In the Minimal Supersymmetric Standard Model, the effective $b$ quark Yukawa coupling to the lightest neutral Higgs boson is enhanced. Therefore, the associated production of the lightest Higgs boson with a $b$ quark is an important discovery channel. We consider the SUSY QCD contributions from squarks and gluinos and discuss the decoupling properties of these effects. A comparison of our exact $O(\alpha_s)$ results with those of a widely used effective Lagrangian approach, the $\Delta_b$ approximation, is also presented.

1. Introduction

In the MSSM, the production mechanisms for the Higgs bosons can be significantly different from that in the Standard Model. For large values of $\tan\beta$, the heavier Higgs bosons, $A$ and $H$, are predominantly produced in association with $b$ quarks. Even for $\tan\beta \sim 5$, the production rate in association with $b$ quarks is similar to that from gluon fusion for $A$ and $H$ production (Dittmaier et al. [2011]). For the lighter Higgs boson, $h$, the dominant production mechanism at both the Tevatron and the LHC is production with $b$ quarks for light $M_A (\lesssim 200$ GeV$)$, where the $b\bar{b}h$ coupling is enhanced. Both the Tevatron [Benjamin et al. [2010]] and the LHC experiments [Chatrchyan et al. [2011]] have presented limits Higgs production in association with $b$ quarks, searching for the decays $h \rightarrow \tau^+\tau^-$ and $bb$. These limits are obtained in the context of the MSSM are sensitive to the $b$-squark and gluino loop corrections which we consider here.

The rates for $bh$ associated production at the LHC and the Tevatron have been extensively studied (Dawson et al. [2006], Campbell et al. [2004], Maltoni et al. [2003], Dawson et al. [2005], Dittmaier et al. [2004], Dicus et al. [1999], Dawson et al. [2004], Maltoni et al. [2003]). In the 4-flavor number scheme, the lowest order processes for producing a Higgs boson and a $b$ quark are $gg \rightarrow b\bar{b}h$ and $qq \rightarrow b\bar{b}h$ (Dawson et al. [2006], Campbell et al. [2004], Maltoni et al. [2003]). In the 4-flavor number scheme, the lowest order process is $bg \rightarrow bh$ ($bg \rightarrow b\bar{b}$). The two schemes represent different orderings of perturbation theory and calculations in the two schemes produce rates which are in qualitative agreement (Dittmaier et al. [2011], Campbell et al. [2004]). In this paper, we use the 5-flavor number scheme for simplicity. The resummation of threshold logarithms (Field et al. [2007]), electroweak corrections (Dawson and Jaiswal [2010], Beccaria et al. [2010]) and SUSY QCD corrections (Dawson and Jackson [2008]) have also been computed for $bh$ production in the 5-flavor number scheme.

Here, we focus on the role of squark and gluino loops. The properties of the SUSY QCD corrections to the $b\bar{b}h$ vertex, both for the decay $h \rightarrow b\bar{b}$ (Dabelstein [1995], Hall et al. [1994], Carena et al. [2000], Guasch et al. [2003]) and the production, $b\bar{b} \rightarrow h$ (Dittmaier et al. [2004], Guasch et al. [2003], Haber et al. [2001], Harlander and Kilgore [2003]), were computed long ago. The contributions from $b$ squarks and gluinos to the lightest MSSM Higgs boson mass are known at 2-loops (Heinemeyer et al. [2005], Brignole et al. [2002]), while the 2-loop SQCD contributions to the $b\bar{b}h$ vertex is known in the limit in which the Higgs mass is much smaller than the squark and gluino masses (Noth and Spira [2010, 2008]). The contributions of squarks and gluinos to the on-shell $b\bar{b}h$ vertex are non-decoupling for heavy squark and gluino masses and decoupling is only achieved when the pseudoscalar mass, $M_A$, also becomes large.

