominantly decay into $WW$ or $WW^*$ (For instance, in the type-II seesaw mechanism the triplet acquires a vacuum expectation value around 1 GeV), and then it is found that $H^{\pm\pm}$ with mass even below $2m_W$ remains untouched by the current collider searches. Searching for such a $H^{\pm\pm}$ at the LHC is the topic of this paper. We perform detailed signal and background simulation, especially including the non-prompt $t\bar{t}$ background which is the dominant one nevertheless ignored before. We show that such $H^{\pm\pm}$ should be observable at the 14 TeV LHC with 10–30 fb$^{-1}$ integrated luminosity.

1 Introduction

At the large hadron collider (LHC), the searches for new physics beyond the standard model (SM) have a preference for the colored particles. It is due to two reasons. First, from the argument for solving the gauge hierarchy problem, colored partners of top quark are expected, to cancel the quadratic divergence of Higgs mass incurred by top quark. Second, viewing from detectability, colored particles have sizable production rates even at the well motivated TeV scale. Nevertheless, it is also of importance to investigate the status and prospects of new electroweak (EW) particles. They are not less motivated in particle physics. But at the LHC these particles, typically with small production rates, are inclined to be buried in the huge SM EW and/or QCD backgrounds, except for those with characterized signatures, e.g., large missing transverse energy or same-sign di-lepton (SSDL). The latter frequently originates from particles with a larger electric charge, and the doubly charged Higgs bosons, denoted as $H^{\pm\pm}$, is a good case in point.

A lot of works have been done on the LHC search for $H^{\pm\pm}$ that come from the $(\text{scalar})\ SU(2)_L$ triplet representation with hypercharge $\pm 1$ (denoted as $\Delta$).$^1$ As a matter of fact, extension to the SM Higgs sector by $\Delta$ is well inspired by various new physics contexts, e.g., solving the hierarchy problem [1,2], providing a viable dark matter candidate [3–6] and in particular generating neutrino masses via the seesaw mechanism [7–15]. In supersymmetry, such triplets provide an effective way to lift the SM-like Higgs boson mass, thus greatly relieving the fine-tuning problem [16]. In addition, a light $\Delta$ on the loop of Higgs decay into a pair of photon may appreciably affect the corresponding branching ratio [16–20]; it would be of particular interest if we were at the early stage of LHC, which hinted a sizable di-photon excess.

Most of the previous works on $H^{\pm\pm}$ searches concentrate on the heavy mass region, while in this article we will focus on the complementary region, the light mass region, i.e. lighter than $2m_W$ but above $m_W$. Extensive attentions are paid on the decay modes of $H^{\pm\pm}$ dominated by either the SSDL [21–23] or di-$W$ [24–27], or the cascade decay among scalar fields [28–35]. For a comprehensive discussion on the relative importance of the decay channels of $H^{\pm\pm}$, see Ref. [36].

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$^1$ $H^{\pm\pm}$ can also be arranged in a singlet [40,41], doublet [42] $SU(2)_L$ and even higher dimensional [43–52] representations. Some of them may produce similar signatures studied in this paper.
LHC searches for the $CP$-odd Higgs boson with a jet substructure analysis

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The LHC searches for the $CP$-odd Higgs boson $A$ are studied (with masses from 300 GeV to 1 TeV) in the context of the general two-Higgs-doublet model. With the discovery of the 125 GeV Higgs boson at the LHC, we highlight one promising discovery channel of $A \rightarrow hZ$. This channel can become significant for a heavy $CP$-odd Higgs boson after the global signal fitting to the 125 GeV Higgs boson in the general two-Higgs-doublet model. It is particularly interesting in the scenario where two $CP$-even Higgs bosons in the two-Higgs-doublet model have the common mass of 125 GeV. Since the final states involve a standard-model-like Higgs boson, we apply the jet substructure analysis of tagging the fat Higgs jet in order to eliminate the standard-model background sufficiently. After performing the kinematic cuts, we present the LHC search sensitivities for the $CP$-odd Higgs boson with mass up to 1 TeV via this channel.

