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Full Text

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Abstract

In light of the recent LHC Higgs search data, we investigate the pair production of a SM-like Higgs boson around 125 GeV in the MSSM and NMSSM. We first scan the parameter space of each model by considering various experimental constraints, and then calculate the Higgs pair production rate in the allowed parameter space. We find that in most cases the dominant contribution to the Higgs pair production comes from the gluon fusion process and the production rate can be greatly enhanced, maximally 10 times larger than the SM prediction (even for a TeV-scale stop the production rate can still be enhanced by a factor of 1.3). We also calculate the ^{2} value with the current Higgs data and find that in the most favored parameter region the production rate is enhanced by a factor of 1.45 in the MSSM, while in the NMSSM the production rate can be enhanced or suppressed (_SUSY/ _SM varies from 0.7 to 2.4).

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Introduction

Based on the combined data collected at center-of-mass energies of 7 TeV and 8 TeV, the experimental program to probe the mechanism of electroweak symmetry breaking at the LHC has recently witnessed the discovery of a new particle around 125 GeV [1]. The properties of this particle, according to the updated analyses of the ATLAS and CMS collaborations at the end of 2012 [2], roughly agree with the Standard Model (SM) prediction and thus it should play a role in both symmetry breaking and mass generation. However, the issue of whether this particle is the SM Higgs boson remains open, and indeed there are motivations, such as the gauge hierarchy problem and the excess in the diphoton channel over the SM prediction [1, 2], to consider new physics interpretations of this boson. Studies in this direction have been performed intensively in low-energy supersymmetry (SUSY), and it was found that some SUSY models can naturally provide a 125 GeV Higgs boson [3–5] and fit the data better than the SM [6] (similar studies have also been performed in non-SUSY models such as little Higgs models and two-Higgs-doublet or Higgs-triplet models [7]).

After the discovery of the Higgs boson, the next important task for the LHC is to test the properties of this Higgs boson by measuring all possible production and decay channels with high luminosity. Among the production channels, Higgs pair production is a rare process at the LHC. Since it can play an important role in testing the Higgs self-couplings [8, 9] (the determination of which is indispensable for reconstructing the Higgs potential), it will be measured at the LHC with high luminosity.

In the SM, Higgs pair production at the LHC proceeds through the parton process gg → hh via heavy quark-induced box diagrams and also through the production of an off-shell Higgs which subsequently splits into two on-shell Higgs bosons [10, 11]. The production rate is rather low for $\sqrt{s} = 14$ TeV, about 20 fb at leading order [10] and reaching roughly 35 fb after including next-to-leading order QCD corrections [8]. The capability of the LHC to detect this production process was investigated in [12–15]. These analyses showed that for a 125 GeV Higgs boson the most efficient channel is gg → hh → b¯b with 6 signal events over 14 background events expected for 600 fb^{1} integrated luminosity after considering b¯bW W and some elaborate cuts [12] (detection through other channels like hh → b¯b has also been studied recently [13, 14]). In principle, the capability can be further improved if the recently developed jet substructure technique [16] is applied for Higgs tagging.

Higgs pair production at the LHC may also serve as a sensitive probe for new physics. In supersymmetric models such as the Minimal Supersymmetric Standard Model (MSSM) [17], the pair production of the SM-like Higgs boson receives additional contributions from loops of third-generation squarks and also from the parton process b¯b → H_i → hh with H_i denoting a CP-even non-standard Higgs boson [18, 19]. It was found that in some cases (e.g., a light stop with a large trilinear soft-breaking parameter A_t and/or a large tan together with moderately light H_i), these new contributions may dominate over the SM contribution, and as a result, the pair production rate may be enhanced by several orders of magnitude [18, 19]. Note that since experimental constraints (direct or indirect) on the SUSY parameter space have become increasingly stringent, the previous MSSM results should be updated by considering the latest constraints. This is one aim of this work. Specifically, we will consider the following new constraints:

