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Abstract

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Full Text

Preamble

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Higgs decay to dark matter in low energy SUSY: is it detectable at the LHC?

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Abstract

Due to the limited statistics so far accumulated in the Higgs boson search at the LHC, the Higgs boson property has not yet been tightly constrained and it is still allowed for the Higgs boson to decay invisibly to dark matter with a sizable branching ratio. In this work, we perform a comparative study for the Higgs decay to neutralino dark matter by considering three different low energy SUSY models: the minimal supersymmetric standard model (MSSM), the next-to-minimal supersymmetric standard model (NMSSM) and the nearly minimal supersymmetric standard model (nMSSM). Under current experimental constraints at 2 level (including the muon $g - 2$ and the dark matter relic density), we scan over the parameter space of each model. Then in the allowed parameter space we calculate the branching ratio of the SM-like Higgs decay to

neutralino dark matter and examine its observability at the LHC by considering three production channels: the weak boson fusion $VV \rightarrow h$, the associated production with a Z-boson $pp \rightarrow hZ + X$ or a pair of top quarks $pp \rightarrow ht\bar{t} + X$. We find that in the MSSM such a decay is far below the detectable level; while in both the NMSSM and nMSSM the decay branching ratio can be large enough to be observable at the LHC. We conclude that at the LHC the interplay of detecting such an invisible decay and the visible di-photon decay may allow for a discrimination of different SUSY models.

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INTRODUCTION

As a cornerstone of the Standard Model (SM) and also the last undiscovered piece, the Higgs boson has been intensively searched in collider experiments. The foregone colliders LEP II and Tevatron yielded null search results, setting a lower bound of 114.4 GeV on the Higgs mass [1] and excluding a Higgs boson with a mass around 2MW [2], respectively. The ongoing Large Hadron Collider (LHC) took over the Higgs-hunting task and recently reported its search results. Based on an integrated luminosity of 4.9 fb^{-1} collected at $\sqrt{s} = 7 \text{ TeV}$, the two experimental groups at the LHC independently further narrowed down the Higgs mass region (at 95% C.L. the CMS collaboration excluded 127–600 GeV while the ATLAS collaboration excluded 112.7–115.5 GeV, 131–238 GeV and 251–466 GeV) and both hinted to a Higgs boson around 125 GeV [3]. Such a finding has stimulated some theoretical studies for a Higgs boson near 125 GeV in low energy supersymmetry [4] and other models [5].

Of course, if the LHC hint of a 125 GeV Higgs from the di-photon channel is confirmed in the future, it would severely constrain or exclude those new physics models in which some new exotic decay modes are open and suppress the di-photon signal rate. But so far the statistics at the LHC is too small to constrain the Higgs boson property, let alone the precision measurement of the Higgs decay branching ratios. Therefore, it is still allowed for the Higgs boson to decay exotically, such as invisibly to dark matter, with a sizable branching ratio. Theoretically, the Higgs decay to dark matter can indeed occur in some new physics models, such as the gauge singlet extensions of the SM [7], the SM with a heavy fourth generation [8], the large extra dimension model [9], the technicolor model [10], the little Higgs models [11] and the non-linearly realized supersymmetric model [12] and the MSSM with a singlet [13]. In this work, we will perform a comparative study for the Higgs decay to neutralino dark matter by considering three different low energy SUSY models: the minimal supersymmetric standard model (MSSM) [14–16], the next-to-minimal supersymmetric standard model (NMSSM) [17, 18] and the nearly minimal supersymmetric standard model (nMSSM) [19–21]. As will be shown, in both the NMSSM and nMSSM, the SM-like Higgs boson can decay to neutralino dark matter with a sizable branching ratio. In case that the Higgs boson decays to dark matter with a sizable branching ratio, detecting such a decay at the LHC will be important

because in this case the conventional visible decays into $\gamma\gamma$, $b\bar{b}$, W^+W^- and ZZ are often suppressed. Obviously, the main production channel via gluon fusion $gg \rightarrow h$ is not usable because it just gives missing energy. It was found through Monte Carlo simulations that the production via vector boson fusion (VBF) $pp \rightarrow hqq$ and the associated productions $pp \rightarrow hZ$ and $pp \rightarrow ht\bar{t}$ can offer the opportunity to detect the Higgs decay to dark matter [22-24]. So in this work we choose these three production channels to display the observability of Higgs decay to dark matter in low energy SUSY.