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1. INTRODUCTION

The study of the Higgs mechanism [1–3] has become more interesting and important since the discovery of the 125 GeV Higgs boson at the LHC 7 TeV runs. The properties of the 125 GeV Higgs boson, such as the coupling strengths with standard-model (SM) fermions and gauge bosons [4], its spin and parity [5], and the exotic decay channels [6], will be further measured in the next LHC runs and the future high-energy colliders. From various motivations, the SM Higgs mechanism is far from being complete. New physics models beyond the SM are proposed to address different questions, which typically contain new states in the spectrum. In many of them, the electroweak symmetry breaking is due to the extended Higgs sector. Examples include the minimal supersymmetric extension of the SM [7], the twin Higgs models [8], and the composite Higgs models [9]. The future experimental searches for the new degrees of freedom in the spectra provide direct avenues for revealing the new physics underneath.

A very widely studied scenario beyond the minimal one-doublet setup is the two-Higgs-doublet model (2HDM), which is the low-energy description of the scalar sectors in many new physics models. A recent review of the phenomenology in the context of the general 2HDM can be found in Ref. [10]. References [11–27] studied the 2HDM phenomenology at the LHC in light of the Higgs discovery. The scalar spectrum in the 2HDM contains five states, namely, two neutral $CP$-even Higgs bosons ($h, H$), one neutral $CP$-odd Higgs boson $A$, and two charged Higgs bosons $H^\pm$. Often, one would interpret the lighter $CP$-even Higgs boson $h$ as the one discovered at the LHC. In the context of the general 2HDM, each Higgs boson mass is actually a free parameter before applying any constraint. A special parameter set in the general 2HDM is when two $CP$-even Higgs bosons ($h, H$) are degenerate in mass. The diphoton signal predictions with this special parameter choice in the 2HDM scenario were studied in Ref. [14].

Within the framework of the 2HDM, we study the future LHC searches for the $CP$-odd Higgs boson $A$ at the 14 TeV run. The previous experimental searches often focus on the benchmark models in the minimal supersymmetric standard model, which has type-II 2HDM Yukawa couplings. Thus, the interesting final states to be looked for are the $A \rightarrow b\bar{b}$ [28,29] and $A \rightarrow \tau^+\tau^-$ [30–36] since the relevant Yukawa couplings are likely to be significantly enhanced. Different from the existing experimental search modes, we focus on the decay channel of $A \rightarrow hZ$. The previous studies to this search channel at the LHC include Refs. [13,15,19], where the final states of $b\bar{b}\ell^+\ell^-$, $\tau^+\tau^-\ell^+\ell^-$, and $ZZZ$ were studied. Also, an experimental analysis of this search channel with multiple lepton and photon final states was carried out at the LHC 8 TeV run [37]. Here, in our analysis, we will focus on the $b\bar{b}\ell^+\ell^-$ final state coming from the decay channel of $A \rightarrow hZ$. In this case, the final states involve a SM-like Higgs boson...
Testing the littlest Higgs model with T-parity at the LHC Run-II

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We study the littlest Higgs model with T-parity (LHT) in the process of $pp \rightarrow W_H^- W_H^+ \rightarrow W^+ W^- A_H A_H$ at the 14 TeV LHC. With the W-jet tagging technique, we demonstrate that the bulk of the model parameter space can be probed at the level of more than $5\sigma$ in the signature of two fat W jets plus large missing energy. Furthermore, we propose a novel strategy of measuring the principle parameter $f$ that is crucial to test the LHT model and to fix mass spectrum, including the dark matter particle. Our proposal can be easily incorporated into the current experimental program of diboson searches at the LHC Run-II.