An effective Lagrangian approach, the $\Delta_b$ approximation [Hall et al. [1994], Carena et al. [2000]), can be used to approximate the SQCD contributions to the on-shell $b\bar{b}h$ vertex and to resum the $(\alpha_s, \tan\beta/M_{\text{SUSY}})^n$ enhanced terms. The numerical accuracy of the $\Delta_b$ effective Lagrangian approach has been examined for a number of cases. The 2-loop contributions to the lightest MSSM Higgs boson mass of $O(\alpha_s\alpha_t\alpha_s)$ were computed by Heinemeyer et al. [2005] and Brignole et al. [2002], and it was found that the majority of these corrections could be absorbed into a 1-loop contribution by defining an effective $b$ quark mass using the $\Delta_b$ approach. The sub-leading contributions to the Higgs boson mass (those not absorbed into $\Delta_b$) are then of $O(1$ GeV$)$. The $\Delta_b$ approach also yields an excellent approximation to the SQCD corrections for the decay process $h \rightarrow b\bar{b}$ (Guasch et al. [2003]). It is particularly interesting to study the accuracy of the $\Delta_b$ approximation for production processes where one of the $b$ quarks is off-shell. The SQCD contributions from squarks and gluinos to the...
inclusive Higgs production rate in association with \( b \) quarks has been studied extensively in the 4FNS by
\cite{Dittmaier2007}, where the the lowest order contribution is \( gg \to bbh \). In the 4FNS, the inclusive

cross section including the exact 1-loop SQCD corrections is reproduced to within a few percent using the \( \Delta_b \)

approximation. However, the accuracy of the \( \Delta_b \) approximation for the MSSM neutral Higgs boson production

in the 5FNS has been studied for only a small set of MSSM parameters in Ref. \cite{Dawson2008}. The major new result of this paper is a detailed study of the accuracy of the \( \Delta_b \) approach in the 5FNS for the

\( bg \to bh \) production process. In this case, one of the \( b \) quarks is off-shell and there are contributions which are

not contained in the effective Lagrangian approach.

In this article, we give a brief review of the effective Lagrangian approximation in section 1. In section 2,

we summarize the SQCD calculations for \( bg \to bh \) \cite{Dawson2008} including terms which are

enhanced by \( m_b \tan \beta \) \cite{Dawson2011}. Analytic results for the SQCD corrections to \( bg \to bh \) in the extreme mixing scenarios in the \( b \) squark sector have been calculated by \cite{Dawson2011} and are presented

in Section 3. Section 4 contains numerical results for the \( \sqrt{s} = 7 \) TeV LHC. Finally, our conclusions are

summarized in Section 5.

\section{SQCD Contributions to \( gb \to bh \)}

\subsection{\( \Delta_b \) Approximation: The Effective Lagrangian Approach}

Loop corrections which are enhanced by powers of \( \alpha_s \tan \beta \) can be included in an effective Lagrangian approach

\cite{Hall1994, Carena2000, Guasch2003}. Using the effective Lagrangian, which we term

the Improved Born Approximation (or \( \Delta_b \) approximation), the cross section is written in terms of the effective
coupling,

\[
g_{\Delta_b}^{bh} \equiv g_{bh} \left( \frac{1}{1 + \Delta_b} \right) \left( 1 - \frac{\Delta_b}{\tan \beta \tan \alpha} \right),
\]

where

\[
g_{bh} = -\left( \frac{\sin \alpha}{\cos \beta} \right) \frac{\mu_R}{\mu_{SM}}
\]

and the 1-loop contribution to \( \Delta_b \) from sbottom/gluino loops is \cite{Hall1994, Carena2000, Guasch2003}

\[
\Delta_b = \frac{2\alpha_s(M_S)}{3\pi} M_{\tilde{b}} \tan \beta I(M_{\tilde{b}_1}, M_{\tilde{b}_2}, M_{\tilde{g}}),
\]

where the function \( I(a, b, c) \) is,

\[
I(a, b, c) = \frac{1}{(a^2 - b^2)(b^2 - c^2)(a^2 - c^2)} \left( a^2 b^2 \log \left( \frac{a^2}{b^2} \right) + b^2 c^2 \log \left( \frac{b^2}{c^2} \right) + c^2 a^2 \log \left( \frac{c^2}{a^2} \right) \right),
\]