Note that although the Higgs decay to neutralino dark matter has been discussed in some specific SUSY models, it is necessary to give a comparative study in different SUSY models. In [6] the authors used the limited LHC statistics of the di-photon signal rates to set constraints on the invisible Higgs decay in the MSSM and found that the invisible Higgs decay branching ratio around 10% is allowed. In this work, we want to know in the SUSY parameter space allowed by current experiments whether the Higgs decay to neutralino dark matter is detectable at the LHC. This is necessary for two reasons: (i) Different SUSY models usually give rather different phenomenology and it is interesting to perform a comparative study; (ii) We want to know in the SUSY parameter space allowed by current experiments whether the Higgs decay to neutralino dark matter is detectable at the LHC. If in some model this decay is found to be accessible at the LHC, we further want to know how large the parameter space can be covered by searching for such an invisible decay at the LHC. This work is organized as follows. In Sec. II, we briefly describe the three SUSY models. In Sec. III, through a scan over the parameter space we present the branching ratio of Higgs decay to neutralino dark matter and show the observability at the LHC. Finally, the conclusion is given in Sec. IV.

II. THE SUSY MODELS

In a renormalizable supersymmetric theory, the interactions and masses of all particles are determined by their gauge transformation properties and the superpotential. The superpotential is a holomorphic function of chiral superfields $\hat{\Phi} = (\phi, \psi, F)$, with ϕ , ψ and F being respectively the bosonic, fermionic and auxiliary fields, and takes a form [15]

$$W = L_i \hat{\Phi}_i + \frac{1}{2} M_{ij} \hat{\Phi}_i \hat{\Phi}_j + \frac{1}{6} y_{ijk} \hat{\Phi}_i \hat{\Phi}_j \hat{\Phi}_k$$

where the parameters L should be of dimension $[\text{mass}]^2$ and is only allowed if $\hat{\Phi}$ is a gauge singlet. The mass matrix M can only be non-zero when the supermultiplets $\hat{\Phi}$ and $\hat{\Phi}$ are conjugates of each other under gauge transformation. And the dimensionless coefficients y can only be non-zero when $\hat{\Phi} \hat{\Phi} \hat{\Phi}$ forms a gauge singlet.

The MSSM is the most economical realization of supersymmetry in particle physics, which has two Higgs doublets \hat{H} and \hat{H} and its superpotential is given

by [15]

$$W_{MSSM} = W_F + \mu \hat{H}_u \cdot \hat{H}_d$$

with W_F given by

$$W_F = u Y_u \hat{Q} \cdot \tilde{H}_u - d Y_d \hat{Q} \cdot \hat{H}_d - e Y_e \hat{L} \cdot \hat{H}_d$$

The MSSM has the so-called μ -problem. The NMSSM extends the MSSM by adding a gauge singlet superfield \hat{S} , and its superpotential is [17]

$$W_{NMSSM} = W_F + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3$$

The nMSSM is a variant of the NMSSM with the cubic term \hat{S}^3 replaced by a tadpole term [19]

$$W_{nMSSM} = W_F + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \xi_F \hat{S}$$

In the NMSSM and nMSSM, the μ -term is dynamically generated through the VEV of \hat{S} , i.e., $\mu = \lambda \langle \hat{S} \rangle$.

After electroweak symmetry breaking, the neutral CP-even Higgs bosons mix and form the mass eigenstates. In the MSSM, there are two CP-even Higgs bosons h and H (with $m_h < m_H$). In the NMSSM and nMSSM, there are three CP-even Higgs bosons h , h_1 and h_2 (with $m_h < m_{h_1} < m_{h_2}$). The neutral CP-odd Higgs bosons are one in the MSSM (A) and two in the NMSSM/nMSSM (a , a_1 with $m_a < m_{a_1}$). The charged Higgs bosons are H^\pm and H^\pm in all three models.

The neutralinos are the mixtures of bino (B), wino (W), higgsinos (H_1, H_2) and singlino (S). In the basis $\tilde{\chi}^0 = (B, W, H_1, H_2, S)$, the neutralino mass matrix is

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_u}{\sqrt{2}} & \frac{g_1 v_d}{\sqrt{2}} & 0 \\ 0 & M_2 & \frac{g_2 v_u}{\sqrt{2}} & -\frac{g_2 v_d}{\sqrt{2}} & 0 \\ -\frac{g_1 v_u}{\sqrt{2}} & \frac{g_2 v_u}{\sqrt{2}} & 0 & -\mu & -\lambda v_d \\ \frac{g_1 v_d}{\sqrt{2}} & -\frac{g_2 v_d}{\sqrt{2}} & -\mu & 0 & -\lambda v_u \\ 0 & 0 & -\lambda v_d & -\lambda v_u & 2\kappa S \end{pmatrix}$$

for the NMSSM. For the nMSSM, the matrix is obtained by setting $\kappa = 0$ and adding a tadpole term. For the MSSM, the matrix is the upper-left 4×4 submatrix with κ being a free parameter.

