Associated Higgs production with bottom quarks at hadron colliders

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Higgs-boson production in association with bottom quarks, $p\bar{p}/pp \to b\bar{b}H+X$, is an important discovery channel for supersymmetric Higgs particles at the Tevatron and the LHC. We present higher-order QCD predictions for inclusive cross sections and for the production of a Higgs boson in association with high-$p_T$ bottom quarks. We compare calculations performed in a four-flavour scheme based on the parton processes $gg, q\bar{q} \to b\bar{b}H$ with five-flavour scheme calculations based on bottom-quark scattering.

1. Introduction

The Higgs mechanism is a cornerstone of the Standard Model (SM) and its supersymmetric extensions. The masses of the fundamental particles, electroweak gauge bosons, leptons, and quarks, are generated by interactions with Higgs fields. The search for Higgs bosons is thus one of the most important endeavours in high-energy physics and is being pursued at the upgraded proton–antiproton collider Tevatron with a centre-of-mass (CM) energy of 1.96 TeV, followed in the near future by the proton–proton collider LHC with 14 TeV CM energy.

Various channels can be exploited to search for Higgs bosons at hadron colliders. Higgs radiation off bottom quarks \[ p\bar{p}/pp \to b\bar{b}H+X \] (1) is the dominant Higgs-boson production mechanism in supersymmetric theories at large $\tan \beta$, where the bottom–Higgs Yukawa coupling is strongly enhanced.\(^1\)

2. $b\bar{b}H$ production mechanisms

In a four-flavour scheme with no $b$ quarks in the initial state, the lowest-order QCD processes for associated $b\bar{b}H$ production are gluon–gluon fusion and quark–antiquark annihilation\(^2\)

\[ gg \to b\bar{b}H \quad \text{and} \quad q\bar{q} \to b\bar{b}H , \]

as shown in Fig. 1(a). The inclusive cross section for $gg \to b\bar{b}H$ develops potentially large logarithms $\propto \ln(\mu_F/m_b)$, which arise from the splitting of gluons into nearly collinear $b\bar{b}$ pairs. The large scale $\mu_F \propto M_H$ corresponds to the upper limit of the collinear region up to which factorization is valid. It has been argued that $\mu_F \approx M_H/4$ [2]. The $\ln(\mu_F/m_b)$ terms can be summed to all orders in perturbation theory by introducing bottom parton densities (the five-flavour scheme) [3]. The five-flavour scheme is based on the approximation that the outgoing $b$ quarks are at small transverse momentum. In this scheme, the leading-order (LO) process for the inclusive $b\bar{b}H$ cross section is $b\bar{b}$ fusion, $b\bar{b} \to H$ (Fig. 1(b)). The incoming $b$ partons are given

![Generic set of leading order Feynman diagrams for $gg \to b\bar{b}H$ (a) and $b\bar{b} \to H$ (b).]

Figure 1. Generic set of leading order Feynman diagrams for $gg \to b\bar{b}H$ (a) and $b\bar{b} \to H$ (b).

\(^1\)The parameter $\tan \beta = v_2/v_1$ is the ratio of the vacuum expectation values of the two Higgs fields generating the masses of up- and down-type particles in supersymmetric extensions of the SM. $H = H_{SM}, h^0, H^0$ may denote the SM Higgs boson or any of the CP-even neutral Higgs bosons of supersymmetric theories.

\(^2\)The $b\bar{b}H$ cross section at the Tevatron and the LHC is completely dominated by gluon-induced parton processes.
zero transverse momentum at leading order, and acquire transverse momentum at higher order. If one demands that at least one $b$ quark is observed at large transverse momentum, the leading parton process in the five-flavour scheme is $gb \rightarrow bH$.

A final state with two high-$p_T$ $b$ quarks cannot be described by $b$-parton densities and has to be calculated through $gg \rightarrow bbH$.

To all orders in perturbation theory the four- and five-flavour schemes are identical, but the way of ordering the perturbative expansion is different, and the results do not match exactly at finite order. In Fig. 2 we compare the LO predictions for the total $bbH$ cross section at the LHC in the two schemes. Both calculations exhibit a strong scale dependence. Fixing the renormalization and factorization scales to $\mu = M_H$ the five-flavour scheme prediction exceeds the four-flavour scheme prediction by more than a factor of five. A similar pattern is found for the inclusive $bbH$ cross section at the Tevatron.