The Improved Born Approximation consists of rescaling the tree level cross section, \( \sigma_0 \), by the coupling of Eq. \ref{eq:ib}

\[
\sigma_{IBA} = \left( \frac{g_{\Delta_b}}{g_{bh}} \right)^2 \sigma_0.
\]

The Improved Born Approximation has been shown to accurately reproduce the full SQCD calculation of

\( pp \to t\bar{b}H^+ \) \cite{Berger2005, Dittmaier2009}. The one-loop result including the SQCD corrections

for \( bg \to bh \) can be written as,

\[
\sigma_{SQCD} \equiv \sigma_{IBA} \left( 1 + \Delta_{SQCD} \right),
\]

where \( \Delta_{SQCD} \) is found from the exact SQCD calculation summarized in Appendix B of \cite{Dawson2011}.
2.2. Full One-loop SQCD Contributions to $gb \rightarrow bh$

The SQCD contributions to the $gb \rightarrow bh$ process have been computed in Ref. [Dawson and Jackson 2008] in the $m_b = 0$ limit and further, in Ref. [Dawson et al. 2011] where terms which are enhanced by $m_b \tan \beta$ have been included.

The tree level diagrams for $g(q_1) + b(q_2) \rightarrow b(p_b) + h(p_h)$ are shown in Fig. 1. The amplitude can be written as a sum of following dimensionless spinor products

$$M_\mu^s = \frac{\bar{\tau}(p_b) (\not{q}_1 + \not{q}_2) \gamma^\mu u(q_2)}{s},$$

$$M_\mu^t = \frac{\bar{\tau}(p_b) \gamma^\mu (p_b - \not{q}_1) u(q_2)}{t},$$

$$M_\mu^1 = q_2^2 \tau(p_b) u(q_2),$$

$$M_\mu^2 = \frac{\bar{\tau}(p_b) \gamma^\mu u(q_2)}{m_b},$$

$$M_\mu^3 = p_b^2 \tau(p_b) \not{q}_1 u(q_2),$$

$$M_\mu^4 = q_2^2 \tau(p_b) \not{q}_1 u(q_2).$$

(7)

where $s = (q_1 + q_2)^2$, $t = (p_b - q_1)^2$ and $u = (p_b - q_2)^2$. In the $m_b = 0$ limit, the tree level amplitude depends only on $M_\mu^s$ and $M_\mu^t$, and $M_\mu^1$ is generated at one-loop. When the effects of the $b$ mass are included, $M_\mu^2$, $M_\mu^3$, and $M_\mu^4$ are also generated.

The tree level amplitude is

$$A_{\alpha\beta}^{s} | 0 = -g_s g_{bhh} (T^a)_{\alpha\beta} \epsilon_\mu(q_1) \{M_\mu^s + M_\mu^t\},$$

(8)

and the one loop contribution can be written as

$$A_{\alpha\beta}^{s} = -\frac{\alpha_s(\mu_R)}{4\pi} g_s g_{bhh} (T^a)_{\alpha\beta} \sum_j X_j M^*_j \epsilon_\mu(q_1).$$

(9)

For detailed calculation of counter-terms and the coefficients $X_j$, cf. [Dawson et al. 2011].

3. Results for Maximal and Minimal Mixing in the $b$-Squark Sector

3.1. Maximal Mixing

The SQCD contributions to $bg \rightarrow bh$ can be examined analytically in several scenarios. In the maximal mixing scenario,

$$|\tilde{m}_L^2 - \tilde{m}_R^2| << \frac{m_b}{1 + \Delta_0} |X_b|.$$

(10)
We expand in powers of $\frac{|\tilde{m}_L^2 - \tilde{m}_R^2|}{m_{S,b} X_b}$. In this case the sbottom masses are nearly degenerate,

$$M_{b_S}^2 = \left| M_{b_1}^2 - M_{b_2}^2 \right| = \frac{1}{2} \left[ M_{b_1}^2 + M_{b_2}^2 \right]$$

$$\left| M_{b_1}^2 - M_{b_2}^2 \right| = \left( \frac{2m_b}{1 + \Delta_b} \right) \left( 1 + \frac{(\tilde{m}_L^2 - \tilde{m}_R^2)(1 + \Delta_b)^2}{8m_b^2 X_b} \right) \ll M_S^2.$$  \hspace{1cm} (11)