- The currently measured Higgs boson mass m_h = 125 GeV [2]. In SUSY this mass is sensitive to radiative corrections and thus the third-generation squark sector has been tightly constrained.
- The LHC search for third-generation squarks [20]. So far, although the relevant bounds are rather weak and usually hypothesis-dependent, it has become increasingly clear that a stop lighter than about 200 GeV is strongly disfavored.
- The observation of B_s → by LHCb [21]. In the MSSM it is well known that the branching ratio of B_s → is proportional to tan /m_A for a moderately light H [22]. Since the experimental value of B_s → coincides well with the SM prediction, tan as a function of m_H has been upper bounded.
- The LHC search for a non-standard Higgs boson H through the process pp → H → [23]. Such searches rely on the enhanced H¯bb coupling, and the null signal seen by the LHC experiments implies that a broad region in the tan -m_H plane has been ruled out.
- The global fit of SUSY predictions for various Higgs signals to the Higgs data reported by the ATLAS and CMS collaborations [24], the dark matter relic density [25], as well as the XENON2012 dark matter search results [26] can also constrain SUSY parameters in a complex way.

Another motivation for this work comes from the fact that the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [27] is found to be more favored by the Higgs data and fine-tuning arguments [6]. So far, studies on Higgs pair production in the NMSSM are still absent, so it is necessary to extend the study to the NMSSM.

This paper is organized as follows. In Sec. II we briefly introduce the features of the Higgs sector in the MSSM and NMSSM. Then in Sec. III we present our results for Higgs pair production in both models, along with some intuitive understanding of the results. Finally, we summarize our conclusions in Sec. IV.

II. Higgs Sector in MSSM and NMSSM

As the most economical realization of SUSY in particle physics, the MSSM [17] has been intensively studied. However, since this model suffers from problems such as the unnaturalness of the parameter, it is well motivated to go beyond this minimal framework. Among extensions of the MSSM, the NMSSM as the simplest extension by a singlet field [27] has received much attention. The differences between the two models arise from their superpotentials and soft-breaking terms, which are given by:

W_MSSM = Y_u Q̂ H_u Û + Y_d Q̂ H_d D̂ + Y_e L̂ H_d Ê + Ĥ_u · Ĥ_d

W_NMSSM = Y_u Q̂ H_u Û + Y_d Q̂ H_d D̂ + Y_e L̂ H_d Ê + Ŝ Ĥ_u · Ĥ_d + Ŝ³

V_MSSM = m̃_u²|H_u|² + m̃_d²|H_d|² + (B H_u · H_d + h.c.)

V_NMSSM = m̃_u²|H_u|² + m̃_d²|H_d|² + m̃_S²|S|² + (A_ S H_u · H_d + A_ S³ + h.c.)

Here Ĥ_i (i = u, d) and Ŝ denote gauge doublet and singlet Higgs superfields respectively, Q̂, Û, D̂, L̂ and Ê represent matter superfields with Y_i (i = u, d, e) being their Yukawa coupling coefficients, m̃_i (i = u, d, S), B, A_ , and A_ are all soft-breaking parameters, and the dimensionless parameters and reflect coupling strengths of Higgs self-interactions. Note that the -term in the MSSM is replaced by Higgs self-interactions in the NMSSM, so when the singlet field Ŝ develops a vacuum expectation value s, an effective is generated by _eff = s.

As in the general treatment of multiple-Higgs theories, one can write the Higgs fields in the NMSSM as:

H_u = (v_u + _u + i _u, 0) H_d = (0, v_d + _d + i _d) S = s + (+ i)

and diagonalize their mass matrices to obtain Higgs mass eigenstates:

(_u, _d,) = U_H (H , H , H) (_u, _d,) = U_A (A , A , G)

Here H , H , H with convention m_H < m_H < m_H and A , A with convention m_A < m_A denote the physical CP-even and CP-odd Higgs bosons respectively, G and G are Goldstone bosons eaten by Z and W bosons respectively, and H is the physical charged Higgs boson. The Higgs sector in the MSSM can be treated similarly except that it predicts only two physical CP-even states and one physical CP-odd state, and consequently, the rotation matrices U_H and U_A are reduced to 2×2 matrices.