The lightest neutralino ($\tilde{\chi}^0$) is assumed to be the lightest supersymmetric particle (LSP) and makes up the cosmic dark matter. The interactions of the Higgs

bosons with b^-b , γ , WW and $\tilde{\chi}^0\tilde{\chi}^0$ are needed for our analysis. In the NMSSM, they are given by [28]

$$\begin{aligned} \mathcal{L}_{int} = & \frac{gm_b}{2m_W \cos \beta} S_{i1} \bar{b}_L b_R h_i + \frac{gm_\tau}{2m_W \cos \beta} S_{i1} \bar{\tau}_L \tau_R h_i \\ & + \frac{g^2}{4} W_\mu^+ W^{-\mu} (h_u S_{i1} + h_d S_{i2}) h_i \\ & + \frac{1}{2} \kappa S_{i3} N_{15} N_{15} + \lambda (S_{i1} \Pi_{45} + S_{i2} \Pi_{35}) + S_{i3} \Pi_{34} \end{aligned}$$

where $\Pi = N N + N N$. The couplings in the nMSSM can be obtained by setting $\mu = 0$, κ , S and N to zero.

III. NUMERICAL RESULTS AND DISCUSSIONS

We scan over the parameter space of each model under current experimental constraints at 2 level (including the muon $g - 2$ and the dark matter relic density), and for each survived sample we calculate the Higgs spectrum, decay branching ratios and production rates at the LHC. In our calculation we use the package NMSSMTools [28] and extend it to the nMSSM. For the calculation of $h \rightarrow \gamma\gamma$ in the SM, we use the package Hdecay [29]. For the Higgs production cross sections, we use the code on the website [30]. For parton distributions we use CTEQ6L [31] with the renormalization and factorization scales chosen to be the sum of the masses of the produced particles.

In order to reduce the number of free parameters, we assume the following relations: - Gaugino mass unification: $3M_1/5 = M_2 = M_3$ - For moderate $\tan \beta$ (< 50), we assume the soft-breaking parameters in the squark and slepton sectors to be 100 GeV for the smuon sector and 1 TeV for the others - For the MSSM we allow the third-generation squark mass parameters to vary in a wide range

The experimental constraints we consider include: 1. LEP bounds on sparticle masses and on the Higgs sector from $e e \rightarrow hZ$ ($hA \rightarrow b^-b$ and $\gamma\gamma$) [33] 2. LEP-II constraints on neutralino production ($e e \rightarrow \tilde{\chi}^0\tilde{\chi}^0$) $< 10^{-1}$ pb ($i, j > 1$) [33] 3. Tevatron bounds on sparticle masses and on stop/sbottom pair production [34, 35] 4. Recent LHC bounds on the Higgs sector from $\gamma\gamma$, $\gamma\gamma$, WW and ZZ signal rates [36, 37] 5. B-physics constraints like $b \rightarrow s$ and $B \rightarrow \mu\mu$ [38] 6. Electroweak precision observables [39]

The parameter ranges we scan are:

For the MSSM: - $1 < \tan \beta < 50$ - $100 \text{ GeV} < \mu < 500 \text{ GeV}$ - $100 \text{ GeV} < M_A < 200 \text{ GeV}$ - $500 \text{ GeV} < M_{A'} < 3 \text{ TeV}$ - $100 \text{ GeV} < M_{\tilde{q}} < 2 \text{ TeV}$ - $-3 \text{ TeV} < A_{t,b} < 3 \text{ TeV}$

For the NMSSM: $-0.1 < \mu < 0.7 - 0.1 < \tan\beta < 0.5 - 1 < \tan\beta < 5 - 100 \text{ GeV} < (M_0, M_{A_1}) < 1 \text{ TeV} - 50 \text{ GeV} < M < 150 \text{ GeV} - 0 < A_0 < 1 \text{ TeV} - -500 \text{ GeV} < A_0 < 0$

For the mNSSM: $-0.1 < \mu < 0.7 - 1 < \tan\beta < 10 - 50 \text{ GeV} < (M_0, M_1, M_{A_1}) < 1 \text{ TeV} - 0 < A_0 < 1 \text{ TeV} - 0 < M_S < 500 \text{ GeV} - -1 < \mu_F < 1$

Note that our scan is not a general scan but focuses on the parameter space where the SM-like Higgs can decay to neutralino dark matter. Since our purpose is to figure out if such a decay is detectable at the LHC, we only scan over the parameter space that is potentially able to produce a sizable invisible branching ratio.