I. MOTIVATION

The mystery of why the mass of the Higgs boson is at the weak scale has remained after the Higgs discovery at the Large Hadron Collider (LHC). One possibility is given in the framework of little Higgs models in which the Higgs boson emerges as a pseudo-Nambu-Goldstone boson in the mechanism of collective symmetry breaking [1,2]. The original construction of the little Higgs model suffers severely from electroweak precision tests that demand the collective symmetry breaking scale $f (= \Lambda / 4\pi)$ to be large [3]. Therefore, the model reintroduces the fine-tuning and has little relevance to the current high energy collider physics program. The stringent constraints can be naturally released when a discrete symmetry, called T-parity, is imposed [4–6]. All the corrections to electroweak observables are loop induced. The value of $f$, then, can be as low as 500 GeV [7], and the masses of new heavy resonances are below TeV.

In this article we consider the littlest Higgs model with T-parity (LHT), which is based on an $SU(5)/SO(5)$ nonlinear sigma model whose low energy Lagrangian is described in detail in Ref. [8–10]. In the model under the T-parity transformation the standard model (SM) particles are neutral while all the new particles are odd, except a top-quark partner that cancels out the SM top quark’s contribution to the quadratic divergence in radiative corrections of mass parameter of the Higgs boson. The characteristics of the LHT are the dependence of few free parameters and the tight mass relation between heavy gauge bosons. For example, after the electroweak symmetry breaking, the masses of the T-parity partners of the photon ($A_H$) and W-boson ($W_H$) are generated as

$$M_{A_H} = \frac{g f}{\sqrt{5}} \left(1 - \frac{5v^2}{8f^2}\right), \quad M_{W_H} = g' f \left(1 - \frac{v^2}{8f^2}\right) \quad (1)$$

where $v$ is the vacuum expectation value, and $g$ and $g'$ are the gauge couplings of $SU(2)_L$ and $U(1)_Y$, respectively. Because of the smallness of the $U(1)_Y$ gauge coupling constant $g'$, the T-parity partner of the photon $A_H$ tends to be the lightest T-odd particle in the LHT, which serves the dark matter (DM) candidate [11]. Given the $SU(2)_L$ gauge coupling constant $g$ and the vacuum expectation value $v$ ($\approx 246$ GeV) being measured in SM electroweak processes, the measurement of $M_{W_H}$ could determine the value of $f$, the most important parameter of the LHT model. That in turn determines $M_{A_H}$ (the DM mass), which is crucial for other experiments of dark matter searches, e.g., direct and indirect searches for dark matter. We demonstrate that the scale $f$ can be determined through the production of the charged heavy gauge boson pair ($W_H^+ W_H^-$) at the LHC.

The $W_H$ boson almost entirely decays into a pair of $W$ and $A_H$ bosons in the LHT model [12]. Therefore, the collider signature of the $W_H^+ W_H^-$ production is controlled by decay products of the $W$ bosons from the $W_H$ decays. Both the leptonic and hadronic decay of the $W$ bosons in the $W_H^+ W_H^-$ production have been studied in Refs. [12,13], which pointed out that, owing to invisible DM particles in the final state, the event reconstruction is difficult. For example, one immediately confronts two difficulties that preclude the event reconstruction in the hadronic mode: (i) unknown DM mass and undetectable (DM momentum; and (ii) the $W$ boson being highly boosted such that its decay product tends to be highly collimated and hard to

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LHC searches for heavy neutral Higgs bosons with a top jet substructure analysis

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We study the LHC searches for the heavy $CP$-odd Higgs boson $A$ and $CP$-even Higgs boson $H$ in the context of a general two-Higgs-doublet model. Specifically, we consider the decay mode of $A/H \to \bar{t}t$ through the $\bar{t}$ associated production channels. In the so-called “alignment limit” of the two-Higgs-doublet model, this decay mode can be the most dominant one. By employing the HEPTopTagger and the multivariate analysis method, we present the search sensitivities for both $CP$-odd Higgs boson $A$ and $CP$-even Higgs boson $H$ via this channel with multiple top quarks at the high-luminosity LHC runs.

