Complete one-loop effects of SUSY QCD in bb?hbb?hb$\bar{b}$h production at the LHC under current experimental constraints postprint

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Abstract

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Preamble

Complete one-loop effects of SUSY QCD in b¯bh production at the LHC under current experimental constraints
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Abstract

Inspired by the recent LHC Higgs data and null search results for supersymmetry (SUSY), we scan the parameter space of the Minimal Supersymmetric Standard Model (MSSM) with relatively heavy sparticles (1–3 TeV). Within the parameter space allowed by current collider experiments and dark matter detection limits, we calculate the complete one-loop SUSY QCD corrections to pp → b¯bh at the LHC with $\sqrt{s} = 14$ TeV and obtain the following observations: (i) For large values of tan β and low values of m_A, the SUSY QCD effects can be quite large, but such parameter regions have been excluded by the latest LHC search results for H/A → $\tau^+\tau^-$; (ii) For modest values of tan β and m_A that have so far survived all experimental constraints, the SUSY QCD corrections can maximally reach about −9%.

PACS numbers:

Introduction

Very recently, the ATLAS and CMS collaborations have independently reported the observation of a Higgs-like resonance with a mass of about 125 GeV [1]. At the same time, the CDF and D0 collaborations have also updated their combined results for Higgs searches in the b¯b channel, which support the LHC observation [2]. Since the Minimal Supersymmetric Standard Model (MSSM) predicts a SM-like Higgs boson with a mass below 130 GeV, the observation of such a 125 GeV Higgs boson supports SUSY, albeit with significant restrictions on the SUSY parameter space [3].

Meanwhile, direct searches for SUSY particles (sparticles) have been performed at the LHC. Based on approximately 5 fb^{-1} of luminosity, the ATLAS and CMS collaborations have reported null results and obtained bounds on sparticle masses of about 1 TeV for the gluino and first-generation squarks [4], 330 GeV for electroweak gauginos, 180 GeV for sleptons [5], 465 GeV for stops, and 480 GeV for sbottoms [6]. These bounds indicate that SUSY may be heavier than expected and that sparticles could be significantly heavier than the electroweak scale [7, 8].

If sparticles are heavy and beyond the LHC's scope for direct production, searching for indirect SUSY effects via loop corrections becomes crucial. Since loop effects from heavy sparticles are typically small, we must identify processes where heavy sparticles produce sizable residual loop effects. One class of such processes involves Higgs production at the LHC, such as tH^- and hb¯b production, where heavy sparticles can generate substantial residual loop effects for small values of m_A and large values of tan β [9, 10] (these effects vanish as m_A becomes large). The reason for these residual loop effects is that the couplings in the loops are proportional to certain SUSY mass parameters and can be enhanced by large tan β values.

In this work, we focus on hb¯b production at the LHC and calculate the complete one-loop SUSY QCD corrections to this process. As an important Higgs production channel in the MSSM, this process has been studied in the literature [10], where residual SUSY QCD effects were found to be large (reaching -40% for tan $\beta = 30$). We revisit this production for several reasons: First, previous calculations of SUSY QCD corrections to this process were only partial (considering only corrections to the hb¯b vertex). The complete one-loop corrections involve pentagon Feynman diagrams, whose calculations are rather complicated and have not been performed. Second, the CMS collaboration has recently measured this channel and provided constraints on the tan β versus m_A plane [11]. Since residual SUSY QCD effects in this production are sensitive to tan β and m_A values, we should update the calculations by incorporating these new constraints. Moreover, other experimental constraints, such as dark matter direct detection limits and the SM-like Higgs boson mass around 125 GeV, are also quite restrictive and should be considered.

In this work, we consider all current experimental constraints to scan the MSSM parameter space and then calculate the process pp $\rightarrow$ b¯bh with complete one-loop SUSY QCD corrections within the allowed parameter space.

The paper is organized as follows. In Sec. II we describe the calculations for the process pp → b¯bh. In Sec. III we present numerical results. Finally, we draw conclusions in Sec. IV.