In Fig. 1 [Figure 1: see original paper] we show the scatter plots of the parameter space that survives all constraints. In the upper frames, the samples denoted by crosses (sky-blue) show the branching ratio of $h \rightarrow \tilde{\chi}^0 \tilde{\chi}^0$ while the samples denoted by circles (magenta) show the branching ratio of $h \rightarrow b\bar{b}$. The solid curves (blue) denote the SM prediction for the branching ratio of $h \rightarrow b\bar{b}$. In the lower frames, the samples denoted by times (red) show the ratio $\frac{\sigma_{\text{SUSY}}(\text{pp} \rightarrow h \rightarrow \tilde{\chi}^0 \tilde{\chi}^0)}{\sigma_{\text{SM}}(\text{pp} \rightarrow h \rightarrow b\bar{b})}$ at the LHC (7 TeV). In this figure and below, ‘ h_{SM} ’ denotes the Higgs boson in the SM, ‘ h ’ denotes the lightest neutral Higgs boson in the MSSM, and ‘ h ’ denotes the SM-like Higgs boson in the NMSSM and mNSSM (the doublet component of h is over 60%).

From Fig. 1 we have the following observations:

- In each model the SM-like Higgs boson can have a mass near 125 GeV, as hinted by the recent LHC results.
- In the MSSM the SM-like Higgs boson dominantly decays to $b\bar{b}$ (just like in the SM), and the decay $h \rightarrow \tilde{\chi}^0 \tilde{\chi}^0$ has a very small branching ratio (below about 10%), making it far below the detectable level. The di-photon signal rate is close to the SM prediction.
- In the NMSSM the decay $h \rightarrow \tilde{\chi}^0 \tilde{\chi}^0$ can have a sizable branching ratio (up to 80%). The di-photon signal rate can be either enhanced or suppressed compared to the SM, depending on the parameter space.
- In the mNSSM the decay $h \rightarrow \tilde{\chi}^0 \tilde{\chi}^0$ is dominant over $h \rightarrow b\bar{b}$ in a large part of the parameter space, making it observable at the LHC. The di-photon signal rate is suppressed.

In Fig. 2 [Figure 2: see original paper] we show the observability of the invisible Higgs decay at the LHC (7 TeV) through the three production channels. We plot the quantity $\sigma_{\text{SUSY}} \times \text{Br}(h \rightarrow \tilde{\chi}^0 \tilde{\chi}^0)$ normalized by the SM Higgs production rate σ_{SM} . The solid curves show the 2σ sensitivity [23-25] of the ATLAS detector at the LHC (7 TeV) with 10 fb^{-1} , 30 fb^{-1} and 100 fb^{-1} (the region above each curve is the observable region). From Fig. 2 we see that:

- For the MSSM, the invisible decay is far below the detectable level for all three production channels.
- For the NMSSM, the invisible decay is detectable in a sizable part of the

parameter space through the VBF and associated production channels with integrated luminosity of 30 fb^{-1} or more.

- For the nMSSM, the invisible decay is detectable in most of the parameter space even with 10 fb^{-1} of data, especially through the VBF channel.

IV. CONCLUSION

We examined the Higgs decay to neutralino dark matter in low energy SUSY by considering three different models: the MSSM, NMSSM and nMSSM. Under current experimental constraints at 2 level (including the muon $g - 2$ and the dark matter relic density), we scanned over the parameter space of each model and calculated the branching ratio of the SM-like Higgs decay to neutralino dark matter. We then examined its observability at the LHC by considering three production channels: the weak boson fusion $VV \rightarrow h$, the associated production with a Z-boson $pp \rightarrow hZ + X$ or a pair of top quarks $pp \rightarrow ht\bar{t} + X$.

Our findings are: 1. In the MSSM such a decay is far below the detectable level. 2. In the NMSSM the decay branching ratio can be large enough to be observable at the LHC in a sizable part of the parameter space. 3. In the nMSSM the decay branching ratio can be dominant and thus detectable in most of the parameter space.

We conclude that at the LHC the interplay of detecting such an invisible decay and the visible di-photon decay may allow for a discrimination of different SUSY models. If the invisible decay is observed, it will provide strong evidence for new physics beyond the SM, particularly for SUSY models with extended Higgs sectors like the NMSSM and nMSSM.

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