This scenario is termed maximal mixing since

$$\sin 2\theta_b \sim 1 - \frac{(\tilde{m}_L^2 - \tilde{m}_R^2)(1 + \Delta_b)^2}{8m_b^2 X_b}.$$  \hspace{1cm} (12)

We expand the contributions of the exact one-loop SQCD calculation (see Appendix B of Dawson et al. 2011) in powers of $1/M_S$, keeping terms to $O(M_{EW}^2/M_S^2)$ and assuming $M_S \sim M_{\tilde{g}} \sim \mu \sim A_b \sim \tilde{m}_L \sim \tilde{m}_R \gg M_W, M_Z, M_h \sim M_{EW}$. In the expansions, we assume the large $\tan \beta$ limit and take $m_b \tan \beta \sim O(M_{EW})$.

The minimal mixing scenario is characterized by a mass splitting between the $b$ squarks which is of order the $b$ squark mass, $|M_{b_1}^2 - M_{b_2}^2| \sim M_S^2$. In this case,

$$|\tilde{m}_L^2 - \tilde{m}_R^2| >> \frac{m_b}{X_b},$$  \hspace{1cm} (14)

and the mixing angle in the $b$ squark sector is close to zero,

$$\cos 2\theta_b \sim 1 - \frac{2m_b^2 X_b^2}{(M_{b_1}^2 - M_{b_2}^2)^2} \left( \frac{1}{1 + \Delta_b} \right)^2.$$  \hspace{1cm} (15)

As in the previous section, the spin and color averaged amplitude-squared is,

$$|\mathcal{A}|^2_{\text{min}} = -\frac{2\alpha_s \pi}{3} (g_{\tilde{g}bb}^2) \left( \frac{M_{b_1}^2 + u^2}{st} \right) \left[ 1 + 2 \left( \frac{\delta_{gbbh}}{g_{bbh}} \right)_{\text{max}} \right]$$

$$+ \frac{\alpha_s}{2\pi} \delta_{\kappa_{\text{min}}} M_{b_S}^2 \frac{M_{b_1}^2}{M_S^2} + O\left( \frac{M_{EW}^2}{M_S^2} \right)^4 \alpha_s^3.$$

3.2. Minimal Mixing

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$$+ \frac{\alpha_s}{2\pi} \delta_{\kappa_{\text{min}}} M_{b_S}^2 \frac{M_{b_1}^2}{M_S^2} + O\left( \frac{M_{EW}^2}{M_S^2} \right)^4 \alpha_s^3.$$

The contributions which are not contained in $\sigma_{IBA}$, $\left( \frac{\delta_{gbbh}}{g_{bbh}} \right)_{\text{min}}$ and $\delta_{\kappa_{\text{min}}} M_{b_S}^2$ are given in Dawson et al. 2011 and again found to be suppressed by $O\left( \frac{M_{EW}^2}{M_S^2} \right)^2$. 


4. Numerical Results

The numerical results for $pp \rightarrow b(b)h$ at $\sqrt{s} = 7 \text{ TeV}$ were presented in [Dawson et al. (2011)]. The renormalization and factorization scales were chosen to be $\mu_R = \mu_F = M_h/2$ and the CTEQ6m NLO parton distribution functions [Nadolsky et al. (2008)] were used. Figs. 2, 3, and 4 show the percentage deviation of the complete one-loop SQCD calculation from the Improved Born Approximation of Eq. 5 for $\tan \beta = 40$ and $\tan \beta = 20$ and representative values of the MSSM parameters. In both extremes of $b$ squark mixing, the Improved Born Approximation approximation is within a few percent of the complete one-loop SQCD calculation and so is a reliable prediction for the rate. This is true for both large and small $M_A$. In addition, the large $M_S$ expansion accurately reproduces the full SQCD one-loop result to within a few percent. These results are expected from the expansions of Eqs. 13 and 16 since the terms which differ between the Improved Born Approximation and the one-loop calculation are suppressed in the large $M_S$ limit.