II. The Description of Calculations

In the MSSM, the lighter CP-even Higgs mass (m__h) is smaller than M__Z at tree level but receives large corrections at the loop level. The leading contributions come from the stop sector and can be expressed as [13]:

h(˜t) (cid:39) $2\pi^2 v^2 \sin^2\beta$ $m\tilde{t}_1 m\tilde{t}_2$ $2m\tilde{t}_1 m\tilde{t}_2$ $6m\tilde{t}_1 m\tilde{t}_2$

where X__t = A__t − cot β is the stop mixing parameter. We see that a large stop mass or a large stop mixing parameter is needed to increase m__h to 125 GeV. In our calculations, we consider collider constraints on the MSSM Higgs sector, using the packages FeynHiggs-2.8.6 [14] and HiggsBounds-3.8.0 [15] to calculate observables in the Higgs sector and require them to satisfy constraints from LEP, Tevatron, and LHC.

The SUSY QCD corrections to hb¯b production at the LHC involve sbottoms and gluinos in the loops. The sbottom mass matrix takes the form [16]:

mbX † mbXb m^2

where:

X__b = A__b − tan β, m^2__˜Q + m^2__b − m^2*Z cos(2β)(½ − sin*^{2} *__W), m*^{2}˜D + m^2__b − m^2__Z cos(2β) $\sin^2$ __W,

and m^2 *˜Q and m*^{2}˜D are respectively the soft-breaking mass parameters for the left-handed squark doublet ˜Q and the right-handed down squark ˜D, A__b is the sbottom soft-breaking trilinear coupling, and is the SUSY-preserving bilinear coupling of the two Higgs doublets in the superpotential. This mass matrix can be diagonalized by a unitary transformation that rotates the weak eigenstates ˜b__L,R to the mass eigenstates ˜b__1,2:

sin ˜b cos ˜b − sin ˜b cos ˜b

with the sbottom masses $m\tilde{b}_{1,2}$ and the mixing angle ˜b determined by:

$m\tilde{b}_{1,2}$ = ½ [m^2 *˜b__L + m*^{2}˜b__R ± √((m^2 *˜b__L − m*^{2}˜b__R)^2 + 4m^2__{bX}^{2}__b)]

tan 2 ˜b = 2m__{bX}b / (m^2 *˜b__L − m*^{2}˜b__R)

We generate the one-loop amplitudes with FeynArts-3.5 [17] and use FormCalc-6.1 [18] to simplify them and express the loop functions. The numerical calculations are performed using LoopTools-2.2 [19].

In Fig. 1 we display representative pentagon Feynman diagrams for the SUSY QCD corrections in the subprocess gg → b¯bh. Due to the absence of massless particles in the loop, all Feynman diagrams with gluinos and sbottoms in the loops are infrared (IR) finite.

We adopt the definitions of scalar and tensor two-, three-, four-, and five-point integral functions presented in Ref. [20]. For the calculation of pentagon diagrams, we use the Passarino-Veltman method [21] to reduce N-point ($N \leq 5$) tensor functions to scalar integrals. Our programs have been used to study SUSY-QCD corrections to the process $pp \to t\bar{t}Z^0$ at the LHC [22] and have been checked against Ref. [23] therein. To further validate the calculation of pentagon diagrams, we used our programs to calculate the NLO QCD corrections to $pp \to t\bar{t}h$ in the SM at the LHC and compared with the results in Ref. [24]. As shown in Table I, our results agree very well with those in Ref. [24].

To preserve supersymmetry, we adopt constrained differential renormalization (CDR) [25] to regulate the ultraviolet divergence (UV) in the self-energy and vertex corrections, which is equivalent to the dimensional reduction method at one-loop level [26].

TABLE I: Comparison of our numerical results for the process $pp \to t\bar{t}h$ in the SM at the LHC with those in Ref. [24], where the LO and NLO QCD corrected cross sections for different Higgs masses are listed with the relevant parameters and PDFs being the same as in Ref. [24], i.e., $_0 = (2m_t + m_h)/2$, $m_t =$ 174 GeV and the MRST PDFs.

m_h (GeV)	our σ_{LO} (fb)	our σ_{NLO} (fb)	σ_{LO} (fb) in [24]	σ_{NLO} (fb) in [24]
120	577.4(4)	701.3(13)	577.3(4)	701.5(18)
130	373.6(2)	452.4(11)	373.4(3)	452.3(12)
140	251.3(4)	305.5(7)	251.6(2)	305.6(8)

In our calculations, we assume a common SUSY mass M_{SUSY} defined by $M_{SUSY} = M_{\tilde{Q}} = M_{\tilde{U}} = M_{\tilde{D}} = M_{\tilde{g}} = A_t = A_b =$. We fix slepton mass parameters $M_{\tilde{L}} = M_{\tilde{E}} = A_\tau = 3$ TeV and scan the following MSSM parameter regions: $5 \leq \tan\beta \leq 60$, 1 TeV $\leq M_{SUSY} \leq$ 3 TeV.

