

Inclusive Production of a Higgs or Z Boson in Association with Heavy Quarks

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Abstract

We calculate the cross section for the production of a Z boson in association with heavy quarks. We suggest that this cross section can be measured using an inclusive heavy-quark tagging technique. This could be used as a feasibility study for the search for a Higgs boson produced in association with bottom quarks. We argue that the best formalism for calculating that cross section is based on the leading-order process $b\bar{b} \rightarrow h$, and that it is valid for all Higgs masses of interest at both the Fermilab Tevatron and the CERN Large Hadron Collider.

I. INTRODUCTION

In the standard model, the Higgs boson has a very weak coupling to bottom quarks. However, in a two-Higgs-doublet model, the coupling of some or all of the physical Higgs particles to bottom quarks can be greatly enhanced. For example, this occurs in the minimal supersymmetric model for large values of $\tan\beta \equiv v_2/v_1$, where v_1 and v_2 are the vacuum expectation values of the Higgs doublets that couple to bottom and top quarks, respectively. If the coupling is sufficiently enhanced, the production of Higgs bosons in association with bottom quarks can be an important process at the Fermilab Tevatron ($p\bar{p}$, $\sqrt{S} = 1.96$ TeV) and the CERN Large Hadron Collider (LHC) (pp , $\sqrt{S} = 14$ TeV). A great deal of attention has been directed towards this process [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26].

In order to separate the signal from the background, and also to identify the production process, it is advantageous to tag one or more of the bottom quarks produced along with the Higgs boson (in addition to the bottom quarks that might result from Higgs decay). Up until now, this has been discussed as the identification of a high- p_T b -tagged jet. However, there exist more inclusive means to identify bottom quarks in the final state at hadron colliders, such as identifying a secondary vertex without requiring the reconstruction of a high- p_T jet [27]. In this paper we would like to lay the groundwork for such a measurement.

As a testing ground for the Higgs, we propose a measurement of the inclusive production of a Z boson in association with heavy quarks.¹ This is more complicated than the Higgs case for three reasons. First, the Z boson is produced in association with both bottom and charm quarks, so both possibilities must be taken into account. Second, Z bosons are dominantly produced in association with light quarks, which can fake a heavy quark. Third, the processes $q\bar{q} \rightarrow ZQ\bar{Q}$ and $qQ \rightarrow ZqQ$ ($Q = c, b$), where the Z couples to the light quarks, are contributions that have no analogue in the Higgs case.

There is a second motivation for this paper. There exist two different formalisms for the calculation of inclusive Higgs production in association with bottom quarks. The first is based on the leading-order (LO) process $gg \rightarrow hbb$, the second on the LO process $b\bar{b} \rightarrow h$.² The advantage of the latter formalism is that it resums, to all orders in perturbation theory,

¹ The production of a Z boson in association with a heavy-quark jet is dealt with in Refs. [28, 29].

² When a b distribution function is used, it is implicit that there is a spectator \bar{b} in the final state.

collinear logarithms of the form $\ln(m_h/m_b)$ that arise in the calculation based on $gg \rightarrow hb\bar{b}$ [30, 31]. It has recently been suggested that both formalisms may be unreliable for Higgs bosons at the Tevatron [32]. We will show evidence that the calculation based on $b\bar{b} \rightarrow h$ is reliable for Higgs masses of experimental interest, and argue for its superiority. However, we also find evidence that the formalism fails as the Higgs mass approaches the machine energy, in agreement with Ref. [32].

The paper is organized as follows. We first discuss, in Section II, the calculation of $b\bar{b} \rightarrow h$, and argue that it is reliable for all Higgs masses of interest at the Tevatron and LHC. We then turn in Section III to inclusive production of a Z boson with heavy quarks. Readers who are only interested in the latter topic may skip directly to that section. We conclude with a discussion of our results.