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I. INTRODUCTION

The discovery of the 125 GeV Higgs boson at the LHC 7+8 TeV runs manifests the Higgs mechanism [1–4] and its role playing in the electroweak symmetry breaking (EWSB). In many of new physics models beyond the SM (BSM), the Higgs sector is extended with several scalar multiplets. Examples include the minimal supersymmetric extension of the SM (MSSM) [5], the left-right symmetric models [6], and the composite Higgs models [7]. There are several Higgs bosons in these models, where at least one of them is identified as the 125 GeV Higgs boson discovered at LHC. Therefore, those extra heavy Higgs bosons are yet to be searched for by the LHC experiments running at $\sqrt{s} = (13$ TeV, 14 TeV) and the future high-energy $pp$ colliders running at $\sqrt{s} = 50–100$ TeV [8,9].

The two-Higgs-doublet model (2HDM) was motivated to provide extra $CP$-violation sources in the scalar sector [10]. Such a setup is also required by the MSSM due to the cancellation of gauge anomaly. To search for the second Higgs doublet, it is important to find the most dominant final states that are consistent with the LHC discovery and measurements of the 125 GeV Higgs boson. The global fits to the $CP$-conserving 2HDM parameter space were previously carried out by several groups [11–14], all of which pointed to the so-called “alignment limit”, i.e., $c_{β−α} → 0$. In these fits, one always assumes the light $CP$-even Higgs boson $h$ in 2HDM being the 125 GeV SM-like Higgs boson discovered by LHC. Another 2HDM parameter to control the size of Higgs boson couplings is the ratio of two Higgs vacuum expectation values (VEVs) $t_β$, with the definition given in Eq. (4). Obviously, it is important to focus on the parameter space that is allowed by the current global fits for the future hunting of the other heavy Higgs bosons in 2HDM. There have been considerable works on the LHC searches for the heavy Higgs bosons in 2HDM through different exotic decay modes, including $A \to hZ/HZ$ [15–18], $H \to hh$ [12,19–23], $A/H \to W^±H^±$ [24], $H \to H^+H^−$ [24], and $H^± \to AW^±/HW^±$ [25]. The current experimental searches at the LHC 8 TeV runs include $A \to hZ$ [26–28] and $H \to hh$ [26,29,30]. Some of the decay modes, such as $A \to hZ$ and $H \to hh$, are due to couplings that are proportional to the alignment parameter $c_{β−α}$. In the exact alignment limit of $c_{β−α} = 0$, these decay modes will be vanishing and are of minor interest for the next-step experimental searches. Other decay modes, such as $A \to HZ$ and $H \to H^+H^−$, which involve another undiscovered heavy scalar in the final states, are usually suppressed by the small phase space. The conventional experimental searches for the heavy Higgs bosons were motivated by the MSSM scenario where the Higgs sector is define by the 2HDM-II setup. For the large-$t_β$ inputs, the heavy Higgs boson couplings with the charged leptons and the down-type quarks are enhanced. Correspondingly, the important experimental search modes are $A/H \to (b\bar{b}, τ^±τ^−)$ [31–39] and $H^± \to (t\bar{b}, τ^±ν)$ [40,41], which mostly exclude the heavy Higgs bosons from the large-$t_β$ parameter space. On the other hand, the final states of $\bar{t}t$ from the heavy neutral Higgs boson decays can be quite important with the low- and intermediate-$t_β$ inputs. The searches for the $\bar{t}t$ final states from the heavy Higgs boson decays are thought to be very challenging, where one has to deal with the large SM background of $pp \to \bar{t}t$. For the
Higgs boson mass and complex sneutrino dark matter in the supersymmetric inverse seesaw models