In our scan we consider the following constraints on the parameter space: (i) We require that bounds for Higgs bosons from LEP, Tevatron, and LHC are satisfied and that the mass of the light CP-even Higgs is in the region 123 GeV $< m_h <$ 129 GeV; (ii) For constraints from flavor physics and electroweak precision data, we check using the package $SuSy_{Flavor}$ v2.0 [27] that they are safely satisfied because we assume relatively heavy sparticles; (iii) We consider dark matter constraints from WMAP relic density and direct detection results using the package MicrOmega v2.4 [28].

III. Numerical Results

Since the b-quark Yukawa coupling may receive large radiative corrections in the MSSM, we use the running b-quark mass (m_b^{DR}) and employ the method introduced in [30] to absorb MSSM corrections into the effective b-quark Yukawa couplings. However, for the b-quark in the final state, we take the pole mass to ensure correct on-shell behavior.

In our numerical calculations, we take the input parameters of the SM as [31]: m_t = 172 GeV, m_b$^{\{MS\}(m\_b}${MS}) = 4.19 GeV, m_Z = 91.1876 GeV, α(m_Z) = 1/127.918. Here m_b$^{\{MS\}(m\_b}${MS}) is the QCD-MS bottom-quark mass, which is related to m_b^{DR} by m_b^{DR} = m_b^{MS} [1 + (α_s/π)(1/4 + 3/2 ln(/m_b) - 3/4 ln(m_b^{MS}/m_b) + (1/144π^2)(73 - 3n_f))] where n_f is the number of active quark flavors. For the strong coupling constant α*s( ), we take its 2-loop evolution with QCD parameter Λ*{n_f=5} = 226 MeV and obtain α_s(m_Z) = 0.118.

We use CTEQ6L1 and CTEQ6M [32] parton distribution functions (PDFs) for the SM tree-level and SUSY QCD one-loop level computations, respectively. The renormalization scale _R and factorization scale _F are chosen to be _R = _F = m_Z. We have numerically verified that all UV divergences in the loop corrections cancel.

In Fig. 2 we project the surviving samples satisfying all experimental constraints onto the planes of tan β and M_h versus m_A, also presenting the excluded regions. It can be seen that a large portion of parameter space (the light blue region) has been ruled out by the 7 TeV LHC data, particularly by searches for new particles decaying into $\tau^+\tau^-$ and measurements of B_s $\to$ $^{+}$ $^{-}$. For small tan β and low-to-moderate m_A regions, the parameter space has been excluded by the non-observation of Higgs bosons at LEP2. We also note that with the very recently released 7+8 TeV LHC results for H/A $\to$ $\tau^+\tau^-$ based on L = 17 fb^{-1} [33], the excluded lower limit on the tan β–m_A plane has been further pushed down and overlaps with the LEP2 exclusion in the low m_A case. Since we require the Higgs boson mass to be in the range 123–129 GeV indicated by LHC data (126 ± 3 GeV), the parameter space that can correctly produce the Higgs boson mass is highly constrained and situated in a region with modest m_A (m_A 200 GeV) and small tan β (6 tan β 12). For other parts of the parameter space, they produce either too heavy a Higgs boson (m_h > 129 GeV when tan β > 12) or too light a Higgs boson (m_h < 123 GeV when tan β < 6).

In Fig. 3 we present separately the pentagon diagram contribution (lower panel) and the total SUSY-QCD contribution (upper panel) for the surviving samples. To show the influence of recent LHC data, we present the complete one-loop SUSY QCD corrections for samples satisfying (red triangles) or not satisfying (green dots) the LHC constraints. We can see that complete SUSY QCD corrections become significant for samples with large tan β and low m_A. This can be understood from the contribution to the effective b-quark Yukawa coupling after integrating out heavy sparticles, which is δy*{hb¯b}* = - (*g*αs m_b^{MS})/(6π m_W cos β sin α) [tan β + cot α] [8]. Since we assume M*{SUSY}* = *M*˜g = , the Yukawa coupling becomes independent of sparticle masses and is greatly enhanced by large tan β.