One distinct feature of the MSSM is that H usually acts as the SM-like Higgs boson (denoted by h hereafter) and its mass is upper bounded by m_Z at tree level. Obviously, to coincide with the LHC discovery of a 125 GeV boson, large radiative corrections to m_h are needed, which in turn usually requires the trilinear soft-breaking parameter A_t to be large. For example, in the case of large m_A and moderate tan , m_h is given by [4]:

m_h² m_Z² cos² 2 + (3m_t)/(4 ²v²) [ln(m̃_t²/m_t²) + (X_t²/m̃_t²)(1 - X_t²/(12m̃_t²))]

where the first term is the tree-level mass and the last two terms are the dominant corrections from the top-stop sector, m̃_t = √(m̃_t m̃_t) (m̃_ti denotes stop mass with convention m̃_t < m̃_t) represents the average stop mass scale and X_t A_t - cot . One can easily check that for a 500 GeV and 1 TeV stop, |A_t| should be respectively about 1.8 TeV and 3.5 TeV to give m_h 125 GeV.

In the NMSSM, m_h exhibits at least two new features [3]. One is that it receives additional contribution at tree level so that:

m_h,tree² = (m_Z² - ²v²) cos² 2 + ²v²

and for 0.7 and tan 1, m_h can reach 125 GeV even without radiative corrections. The other feature is that the mixing between the doublet and singlet Higgs fields can significantly alter the mass. To be more explicit, if the state H is h, the mixing pulls down the mass, while if H acts as h, the mixing pushes up the mass. Another remarkable characteristic of the NMSSM is that in the limit of very small and (but keeping fixed), the singlet field decouples from the theory so that the phenomenology of the NMSSM reduces to the MSSM. Therefore, to obtain a Higgs sector significantly different from the MSSM, one should consider large . Throughout this work, we require > 0.50 and consider two scenarios: > 0.7 in our discussion of the NMSSM.

[Figure 1: see original paper]: Feynman diagrams for the pair production of the SM-like Higgs boson via gluon fusion in the MSSM and NMSSM with H_I denoting a CP-even Higgs (I = 1, 2 for the MSSM and I = 1, 2, 3 for the NMSSM) and q̃_i,j (i, j = 1, 2) for a squark. The diagrams with initial gluons or final Higgs bosons interchanged are not shown here. For the quarks and squarks we only consider the third generation due to their large Yukawa couplings.

NMSSM1 scenario: H acts as the SM-like Higgs boson. For this scenario, the additional tree-level contribution to m_h is canceled by the mixing effect, and if the mixing effect is dominant, the parameters in the stop sector will be tightly limited in order to give m_h 125 GeV.

NMSSM2 scenario: H acts as the SM-like Higgs boson. In this scenario, both the additional tree-level contribution and the mixing effect can push up the mass. Therefore, for appropriate values of and tan , m_h can easily reach 125 GeV even without radiative corrections.

III. Calculations and Numerical Results

In SUSY, the pair production of the SM-like Higgs boson proceeds through the gluon fusion shown in Fig. 1 and the b¯b annihilation shown in Fig. 2. These diagrams indicate that the genuine SUSY contribution to the amplitude is of the same perturbation order as the SM contribution. Therefore, the SUSY prediction for the production rate may significantly deviate from the SM result. To ensure the correctness of our calculation, we verified that we can reproduce the SM results presented in [10] and the MSSM results in [18]. Since the analytic expressions are quite lengthy, we do not present their explicit forms here.

In our numerical calculation we take m_t = 173 GeV, m_b = 4.2 GeV, m_Z = 91.0 GeV, m_W = 80.0 GeV and = 1/128 [28], and use CT10 [29] to generate the parton distribution functions with the renormalization scale _R and the factorization scale _F chosen to be 2m_h. The collision energy of the LHC is fixed to be 14 TeV. We find that for m_h = 125 GeV, the production rate in the SM is 18.7 fb for gg → hh and 0.02 fb for b¯b → hh (the rates change very little when m_h varies from 123 GeV to 127 GeV).