The four- and five-flavour schemes represent different perturbative expansions and they are based on different approximations. In the four-flavour scheme the $g \rightarrow bb$ splitting is calculated exactly, but large logarithms $\ln(\mu_F/m_b)$, with $\mu_F \propto M_H$, appear order by order which may spoil the convergence of the perturbative series. The five-flavour-scheme calculations, on the other hand, are based on a leading-logarithmic collinear approximation to the $g \rightarrow bb$ splitting which allows to sum the logarithms $\ln(\mu_F/m_b)$ to all orders by the introduction of evolved $b$ parton densities.

In an attempt to quantify the quality of the approximations in the two calculational schemes, we have compared the LO cross section for $bbH$ production in the four- and five-flavour schemes with an approximate five-flavour scheme calculation where the evolved $b$-quark parton distribution function is replaced by the calculated $\alpha_s$ contribution to the distribution of heavy quarks in an on-mass shell gluon:

$$\tilde{b}(x, \mu) = \frac{\alpha_s(\mu)}{2\pi} \ln\left(\frac{\mu^2}{m^2_{qg}}\right) \times \int_x^1 \frac{d\xi}{\xi} P_{qg}^{(1)}(x, \xi) g(\xi, \mu).$$

Here $P_{qg}^{(1)}$ is the usual gluon $\rightarrow$ quark splitting function $P_{qg}^{(1)}(\xi) = T_F(\xi^2 + (1-\xi)^2)$ and $g(\xi, \mu)$ is the gluon distribution function. Comparing the four-flavour scheme calculation based on $gg \rightarrow bbH$ with the approximate five-flavour scheme calculation based on $\bar{b}\bar{b} \rightarrow H$ allows one to quantify the impact of approximating the exact $g \rightarrow bb$ splitting with the leading-logarithmic collinear approximation. The difference between the approximate five-flavour scheme calculation and the five-flavour scheme calculation with evolved $b$ parton densities provides an estimate of the effect of summing the $\ln(\mu_F/m_b)$ terms.

The comparison between the four-, five-, and the approximate five-flavour scheme calculations is presented in Fig. 3. We have set all scales equal to $\mu = M_H/4$, which is an appropriate factorization scale choice in the five-flavour scheme [2,4]. The results shown in Fig. 3 imply that the leading logarithmic approximation to the $g \rightarrow bb$ splitting is not very accurate for $bbH$ production at the Tevatron. The LO cross-section prediction based on the $\bar{b}\bar{b} \rightarrow H$ process exceeds the exact calculation through $gg \rightarrow bbH$ by up to a factor 1.5 for $M_H \lesssim 200$ GeV. At the same time, the effect of summing the $\ln(\mu_F/m_b)$ terms is significant, increasing the cross section prediction by up to a factor 1.7 in the same Higgs mass range.

![Figure 2. Scale variation of the LO inclusive cross section prediction for $pp \rightarrow bbH + X$ at the LHC in the four- and five flavour schemes.](image-url)
the LO analysis presented in Fig. 3 suggests that order QCD corrections are included. However, scheme dependences are reduced when higher-M$_b$ ent calculational schemes is more favourable for

Fortunately, the comparison between the differ-

flavour scheme and the four-flavour scheme cal-

inserts show the ratio of the approximate five-

production at the Tevatron and the LHC. The

rithmic approximation to the

the ln($\mu F/\mu_R$) terms is less than about 40% for $M_H \lesssim 200$ GeV.

As we shall demonstrate in Section 4, the scheme dependences are reduced when higher-order QCD corrections are included. However, the LO analysis presented in Fig. 3 suggests that

the approximations involved in both the four- and five-flavour scheme calculations are not very accurate for $bbH$ production at the Tevatron. At the LHC, on the other hand, both schemes should yield reliable and compatible results.

3. Higher-order QCD corrections

The inclusion of higher-order QCD corrections is crucial to reduce the scale and scheme dependence of the LO cross-section predictions. The five-flavour scheme $bb \to H$ process has been calculated to next-to-leading order (NLO) [5] and next-to-next-to-leading order (NNLO) [4] accuracy. The NNLO corrections strongly reduce the renormalization and factorization scale dependences, see also Ref. [6].

The calculation of the NLO QCD corrections to the four-flavour-scheme processes $gg, qq \to QQH$, where $Q$ denotes a generic heavy quark, has been described in Ref. [7]. NLO results for the total $bbH$ cross section [8] and for the production of a Higgs boson in association with high-$p_T$ $b$ quarks [8,9] have been presented in the literature. Figure 4 shows the LO and NLO scale dependence for the total cross section and for the cross section with two high-$p_T$ $b$ quarks [8]. The reduction of the scale dependence at NLO is particularly significant for the exclusive cross section where both $b$ quarks are required to be produced with large transverse momentum.