However, it should be noted that these samples lead to excess production rates for pp → H/A → $\tau^+\tau^-$ and thus have been excluded by current measurements. As m_A increases and tan β decreases, the corrections drop rapidly and approach zero in the decoupling limit. The main reason is that δy_{hb¯b} can be heavily reduced by cancellation between tan β and cot α, which have the relation cot α -tan β - (2m_Z^2 tan β cos^2 β)/m_A^2 for large m_A. From the lower panel of Fig. 3, we see that contributions from pentagon diagrams are small, maximally reaching about 0.8%. This is because in these pentagon diagrams the Higgs boson only couples to sbottoms while the hb¯b vertex does not appear, so the large residual loop effects in the hb¯b vertex are absent in the pentagon diagrams. For samples that survive all constraints, the complete SUSY QCD corrections can only reach about -9% at the LHC with √s = 14 TeV. Detecting such SUSY QCD effects may be challenging in future measurements of the process pp → b¯bh [34].

IV. Conclusion

In this work, we calculated the complete one-loop SUSY QCD corrections to the process pp → b¯bh at the LHC with √s = 14 TeV. We found that large SUSY QCD corrections in the non-decoupling regime with large tan β and low m_A have been excluded by the latest LHC non-standard Higgs search results. For the surviving decoupling regime with modest values of tan β and m_A, the SUSY QCD corrections can maximally reach -9%.

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References

[1] CMS Collaboration, CMS-PAS-HIG-12-020; ATLAS Collaboration, ATLAS-CONF-2012-093.
[2] The TEVNPH Working Group for the CDF and D0 Collaborations, arXiv:1207.0449.
[3] H. Baer, V. Barger, A. Mustafayev, arXiv:1112.3017; arXiv:1202.4038; O. Buchmueller et al., arXiv:1112.3564; S. Akula et al., Phys. Rev. D 85, 075001 (2012) [arXiv:1112.3645 [hep-ph]]; M. Kadastik et al., arXiv:1112.3647; J. L. Feng, K. T. Matchev and D. Sanford, arXiv:1112.3021; N. Karagiannakis, G. Lazarides, C. Pallis, arXiv:1201.2111; L. Roszkowski, E. M. Sessolo, Y. Tsai, arXiv:1202.1503; L. Aparicio, D. G. Cerdeno, L. E. Ibanez, arXiv:1202.0822; K. A. Olive, arXiv:1202.2324; J. Ellis, K. A. Olive, arXiv:1202.3262; A. Fowlie et al., arXiv:1206.0264; S. Akula, P. Nath, G. Peim, arXiv:1207.1839; M. Carena et al. arXiv:1112.3336; arXiv:1205.5842; K. Hagiwara, J. S. Lee and J. Nakamura, arXiv:1207.0802 [hep-ph]; J. Cao et al., arXiv:1207.3698 [hep-ph]; arXiv:1206.3865 [hep-ph]; Phys. Lett. B 710, 665 (2012) [arXiv:1112.4391 [hep-ph]]; JHEP 1203, 086 (2012) [arXiv:1202.5821 [hep-ph]]; Z. Kang et al.,