For each SUSY model we use the package NMSSMTools-3.2.0 [30] to scan over the parameter space and then select samples that give a SM-like Higgs boson in the range of 123–127 GeV and also satisfy various experimental constraints, including those listed in Section I. The strategy of our scan is the same as in [6] except for three updates. First, since the rare decay B_s → has been recently observed with Br(B_s →) = 3.2 ^{1}. . × 10 [21], we use a double-sided limit 0.8 × 10 < Br(B_s →) < 6.2 × 10 . Second, for the LHC search of the non-standard Higgs boson, we use the latest experimental data [23]. The third update is that we require stops heavier than 200 GeV [20]. After the scan, we calculate the Higgs pair production rate in the allowed parameter space. We demonstrate the ratio _SUSY/ _SM for each surviving sample. Of course, such a ratio is less sensitive to higher-order QCD corrections.

In Fig. 3 we show the normalized production rate as a function of the Higgs boson mass for the surviving samples in the MSSM and NMSSM (for the NMSSM we show results for the NMSSM1 and NMSSM2 scenarios defined in Sec. II). This figure shows two common features for the three scenarios. One is that the production rate can deviate significantly from the SM prediction: in most cases the deviation exceeds 30% and in some special cases the production rate can be enhanced by one order of magnitude. The other feature is that for most cases the dominant contribution to the pair production comes from gluon fusion, which is reflected by the approximate overlap of circles (pink) with plus signs (blue). Fig. 3 also exhibits some differences between scenarios. For example, in the MSSM the b¯b annihilation contribution can be dominant for some surviving samples, which never occurs in the NMSSM. Another difference is that NMSSM1 tends to predict a larger production rate than other scenarios.

Now we explain some features of the results in Fig. 3. First, we investigate the cases in the MSSM where b¯b annihilation plays the dominant role in production. We find that they are characterized by a moderately large tan (so that the Hb¯b coupling is enhanced), a moderately light H (300 GeV < m_H < 400 GeV) and a relatively large Hhh coupling. For the NMSSM scenarios, since we are considering the large case, only a relatively small tan is allowed so that the H_i b¯b coupling is never enhanced sufficiently [3].

We also scrutinize the characteristics of the gluon fusion contribution in the MSSM. As a first step, we compare the sbottom loop contribution with the stop loop. We find that for the surviving samples the former is usually much smaller than the latter. Next we divide the amplitude of Fig. 1 into five parts with M , M , M , M and M denoting the contributions from diagrams (1)+(2), (3)+(4), (5), (6)+(7) and (8)+(9)+(10), respectively. Each amplitude is UV finite so we can learn its relative size directly. We find that the magnitudes of M and M are much larger than the others. This can be understood as follows: among the diagrams in Fig. 1, only (3), (4) and (5) involve chiral flipping of the internal stop, so in the limit m̃_t , m̃_t   2m_h the main parts of M and M can be written as:

M + M   Y_t^3 [(A_t/m̃_t) (m̃_t ^{2}/m̃_t ^{2}) (c sin^2 2 _t + c)]

where Y_t is the top quark Yukawa coupling, _t and A_t are respectively the chiral mixing angle and the trilinear soft-breaking parameter in the stop sector, and c and c are coefficients with opposite signs. Since a large A_t is strongly favored to predict m_h   125 GeV in the MSSM [3] and the other contributions are usually proportional to m_t^2/m̃_ti^2 or m_t /m̃_ti , one can easily conclude that M and M should be most important among the five amplitudes. In fact, we verified that without strong cancellation between M and M , the production rate can easily exceed 100 fb for most surviving samples.