II. HIGGS PRODUCTION IN ASSOCIATION WITH HEAVY QUARKS

Inclusive Higgs production in association with bottom quarks may be calculated in two different schemes. One may work in a four-flavor scheme, where the leading-order (LO) process is $gg \rightarrow hb\bar{b}$. This approach yields collinear logarithms of the form $\ln(m_h/m_b)$, which degrade the convergence of the perturbation series. Alternatively, one may work in a five-flavor scheme, where the LO process is $b\bar{b} \rightarrow h$ [30, 31]. The calculation based on $b\bar{b} \rightarrow h$ yields a more convergent perturbation series, since the collinear logarithms are summed into the b -quark distribution functions via the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations. As one calculates to higher and higher order in perturbation theory, the two calculations should approach each other, since they are simply different orderings of the same terms.

The collinear logarithms that arise in $gg \rightarrow hb\bar{b}$ at LO can be captured by an approximate b -quark distribution function,

$$\tilde{b}(x, \mu_F) = \frac{\alpha_S(\mu_F)}{2\pi} \ln\left(\frac{\mu_F^2}{m_b^2}\right) \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y, \mu_F),$$

where $P_{qg}(x) = \frac{1}{2}[x^2 + (1-x)^2]$ is the LO DGLAP splitting function and μ_F is the factorization scale, of order m_h . Unlike the exact b distribution function, the approximate b distribution function does not sum the collinear logarithms. Thus the calculations $gg \rightarrow hb\bar{b}$ and $\tilde{b}\bar{b} \rightarrow h$ should approximately agree if the terms enhanced by collinear logarithms in

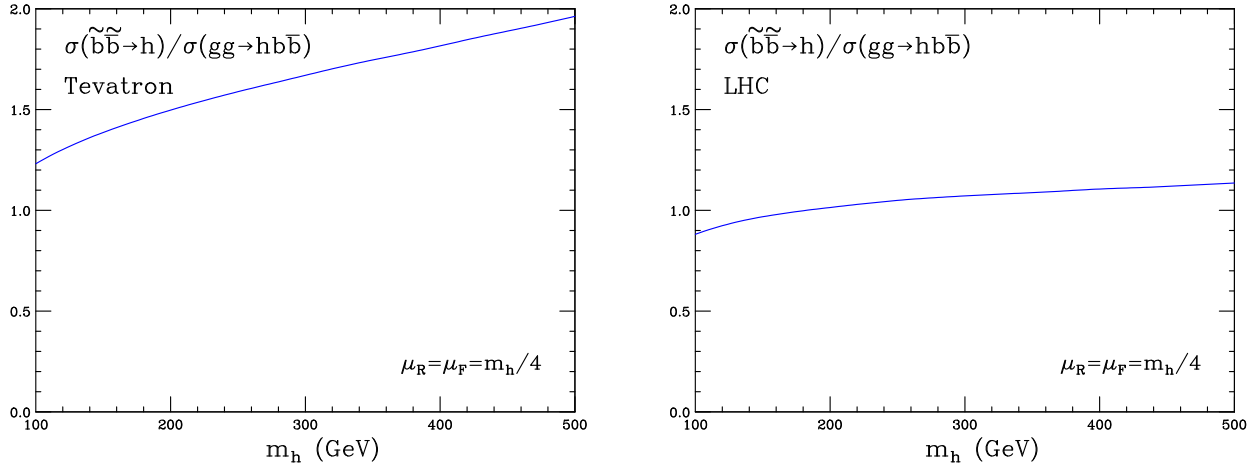


FIG. 1: $\sigma(\tilde{b}\tilde{b} \rightarrow h)/\sigma(gg \rightarrow hb\bar{b})$ vs. m_h at the Tevatron and the LHC, using MRST2001 LO parton distribution functions [33], $m_b = 4.7$ GeV, and $\mu_F (= \mu_R) = m_h/4$.

$gg \rightarrow hb\bar{b}$ are dominant.