Fig. 5 compares the total SQCD rate for maximal and minimal mixing, which bracket the allowed mixing possibilities. For large $M_S$, the effect of the mixing is quite small, while for $M_S \sim 800 \text{ GeV}$, the mixing effects are at most a few fb. The accuracy of the Improved Born Approximation as a function of $m_R$ is shown in Fig. 6 for fixed $M_A$, $\mu$, and $m_L$. As $m_R$ is increased, the effects become very tiny. Even for light gluino masses, the Improved Born Approximation reproduces the exact SQCD result to within a few percent.

![Image](https://via.placeholder.com/150)

Figure 2: Percentage difference between the Improved Born Approximation and the exact one-loop SQCD calculation of $pp \rightarrow bh$ for maximal mixing in the $b$-squark sector at $\sqrt{s} = 7 \text{ TeV}$, $\tan \beta = 40$, and $M_A = 1 \text{ TeV}$.

In Fig. 7, we show the scale dependence for the total rate, including NLO QCD and SQCD corrections (dotted lines) for a representative set of MSSM parameters at $\sqrt{s} = 7 \text{ TeV}$. The NLO scale dependence is quite small when $\mu_R = \mu_F \sim M_h$. However, there is a roughly $\sim 5\%$ difference between the predictions found using the CTEQ6m PDFs and the MSTW2008 NLO PDFs [Martin et al. (2009)]. In Fig. 8, we show the scale dependence for small $\mu_F$ (as preferred by [Maltoni et al. (2003)]), and see that it is significantly larger than in Fig. 7. This is consistent with the results of [Dittmaier et al. (2011), Harlander and Kilgore (2003)].

5. Conclusion

The analytical and numerical results presented in the previous sections clearly demonstrate that deviations from the $\Delta_b$ approximation are suppressed by powers of $(M_{EW}/M_S)$ in the large $\tan \beta$ region. The $\Delta_b$ approximation hence yields an accurate prediction in the 5 flavor number scheme for the cross section for squark and gluino masses at the TeV scale.

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Figure 3: Percentage difference between the Improved Born Approximation and the exact one-loop SQCD calculation of $pp \rightarrow bh$ for maximal mixing in the $b$-squark sector at $\sqrt{s} = 7$ TeV, $\tan \beta = 20$, and $M_A = 250$ GeV.

Figure 4: Percentage difference between the Improved Born Approximation and the exact one-loop SQCD calculation for $pp \rightarrow bh$ for minimal mixing in the $b$-squark sector at $\sqrt{s} = 7$ TeV.

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Figure 5: Comparison between the exact one-loop SQCD calculation for $pp \rightarrow bh$ for minimal and maximal mixing in the $b$ squark sector at $\sqrt{s} = 7$ TeV and $\tan \beta = 40$. The minimal mixing curve has $m_R = \sqrt{2} M_S$ and $\tilde{\theta}_b \sim 0$, while the maximal mixing curve has $m_R = M_S$ and $\tilde{\theta}_b \sim \frac{\pi}{4}$.

Figure 6: Percentage difference between the Improved Born Approximation and the exact one-loop SQCD calculation for $pp \rightarrow bh$ as a function of $m_R$ at $\sqrt{s} = 7$ TeV and $\tan \beta = 40$. 

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Figure 7: Total cross section for \( pp \rightarrow b\overline{b}h \) production including NLO QCD and SQCD corrections (dotted lines) as a function of renormalization/factorization scale using CTEQ6m (black) and MSTW2008 NLO (red) PDFs. We take \( M_{\tilde{g}} = 1 \text{ TeV} \) and the remaining MSSM parameters as in Fig. 2.

Figure 8: Total cross section for \( pp \rightarrow b\overline{b}h \) production including NLO QCD and SQCD corrections as a function of the factorization scale using MSTW2008 NLO PDFs. We take \( M_{\tilde{g}} = 1 \text{ TeV} \) and the remaining MSSM parameters as in Fig. 2.

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