As proof for the validity of Eq. (8), in Fig. 4 we show A_t/m̃_t versus m̃_t , where samples are classified according to the value of R = _SUSY(gg → hh)/ _SM(gg → hh). The left panel indicates that in the MSSM the region characterized by a light m̃_t and a large |A_t/m̃_t | usually predicts a large R. This can be understood as follows. In the MSSM with a light t̃ , the other stop (t̃) must be sufficiently heavy in order to predict m_h   125 GeV [3]. Then, after expressing sin^2 2 _t in terms of A_t and stop masses, one can find that the first term in Eq. (8) scales like (A_t/m̃_t) (m̃_t ^{2}/m̃_t ^{2}), and therefore its value grows rapidly with |A_t/m̃_t | and is unlikely to be canceled by the second term in Eq. (8). The upper left region of the panel reflects such behavior. This panel also indicates that even for t̃ and t̃ at TeV scale, the production rate in the MSSM may still deviate from its SM prediction by more than 30%. This is obvious since A_t in Eq. (8) is usually larger than stop masses [3]. Finally, we note that for m̃_t > 1 TeV, there exist some cases where the deviation is small even for A_t/m̃_t   3. We verified that these cases correspond to a small mass splitting between t̃ and t̃ . In such a situation, the first term in Eq. (8) is proportional to A_t^2/m̃_t ^{2} (since _t   /4), and its contribution to the rate is severely canceled by the second term.

Eq. (8) may also be used to explain the results of the NMSSM1 scenario. In this scenario we verified that the mixing effect on m_h often exceeds the additional tree-level contribution (as discussed in Sec. II), and consequently the soft-breaking parameters in the stop sector are more tightly constrained than in the other two scenarios. For example, given the same values of m̃_t and m̃_t for the three scenarios, the NMSSM1 scenario usually prefers a larger |A_t|. Consequently, this scenario tends to predict the largest production rate according to Eq. (8).

As for the R value in the NMSSM2 scenario, the situation is quite complex because a large   alone can push the value of m_h up to about 125 GeV and thus the soft-breaking parameters in the stop sector are not so constrained by the Higgs mass [3]. Nevertheless, this scenario still has the features that R is maximized for a large A_t and a light t̃ and that R can deviate sizably from unity for TeV-scale stops.

Finally, we focus on samples that predict a SM-like Higgs boson in the best-fitted mass region, 125–126 GeV [24]. For these samples, we calculate the ^{2} value with the LHC Higgs data (for details, see [6, 24]) and show its correlation with the normalized rate _SUSY/ _SM in Fig. 5. This figure indicates that in the MSSM and NMSSM2 scenarios, there exist many samples with ^{2} much smaller than its SM value (^{2}_SM = 16.5), which implies that the MSSM and NMSSM2 scenarios may be favored by current data [6]. In contrast, the NMSSM1 scenario can only slightly improve the fit. From this figure we also see that in the favored parameter space with small ^{2} the production rate can sizably deviate from the SM prediction (while in parameter space with large ^{2} the production rate can be several times larger than the SM value). For example, in the low- ^{2} region of the MSSM, the normalized rate is approximately 1.45, while in the NMSSM2 scenario the rate varies from 0.7 to 2.4.

IV. Summary and Conclusions

Recently, the CMS and ATLAS collaborations announced the discovery of a new resonance whose properties are in rough agreement with the SM Higgs boson. However, the nature of this new state, especially its role in electroweak symmetry breaking, needs to be scrutinized. Therefore, the most urgent task for the LHC is to test the properties of this Higgs-like boson by measuring all possible production and decay channels with high luminosity. Among the production channels, Higgs pair production is a rare process at the LHC. Since it can play an important role in testing the Higgs self-couplings, it will be measured at the LHC with high luminosity.

In this work we studied the pair production of the SM-like Higgs boson in popular SUSY models: the MSSM and NMSSM. To make our study realistic, we first scanned the parameter space of each model by considering various experimental constraints. Then we examined Higgs pair production in the allowed parameter space. We found that for most cases in both models, the dominant contribution to pair production comes from the gluon fusion process with its rate maximized at a moderately light t̃ and a large trilinear soft-breaking parameter A_t. The production rate can be sizably enhanced relative to the SM prediction: _SUSY/ _SM can reach 10, and even for TeV-scale stops it can exceed 1.3. For each model we also calculated its ^{2} with current Higgs data and found that in the most favored parameter region the value of _SUSY/ _SM is approximately 1.45 in the MSSM, while in the NMSSM it varies from 0.7 to 2.4.

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