arXiv:1203.2336 [hep-ph].
[4] ATLAS Collaboration, ATLAS-CONF-2012-109; CMS Collaboration, CMS-PAS-SUS-11-022.
[5] ATLAS Collaboration, ATLAS-CONF-2012-076.
[6] ATLAS Collaboration, ATLAS-CONF-2012-106; G. Aad et al., arXiv:1208.1447 [hep-ex].
[7] D. Feldman, G. Kane, E. Kuflik and R. Lu, Phys. Lett. B 704, 56 (2011); H. Baer et al., JHEP 1010, 018 (2010); A. Cohen, D. B. Kaplan and A. Nelson, Phys. Lett. B 388, 588 (1996); M. Dine, A. Kagan and S. Samuel, Phys. Lett. B 243, 250 (1990).
[8] A. Dobado, M. J. Herrero and D. Temes, Phys. Rev. D 65, 075023 (2002) [hep-ph/0107147]; A. Dobado, M. J. Herrero and S. Penaranda, Eur. Phys. J. C 7, 313 (1999) [hep-ph/9710313].
[9] L. J. Hall, R. Rattazzi and U. Sarid, Phys. Rev. D 50, 7048 (1994) [hep-ph/9306309]; M. S. Carena, M. Olechowski, S. Pokorski and C. E. M. Wagner, Nucl. Phys. B 426, 269 (1994) [hep-ph/9402253]; A. M. Curiel, M. J. Herrero and D. Temes, AIP Conf. Proc. 670, 306 (2003); M. J. Herrero, hep-ph/0109291; M. J. Herrero, S. Penaranda and D. Temes, Phys. Rev. D 64, 115003 (2001); H. E. Haber et al., Phys. Rev. D 63, 055004 (2001) [hep-ph/0007006]; A. Dobado, M. J. Herrero and S. Penaranda, Eur. Phys. J. C 17, 487 (2000) [hep-ph/0002134]; G. Gao et al., Phys. Rev. D 66, 015007 (2002) [hep-ph/0202016]; J. Cao et al., Phys. Rev. D 68, 075012 (2003) [hep-ph/0210211]; N. D. Christensen, T. Han and T. Li, arXiv:1206.5816 [hep-ph]; S. Kanemura, T. Shindou and K. Yagyu, Phys. Lett. B 699, 258 (2011).
[10] G. Gao, R. J. Oakes and J. M. Yang, Phys. Rev. D 71, 095005 (2005) [hep-ph/0412356].
[11] CMS Collaboration, CMS-PAS-HIG-12-027.
[12] S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 713, 68 (2012).
[13] Y. Okada, M. Yamaguchi and T. Yanagida, Prog. Theor. Phys. 85, 1 (1991); J.R. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. B257, 83 (1991); H.E. Haber and R. Hempfling, Phys. Rev. Lett. 66, 1815 (1991).
[14] M. Frank et al., JHEP 0702, 047 (2007); G. Degrassi et al., Eur. Phys. J. C 28, 133 (2003); S. Heinemeyer, W. Hollik and G. Weiglein, Comput. Phys. Commun. 124, 76 (2000); Eur. Phys. J. C 9, 343 (1999).
[15] P. Bechtle et al., Comput. Phys. Commun. 182, 2605 (2011); Comput. Phys. Commun. 181, 138 (2010).
[16] J. F. Gunion and H. E. Haber, Nucl. Phys. B 272, 1 (1986).
[17] T. Hahn, Comput. Phys. Commun. 140, 418 (2001).
[18] T. Hahn, M. Perez-Victoria, Comput. Phys. Commun. 118, 153 (1999).
[19] G. J. van Oldenborgh, Phys. Commun. 66, 1 (1991).
[20] A. Denner, Fortschr. Phys. 41, 307 (1993).
[21] G. 't Hooft and M. Veltman, Nucl. Phys. B153, 365 (1979).
[22] N. Liu, L. Guo, W.-G. Ma, R.-Y. Zhang and L. Han, arXiv:1006.5249 [hep-ph].
[23] A. Lazopoulos, T. McElmurry, K. Melnikov and F. Petriello, Phys. Lett.

B 666, 62 (2008).
[24] W. Beenakker, S. Dittmaier, M. Kramer, B. Plumper, M. Spira and P. M. Zerwas, Nucl. Phys. B 653, 151 (2003) [hep-ph/0211352].
[25] F. del Aguila, A. Culatti, R. Tapia and M. Perez-Victoria, Nucl. Phys. B537, 561 (1999).
[26] W. Siegel, Phys. Lett. B84, 193 (1979); T. Hahn and M. Perez-Victoria, Comput. Phys. Commun. 118, 153 (1999), hep-ph/9807565.
[27] J. Rosiek et al., Comput. Phys. Commun. 181, 2180 (2010); A. Crivellin, L. Hofer and J. Rosiek, JHEP 1107, 017 (2011).
[28] G. Belanger et al., Comput. Phys. Commun. 182, 842 (2011).
[29] J. Dunkley et al. [WMAP Collaboration], Astrophys. J. Suppl. 180, 306 (2009).
[30] T. N. Dao, W. Hollik and D. N. Le, Phys. Rev. D 83, 075003 (2011).
[31] C. Amsler et al., Particle Data Group, Phys. Lett. B 667, 1 (2008).
[32] J. Pumplin et al., JHEP 0602, 032 (2006).
[33] [CMS Collaboration], Note CMS-PAS-HIG-12-050.
[34] J. Dai, J. F. Gunion and R. Vega, Phys. Lett. B 345, 29 (1995); Phys. Lett. B 387, 801 (1996).

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