Recently it was noted that the calculations $gg \rightarrow hb\bar{b}$ and $\tilde{b}\tilde{b} \rightarrow h$ differ substantially at LO for heavy Higgs bosons ($m_h > 100$ GeV) at the Tevatron, the discrepancy increasing with increasing Higgs mass [32]. In contrast, the two calculations agree fairly well at the LHC for $m_h = 100 - 500$ GeV as well as at the Tevatron for $m_h < 100$ GeV. Ref. [32] concludes that both calculations are suspect at the Tevatron for $m_h > 100$ GeV.

We show in Fig. 1 the ratio of $\tilde{b}\tilde{b} \rightarrow h$ to $gg \rightarrow hb\bar{b}$ at both the Tevatron and the LHC. These results agree closely with those of Ref. [32]. We see that the ratio is about 1.5 for $m_h = 200$ GeV at the Tevatron, increasing to nearly 2 for $m_h = 500$ GeV.

Implicit in this argument is the choice of the factorization scale. It was argued in Ref. [20] that the appropriate factorization scale is $\mu_F \approx m_h/4$, and this is the scale that was used in Ref. [32] and Fig. 1. We show below that for heavy Higgs bosons at the Tevatron, a slightly lower scale is more appropriate, and that this partially resolves the large discrepancy between the LO calculations of $gg \rightarrow hb\bar{b}$ and $\tilde{b}\tilde{b} \rightarrow h$.

The argument for the factorization scale made in Ref. [20] is based on an analysis of the collinear logarithm that arises at next-to-leading order (NLO) in the calculation of $b\bar{b} \rightarrow h$, and is in the same spirit as the argument of Refs. [35, 36]. In the collinear region, the NLO differential hadronic cross section scales like $d\sigma/dt \sim 1/t$, where t is the usual Mandelstam variable. We show in Fig. 2 the quantity $-t d\sigma/dt$ vs. $\sqrt{-t}/m_h$ for the NLO process $gb \rightarrow hb$

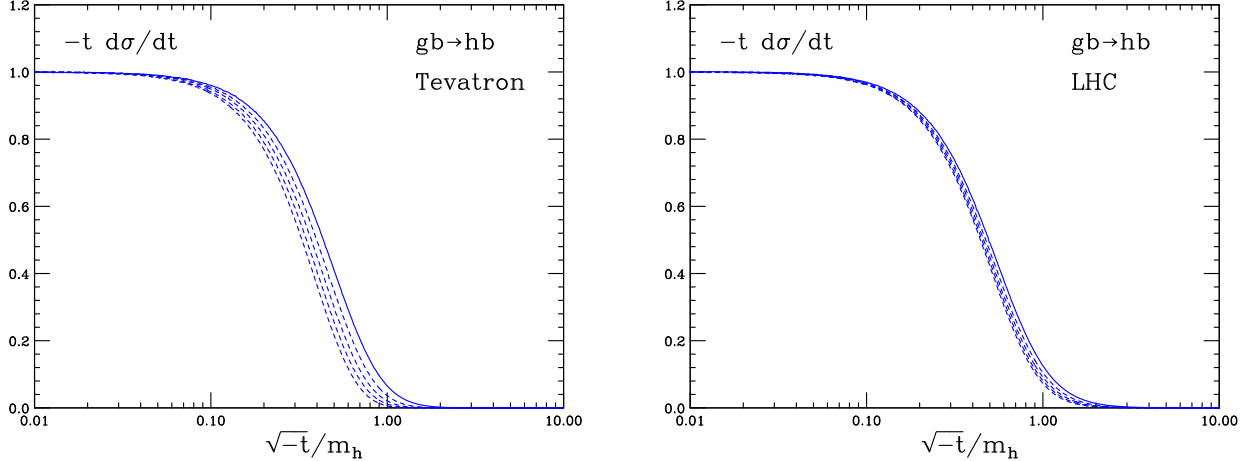


FIG. 2: $-t d\sigma/dt$ vs. $\sqrt{-t}/m_h$ for $gb \rightarrow hb$ at the Tevatron and the LHC. The factorization scale for $b\bar{b} \rightarrow h$ should be chosen near the end of the collinear plateau.

at both the Tevatron and the LHC for $m_h = 100 - 500$ GeV.³ The factorization scale should be chosen near the end of the collinear plateau. At the LHC this plateau ends around $m_h/4$ for the Higgs-boson masses considered. However, at the Tevatron the end of the plateau slowly creeps below $m_h/4$ as the Higgs-boson mass increases (this is also true at the LHC, but much less so).