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Abstract: The discovery of a relatively heavy Standard Model (SM)-like Higgs boson challenges naturalness of the minimal supersymmetric standard model (MSSM) from both Higgs and dark matter (DM) sectors. We study these two aspects in the MSSM extended by the low-scale inverse seesaw mechanism. Firstly, it admits a sizable radiative contribution to the Higgs boson mass $m_h$, up to $\sim 4$ GeV in the case of an IR-fixed point of the coupling $Y_{\nu}LH_u\nu_c$ and a large sneutrino mixing. Secondly, the lightest sneutrino, highly complex as expected, is a viable thermal DM candidate. Owing to the correct DM relic density and the XENON100 experimental constraints, two scenarios survive: a Higgs-portal complex DM with mass lying around the Higgs pole or above $W$ threshold, and a coannihilating DM with slim prospect of detection. Given an extra family of sneutrinos, both scenarios naturally work when we attempt to suppress the DM left-handed sneutrino component, confronting with enhancing $m_h$.

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Diphoton excess, low energy theorem, and the 331 model

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We interpret the diphoton anomaly as a heavy scalar $H_3$ in the so-called 331 model. The scalar is responsible for breaking the $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ gauge symmetry down to the standard model electroweak gauge group. It mainly couples to the standard model gluons and photons through quantum loops involving heavy quarks and leptons. Those quarks and leptons, together with the SM quarks and leptons, form the fundamental representation of the 331 model. We use the low energy theorem to calculate the effective couplings of $H_3 \gamma \gamma, H_3 \gamma \gamma$, $H_3 ZZ, H_3 WW$ and $H_3 Z\gamma$. The analytical results can be applied to new physics models satisfying the low energy theorem. We show that the heavy quark and lepton contribution cannot produce enough diphoton pairs. It is crucial to include the contribution of charged scalars to explain the diphoton excess. The extra neutral $Z'$ boson could also explain the 2 TeV diboson excess observed at the LHC Run-I.

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I. INTRODUCTION

A diphoton resonance around 750 GeV was reported by the ATLAS and CMS Collaborations [1,2] based on 3.2 and 2.6 fb$^{-1}$ of data collected at the 13 TeV LHC. ATLAS observed a local significance of 3.9σ corresponding to a cross section of about 10 ± 3 fb, while CMS found 2.6σ with a smaller cross section of 6 ± 3 fb, and the large excess around 750 GeV is still confirmed by a recent study from ATLAS and CMS [3,4]. The resonance is likely to be a new scalar in the new physics (NP) model beyond the standard model (SM) of particle physics. It has drawn a lot of interest in the field [5–96]. Also, an excess of diboson events around 2 TeV was reported in the LHC Run-I data [97–99]. That has been explained in terms of extra gauge bosons such as additional $Z'$ or $W'$ bosons in several NP models with extended gauge structures. New physics models that can explain both anomalies need to have two new ingredients: extra heavy scalars and gauge bosons. The simplest case is that the 750 GeV resonance is a new weak singlet scalar that couples to photon pairs through a vectorlike quark loop. Many papers add the singlet scalar and vectorlike fermions by hand, while in the so-called 331 model with the $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ gauge group [100,101] these additional particles naturally exist. There are many versions of the 331 model [102–110] which in general share nice features as follows: (i) the anomaly cancellation and the QCD asymptotic freedom require three generation fermions; (ii) the Peccei-Quinn symmetry [111,112] which can solve the strong $CP$ problem is a natural result of gauge invariance in the 331 model [102,103], etc. References [70,72] studied the diphoton excess in the framework of the 331 gauge symmetry in a specific version of the 331 model while in our paper we consider four possible versions of this model. Also, the trinification model of $SU(3)_C \otimes SU(3)_L \otimes SU(3)_C$, which contains the 331 model as subgroup, has been considered recently in Ref. [74] to address the diphoton anomaly.