4. Comparison of 4- and 5-flavour schemes

Despite the sizable scale uncertainty at NLO, the four-flavour-scheme calculation yields a reliable prediction for the inclusive cross section. This is demonstrated in Fig. 5 where the NLO four-flavour scheme calculation is compared with the NNLO calculation of $bb \to H$ (five-flavour scheme). The two calculations are compatible within their respective scale uncertainties for small Higgs masses, while for large Higgs masses the five-flavour scheme tends to yield larger cross sections. As suggested by the LO analysis, Fig. 3, the comparison between the two schemes is more favourable for $bbH$ production at the LHC. ¹

¹Note that Higgs radiation off closed top-quark loops has not been included in the NNLO calculation of $bb \to H$. ³
Figure 4. Scale variation of the NLO cross section prediction for $p\bar{p}/pp \to bbH + X$ at the Tevatron and the LHC in the four-flavour scheme. From Ref. [8].

Requiring a high-$p_T$ b quark in the final state reduces the signal cross section with respect to the inclusive cross section, but the b quark can be used to suppress the background and to identify the Higgs-boson production mechanism. Figure 6 shows the NLO cross section predictions for the production of a Higgs boson plus a single b quark. Results are compared between the four-flavour scheme based on the parton processes $gg, q\bar{q} \to bbH$ with the momentum of one of the b quarks integrated over [8], and the five-flavour scheme based on the process $gb \to bH$ [11]. As for the inclusive cross section, the two approaches agree within their scale uncertainty, but the five-flavour scheme tends to yield larger cross sections.

5. Conclusions

Associated $bbH$ production at the Tevatron and the LHC is an important discovery channel for Higgs bosons at large values of $\tan \beta$ in supersymmetric extensions of the SM, where the bottom Yukawa coupling is strongly enhanced. Results in the four- and five-flavour schemes have been compared, including higher-order QCD corrections.
Figure 6. NLO cross section for pp/\bar{p}p \rightarrow b\bar{b}H+X with one high-p_T b quark at the Tevatron and the LHC in the four-flavour [8] and five-flavour [11] schemes. From Ref. [10].

References

1. R. Raitio and W. W. Wada, Phys. Rev. D 19 (1979) 941; J. N. Ng and P. Zakaraukas, Phys. Rev. D 29 (1984) 876; Z. Kunszt, Nucl. Phys. B 247, 339 (1984).
2. D. Rainwater, M. Spira and D. Zeppenfeld, hep-ph/0203187; T. Plehn, Phys. Rev. D 67 (2003) 014018; F. Maltoni, Z. Sullivan and S. Willenbrock, Phys. Rev. D 67 (2003) 093005; E. Boos and T. Plehn, Phys. Rev. D 69 (2004) 094005.
3. R. M. Barnett, H. E. Haber and D. E. Soper, Nucl. Phys. B 306 (1988) 697; D. A. Dicus and S. Willenbrock, Phys. Rev. D 39 (1989) 751.
4. R. V. Harlander and W. B. Kilgore, Phys. Rev. D 68 (2003) 013001.
5. D. Dicus, T. Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. D 59 (1999) 094016; C. Balazs, H. J. He and C. P. Yuan, Phys. Rev. D 60 (1999) 144001.
6. R. V. Harlander, these proceedings.
7. W. Beenakker, S. Dittmaier, M. Krämer, B. Plümper, M. Spira and P. M. Zerwas, Phys. Rev. Lett. 87 (2001) 201805 and Nucl. Phys. B 653 (2003) 151; L. Reina and S. Dawson, Phys. Rev. Lett. 87 (2001) 201804; L. Reina, S. Dawson and D. Wackeroth, Phys. Rev. D 65 (2002) 053017; S. Dawson, L. H. Orr, L. Reina and D. Wackeroth, Phys. Rev. D 67 (2003) 071503; S. Dawson, C. Jackson, L. H. Orr, L. Reina and D. Wackeroth, Phys. Rev. D 68 (2003) 034022.
8. S. Dittmaier, M. Krämer and M. Spira, hep-ph/0309204.
9. S. Dawson, C. B. Jackson, L. Reina and D. Wackeroth, Phys. Rev. D 69 (2004) 074027.
10. J. Campbell, S. Dawson, S. Dittmaier, C. Jackson, M. Krämer, F. Maltoni, L. Reina, M. Spira, D. Wackeroth and S. Willenbrock, hep-ph/0405302 and hep-ph/0406142.
11. J. Campbell, R. K. Ellis, F. Maltoni and S. Willenbrock, Phys. Rev. D 67 (2003) 095002.

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