To be consistent, we choose the factorization scale to be where $-t d\sigma/dt$ reaches 85% of its value on the collinear plateau. The resulting factorization scale at both the Tevatron and the LHC is given in Table I. We show in Fig. 3 the ratio of $\tilde{b}\tilde{b} \rightarrow h$ to $gg \rightarrow hb\bar{b}$ at both the Tevatron and the LHC with this choice of factorization scale. The ratio approaches unity for large Higgs masses at the LHC, as would be expected if the collinear logarithms dominate. The situation at the Tevatron is more complicated. The ratio is near unity for Higgs masses of experimental interest, indicating that the calculation is reliable. However, as the Higgs mass increases the ratio grows, and continues to grow as the mass approaches the machine energy. This suggests that the calculation based on $b\bar{b} \rightarrow h$ may be unreliable for very heavy Higgs bosons at the Tevatron.

In the full calculation of $b\bar{b} \rightarrow h$ (using the exact b distribution function) it is important to

³ Since this is a NLO process, we use NLO parton distribution functions [34]. We use $\mu_F = m_h$ (the default value), as this graph is being used to determine μ_F . We subsequently check that the curves are not very sensitive to the choice of μ_F .

m_h [GeV]	Tevatron	LHC
100	0.203	0.227
200	0.188	0.219
300	0.176	0.215
400	0.166	0.210
500	0.157	0.206

TABLE I: The factorization scale relative to the Higgs mass, μ_F/m_h , at the Tevatron and the LHC. The factorization scale is determined by the point at which the curves in Fig. 2 reach 85% of their values on the collinear plateau.

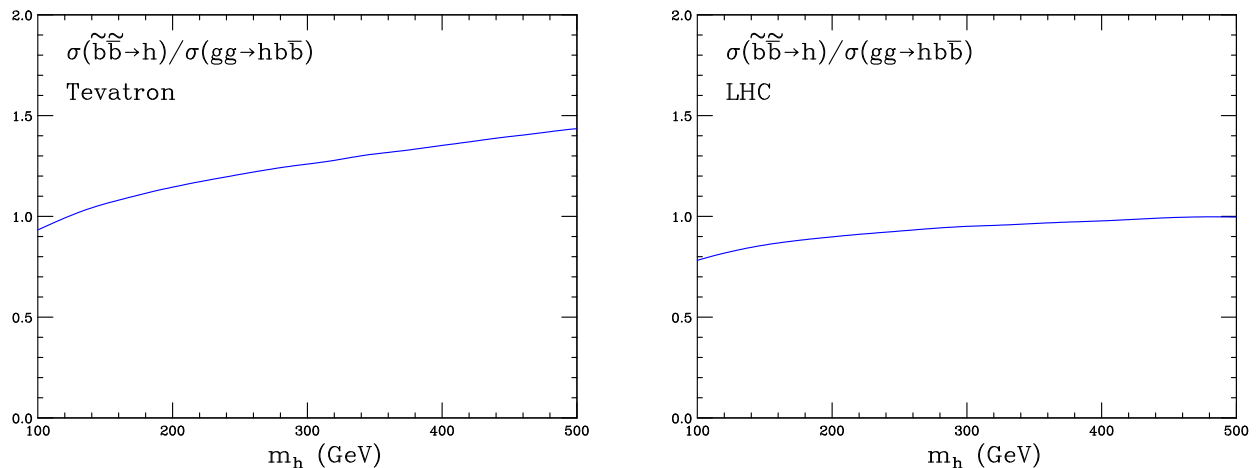


FIG. 3: $\sigma(\tilde{b}\tilde{b} \rightarrow h)/\sigma(gg \rightarrow hb\bar{b})$ vs. m_h at the Tevatron and the LHC, using MRST2001 LO parton distribution functions [33], $m_b = 4.7$ GeV, and $\mu_F (= \mu_R)$ determined from the end of the collinear plateau in Fig. 2 (listed in Table I).

choose the factorization scale near the end of the collinear plateau, but not very important exactly how that is defined. A less-than-optimal choice will be corrected by higher orders. Indeed, the next-to-next-to-leading-order (NNLO) calculation of $b\bar{b} \rightarrow h$ has very little factorization-scale dependence for values of μ_F near the end of the collinear plateau [21].