The 331 model consists of very rich particle spectra. For instance, there will be five new gauge bosons, three new heavy quarks, three new leptons, and six new scalars. That has very rich collider phenomenology at the LHC. There are many versions of the 331 model which can be characterized by a parameter called $\beta$. Models with different $\beta$ have new particles with different electric charges. The 331 model has been studied in detail by Buras et al. in Ref. [113]. In this work we follow the notation in Ref. [113] and consider different versions of the 331 model with $\beta = \pm \sqrt{3}$ and $\pm 1/\sqrt{3}$ to explain the 750 GeV diphoton and 2 TeV diboson excesses.

The paper is organized as follows. In Sec. II, we briefly review the 331 model and introduce the main ingredients of the 331 model needed to explain the diphoton and diboson excesses at the LHC. In Sec. III we explain how the 331 model could explain the diphoton and diboson signal. Finally, we conclude in Sec. IV.

II. THE MODEL

In the 331 model considered in this work, the right-handed fermion fields are treated as singlets of the $SU(3)_L$...
We propose a novel method for probing sleptons in compressed spectra at hadron colliders. The process under study is slepton pair production in $R$-parity conserving supersymmetry, where the slepton decays to a neutralino lightest supersymmetric particle of mass close to the slepton mass. In order to pass the trigger and obtain large missing energy, an energetic monojet is required. Both leptons need to be detected in order to suppress large standard model backgrounds with one charged lepton. We study variables that can be used to distinguish the signal from the remaining major backgrounds, which include $t\bar{t}$, $WW + \text{jet}$, $Z + \text{jet}$, and single top production. We find that the dilepton $m_{T2}$, bound by the mass difference, can be used as an upper bound to efficiently reduce the backgrounds. It is estimated that sleptons with masses up to about 150 GeV can be discovered at the 14 TeV LHC with 100 fb$^{-1}$ integrated luminosity.

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I. INTRODUCTION

Low energy supersymmetry (SUSY) is an attractive theory of physics beyond the standard model (SM). In order to avoid fine-tuning to the Higgs mass, super partners of the SM particles are predicted to be around or below the TeV scale, which is often dubbed “natural supersymmetry”—see Ref. [1] and references therein. However, SUSY searches at the large hadron collider (LHC) have not revealed any signal beyond the standard model, which have put stringent constraints on the SUSY mass spectrum. To reconcile the null results with supersymmetry, one either (partially) gives up naturalness and accepts that the super particles’ masses are beyond the current reach of the 8 TeV LHC (which could, however, be discovered at 14 TeV or a future collider), or assumes SUSY particles are light and accessible, but the signal is hidden in the SM backgrounds. In order not to miss the SUSY signals, both the two possibilities should be explored. One way to hide light SUSY particles is to make the spectrum compressed, that is, the mass splittings among the SUSY particles are so small that the decay products of the SUSY cascades are soft. The signal events that contain such soft particles, including jets, leptons, or photons, are difficult to trigger on, and even if recorded, they are usually buried in SM backgrounds. Special search strategies are required to find the signal events and previous studies include those on a light stop [2–5], a light sbottom [6], gluinos [7], and light electroweakinos [8–14]. In this article, we focus on another important SUSY process, slepton pair production.

We assume the lightest supersymmetric particle (LSP) is a neutralino with mass around 100 GeV. A light slepton with mass close to the LSP mass is not required by naturalness because its loop contribution to the Higgs mass is small. Nevertheless a $5 \sim 20$ GeV mass splitting, which we assume in this article, is certainly possible without “fine-tuning” model parameters. Moreover, such a small splitting is needed to obtain the correct relic density in the co-annihilation scenario [15]. When sleptons are pair produced and each of which decays to a neutralino, we have two soft leptons and missing energy in a signal event. The major SM backgrounds include $t\bar{t}$, $WW + \text{jet}$, $Z(\rightarrow \tau\tau) + \text{jet}$ and single top production. In order to pass the trigger, we require an extra hard jet and large missing energy to be present in the event. This is also the final state particles considered in Refs. [12,14], where the discovery potential of the LHC for quasidegenerate Higgsinos is explored. A crucial observation in the analysis which makes the discovery possible is the fact that the majority of the lepton pairs are produced through off-shell $Z$'s in $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 l\bar{l}$ decays, and the dilepton invariant mass $m_{ll}$ is bound from above by the $\tilde{\chi}_2^0 - \tilde{\chi}_1^0$ mass difference. Therefore, we can apply an upper cut on $m_{ll}$ to eliminate bulk of the background events, while retaining most of the signal events. This feature is unfortunately absent for slepton pair production because the two leptons necessarily come from two different decay chains. For a typical 10 GeV lepton $p_T$ acceptance cut, the dilepton invariant mass spreads from $\sim 10$ GeV to $\sim 80$ GeV, which significantly overlaps with the SM backgrounds. Clearly, a different strategy is needed.