The advantage of the calculation based on the LO process $b\bar{b} \rightarrow h$ is actually twofold. As already discussed, it gives a more convergent perturbation series. In addition, it allows for a higher-order calculation than $gg \rightarrow hb\bar{b}$, since it is a simpler LO process. Indeed, $b\bar{b} \rightarrow h$

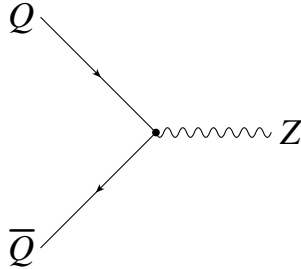


FIG. 4: Feynman diagram for $Q\bar{Q} \rightarrow Z$ ($Q = c, b$). The presence of heavy quarks in the final state is implied by the initial-state heavy quarks.

is known at NNLO [21], while $gg \rightarrow hb\bar{b}$ is known only at NLO [22, 23, 24]. Thus the NNLO calculation of $b\bar{b} \rightarrow h$ is the most accurate existing calculation of inclusive Higgs-boson production in association with bottom quarks. This is reflected by the very mild dependence of the NNLO calculation of $b\bar{b} \rightarrow h$ on the factorization scale in comparison with that of the NLO calculation of $gg \rightarrow hb\bar{b}$ [25]. It would be interesting to study the behavior of the NNLO calculation for very heavy Higgs bosons at the Tevatron.

III. Z PRODUCTION IN ASSOCIATION WITH HEAVY QUARKS

Unlike the case of the Higgs boson, there are a variety of contributions to the inclusive production of a Z boson with heavy quarks. The analogue of the Higgs case is $b\bar{b} \rightarrow Z$, shown in Fig. 4. In the case of the Z boson, one must also consider $c\bar{c} \rightarrow Z$ and $q\bar{q} \rightarrow Z$ ($q = u, d, s$), since both charm quarks and light quarks can fake a b quark. Finally, there are the processes $q\bar{q} \rightarrow ZQ\bar{Q}$ and $qQ \rightarrow ZqQ$ ($Q = c, b$), shown in Figs. 5 and 6, where the Z boson couples to the light quarks. As we will show, these last two processes are more important at the Tevatron than at the LHC.

Let us begin by considering only processes in which the Z boson couples to the heavy quarks. This is completely analogous to the case of the Higgs boson discussed in the previous section. We will then include processes in which the Z boson couples to light quarks, which have no analogue in the Higgs case.

The process $q\bar{q} \rightarrow Z$ has been calculated at next-to-next-to-leading order (NNLO) [37, 38, 39]. We modified this code to extract $Q\bar{Q} \rightarrow Z$ ($Q = c, b$) at NNLO, neglecting the

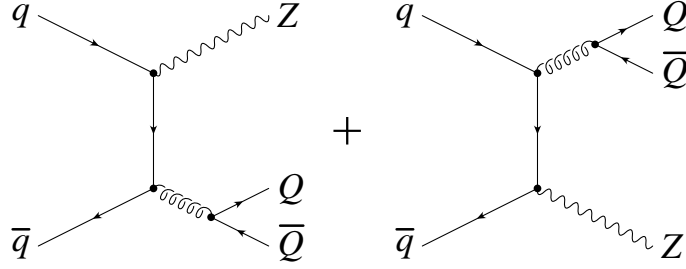


FIG. 5: Feynman diagrams for $q\bar{q} \rightarrow ZQ\bar{Q}$, where the Z couples to the light quarks.

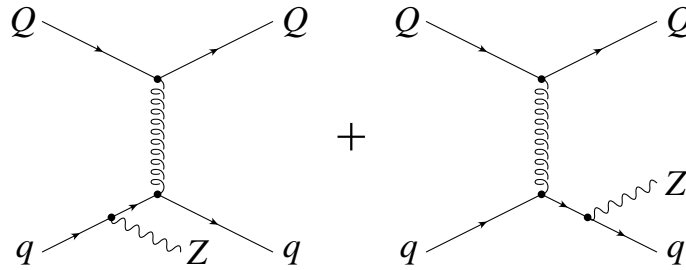


FIG. 6: Feynman diagrams for $qQ \rightarrow ZqQ$, where the Z couples to the light quarks

heavy-quark mass, which is a small effect of order $(m_Q/M_Z)^2 \times 1/\ln^2(M_Z/m_Q)$. We keep (for the moment) only diagrams in which the Z couples to the heavy quarks.⁴ We show in Fig. 7 the factorization-scale dependence of the cross section for $b\bar{b} \rightarrow Z$ at both the Tevatron and the LHC at LO, NLO, and NNLO. The renormalization scale has been set equal to the factorization scale, although this hardly matters as it first enters only at NLO, via the argument of $\alpha_S(\mu_R)$. As expected, the scale dependence decreases with increasing order, to the point where there is almost no scale dependence at NNLO. Similar results are obtained for $c\bar{c} \rightarrow Z$, as shown in Fig. 8.

Also shown on the same plot is the LO cross section in the four-flavor scheme, $gg \rightarrow Zb\bar{b}$. If we were to choose $\mu_F = \mu_R = M_Z$, this calculation would underestimate the true cross section by a factor of 4 at the Tevatron. If we choose the scale as in the previous section, by finding the end of the collinear plateau in $gb \rightarrow Zb$, we find that the appropriate factorization

⁴ This includes NNLO processes with four external heavy quarks of the same flavor. However, we do not include processes with two external charm and two external bottom quarks. These processes contribute less than 1% of the LO cross section.

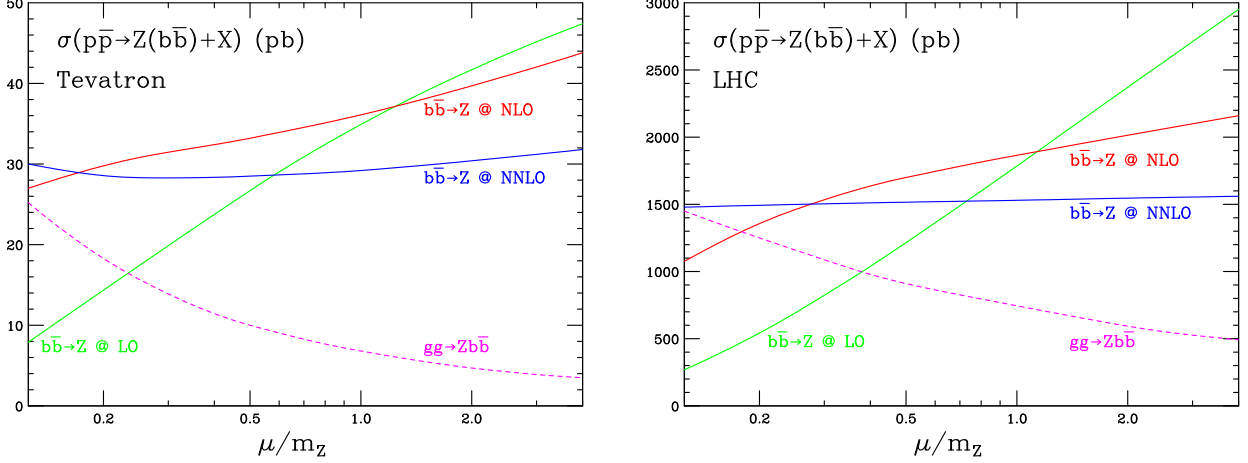


FIG. 7: Factorization-scale dependence of $b\bar{b} \rightarrow Z$ at LO, NLO, and NNLO at the Tevatron and the LHC. Only processes in which the Z couples to the heavy quarks are included. Also shown is $gg \rightarrow Z b\bar{b}$ at LO, using $m_b = 4.7$ GeV. We use the LO, NLO, and NNLO parton distribution functions MRST2001 LO [33] and MRST2002 [34].