In this article, we propose a novel method for searching slepton pairs in a compressed spectrum. In order to exploit the small mass splitting, we consider the $m_{T2}$ variable defined from the two leptons and the missing transverse momentum. This variable, to a good approximation, is bound by the mass difference between the slepton and the
Probing Higgs width and top quark Yukawa coupling from $t\bar{t}H$ and $t\bar{t}t$ productions

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We demonstrate that four top-quark production is a powerful tool to constrain the top Yukawa coupling. The constraint is robust in the sense that it does not rely on the Higgs boson decay. Taking into account the narrow width approximation, the production cross section of $pp \rightarrow t\bar{t}H \rightarrow t\bar{t}xx$ is

$$
\sigma(pp \rightarrow t\bar{t}H \rightarrow t\bar{t}xx) = \sigma^{SM}(pp \rightarrow t\bar{t}H \rightarrow t\bar{t}xx) \times \frac{\kappa_t^2 \kappa_x^2 \Gamma^{SM}_H}{\Gamma_H}
$$

where $\kappa_t \equiv y_{Ht}/y_{Ht}^{SM}$ and $\kappa_x \equiv y_{Hxx}/y_{Hxx}^{SM}$ are the scaling factors of the Higgs couplings. The signal strength $\mu_{t\bar{t}H}^{xx}$, defined as

$$
\mu_{t\bar{t}H}^{xx} \equiv \frac{\sigma}{\sigma^{SM}} = \frac{\kappa_t^2 \kappa_x^2}{R'} \quad \text{with} \quad R' = \frac{\Gamma_H}{\Gamma_H^{SM}}
$$

is expected to be measured with uncertainties [4]

$$
\mu_{t\bar{t}H}^{7\gamma} = 1.00 \pm 0.38, \quad \mu_{t\bar{t}H}^{ZZ} = 1.00 \pm 0.49, \quad \mu_{t\bar{t}H}^{\mu\mu} = 1.00 \pm 0.74, \quad \mu_{t\bar{t}H}^{\text{comb}} = 1.00 \pm 0.32,
$$

at the 14 TeV LHC with $\mathcal{L} = 300$ fb$^{-1}$. Here $\mu_{t\bar{t}H}^{\text{comb}}$ refers to the result of combining multiple Higgs decay modes. The $\kappa_t$, $\kappa_x$, and $\Gamma_H$ parameters in $\mu_{t\bar{t}H}^{xx}$ are independent; therefore, one cannot determine them from the $t\bar{t}H$ production alone. Bounds on the $\kappa_x$, $\kappa_x$, and $R'$ could be derived from a global analysis of various Higgs boson productions and decays [4]. Nevertheless, it is still valuable to consider one specific channel to directly bound on the three parameters. Luckily, there is a large hierarchy among branching ratios of the Higgs decay modes. That ensures that we consider two special cases:

(i) $\Gamma_H = \Gamma_H^{SM}$: it is a good approximation for the $H \rightarrow \mu^+\mu^-$ and $H \rightarrow \gamma\gamma$ modes, because modifications on those rare decays would not dramatically affect the total width. Thus, one can determine the bound on the product of $\kappa_t$ and $\kappa_x$ as

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