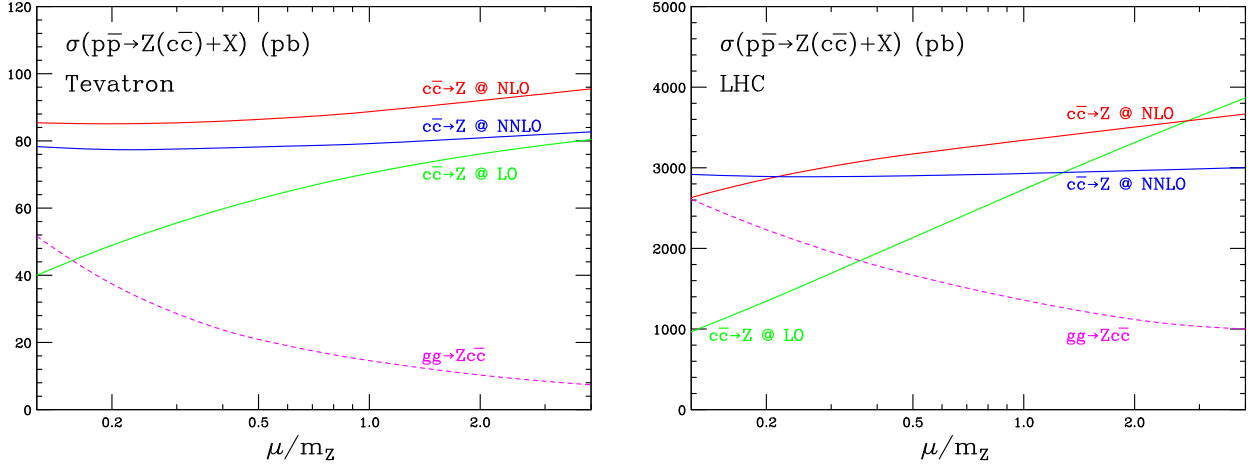


FIG. 8: Same as Fig. 7, but for $c\bar{c} \rightarrow Z$. For $gg \rightarrow Z c\bar{c}$, we use $m_c = 1.4$ GeV.

scale is around $M_Z/3$ at both the Tevatron and the LHC. With this choice of scale, the factor of 4 is reduced to 2. For charm, the corresponding factor is 5 at the Tevatron, reduced to 3. These results mirror a similar result that was obtained in the case of the Higgs [20].

We list in Table II the NNLO cross sections for $b\bar{b} \rightarrow Z$ and $c\bar{c} \rightarrow Z$ at both the Tevatron and the LHC. These cross sections have very little theoretical uncertainty.

We now include processes in which the Z couples to light quarks, shown in Figs. 5 and

6.⁵ Here it is essential to keep the heavy-quark mass nonzero in order to regulate collinear singularities.⁶ While these processes are NNLO with respect to inclusive Z production, $q\bar{q} \rightarrow ZQ\bar{Q}$ is LO with respect to Z production in association with heavy quarks, and $qQ \rightarrow ZqQ$ is NLO. The correct power counting is obtained when one recalls that a heavy-quark distribution function is intrinsically of order $\alpha_S \ln(\mu_F/m_Q)$ [40]. The analogous processes for heavy-quark structure functions in deep-inelastic scattering, F_i^Q , have been discussed in Ref. [41].

There are two serious drawbacks to the calculations of these processes. First, the cross sections contain factors of $\ln(M_Z/m_Q)$, due to the collinear singularities, which are not resummed. This is related to the fact that we are calculating a semi-inclusive quantity, namely Z production in association with heavy quarks. If we were instead calculating the inclusive Z cross section, this issue would not arise. Fracture functions may be useful in this context [42]. Second, and more importantly, these processes are only known at LO at this time (with a nonzero quark mass).⁷ The NLO calculation is an important missing result for this as well as many other analyses (the same holds true of $q\bar{q} \rightarrow WQ\bar{Q}$). Thus our calculation of these processes is relatively crude. This is a serious problem at the Tevatron, but less so at the LHC, where these processes are relatively less important. It is desirable both to obtain NLO results for $q\bar{q} \rightarrow ZQ\bar{Q}$ and $qQ \rightarrow ZqQ$ (with finite m_Q) and to develop a formalism that allows the resummation of the collinear logarithms.⁸

We give in Table II the cross sections for the various processes that contribute to Z production in association with heavy quarks. We also give the inclusive Z cross section at NNLO. Although this cross section is two orders of magnitude larger than that of any of the processes that produce a Z in association with heavy quarks, the mistag rate for light

⁵ We also consider the process $Q\bar{Q} \rightarrow Zq\bar{q}$, where the Z couples to the light quarks. We find this to be numerically negligible. The interference with the same process, but where the Z couples to the heavy quarks, is also negligible.

⁶ We also evaluate the interference of these processes with the similar processes in which the Z is radiated from the heavy quark. This may be done in the limit of vanishing heavy-quark mass, since there are no collinear singularities. We find that these interference contributions are numerically negligible.

⁷ The process $q\bar{q} \rightarrow ZQ\bar{Q}$ is known at NLO with a vanishing quark mass, which is relevant when the heavy quarks are produced at high p_T [43].

⁸ The collinear logarithm that occurs in $qQ \rightarrow ZqQ$ also occurs in the process $qg \rightarrow ZqQ\bar{Q}$, where the initial gluon splits to $Q\bar{Q}$. Thus the same issues arise in a calculation that does not make use of a heavy-quark distribution function.

Process		Tevatron	LHC
$Z(b\bar{b})$	$b\bar{b} \rightarrow Z$ (NNLO)	28.3	1500
	$q\bar{q} \rightarrow Zb\bar{b}$ (LO)	19	120
	$qb \rightarrow Zqb$ (LO)	5.9	430
$Z(c\bar{c})$	$c\bar{c} \rightarrow Z$ (NNLO)	77.7	2890
	$q\bar{q} \rightarrow Zc\bar{c}$ (LO)	69	430
	$qc \rightarrow Zqc$ (LO)	21	1200
Inclusive Z		7510	56700

TABLE II: Cross sections (pb) for the various contributions to Z production in association with heavy quarks. We use the MRST2002 NNLO parton distribution functions [34] with $\mu_F = \mu_R = M_Z/3$.

quarks and gluons is on the order of 1%, so this background is not overwhelming.

IV. CONCLUSIONS

Our results for Z production in association with heavy quarks are summarized in Table II. The final row is the inclusive Z cross section calculated at next-to-next-to-leading order (NNLO). Each row above that corresponds to some subset of this calculation, with heavy quarks in the final state, either implicitly (such as $Q\bar{Q} \rightarrow Z$) or explicitly (such as $q\bar{q} \rightarrow ZQ\bar{Q}$). We see that there are a large variety of processes that contribute to Z production in association with heavy quarks. Taken together, they constitute 3% of the inclusive Z cross section at the Tevatron, and 12% at the LHC. The measurement of these fractions will require simulation of the acceptances and tagging efficiencies of the various processes. We advocate using an inclusive tagging technique to maximize the number of signal events.

The measurement of Z production in association with heavy quarks is interesting in its own right, but also as a feasibility study for Higgs production in association with bottom

quarks. In this paper we have argued that the best formalism for the calculation of the latter process is based on the leading-order process $b\bar{b} \rightarrow h$, and that this calculation is valid for all Higgs masses of interest at both the Tevatron and the LHC. The most accurate calculation of this process is the NNLO cross section given in Ref. [21]. We also showed evidence that this formalism fails as the Higgs mass approaches the machine energy.

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