hep-ph/0510362
CERN-PH-TH/2005-064
FERMILAB-PUB-05/487-T
ILL-(TH)-05-04
February 2, 2008

Production of a Z Boson and Two Jets with One Heavy-Quark Tag

J. Campbell[1], **R. K. Ellis**[1,2], **F. Maltoni**[1,3], and **S. Willenbrock**[4]

[1]CERN, CH-1211 Geneva 23, Switzerland

[2]Theoretical Physics Department, Fermi National Accelerator Laboratory
P. O. Box 500, Batavia, IL 60510

[3]Institut de Physique Théorique, Université Catholique de Louvain
Chemin du Cyclotron, 2, B-1348 Louvain-la-Neuve, Belgium

[4]Department of Physics, University of Illinois at Urbana-Champaign
1110 West Green Street, Urbana, IL 61801

Abstract

We present a next-to-leading-order calculation of the production of a Z boson with two jets, one or more of which contains a heavy quark ($Q = c, b$). We show that the cross section with only one heavy-quark jet is larger than that with two heavy-quark jets at both the Fermilab Tevatron and the CERN LHC. These processes are the dominant irreducible backgrounds to a Higgs boson produced in association with a Z boson, followed by $h \to b\bar{b}$. Our calculation makes use of a heavy-quark distribution function, which resums collinear logarithms and makes the next-to-leading-order calculation tractable.

1 Introduction

The discovery of new physics at hadron colliders often relies on a detailed understanding of standard-model background processes. Prominent among these is the production of weak bosons (W, Z) in association with jets, one or more of which contains a heavy quark $(Q = c, b)$. The prime example is the discovery of the top quark at the Fermilab Tevatron, which required a thorough understanding of the W+jets background, with one or more heavy-quark jets [1, 2, 3]. The discovery of single-top-quark production via the weak interaction requires an even more sophisticated understanding of this background [4, 7].

In this paper we present a next-to-leading-order (NLO) calculation of the production of a Z boson in association with two or more jets, one or more of which contains a heavy quark. This is the dominant irreducible background to the production of a Higgs boson in association with a Z boson, followed by $h \to b\bar{b}$ [5, 6]. This signal is currently being sought at the Tevatron with either one or both b jets tagged [8]. The calculation we present provides the irreducible background at NLO for both cases.

The production of a Z boson plus two jets with at least one heavy-quark jet is also a background to the production of a Higgs boson in association with one or more b jets, which is a discovery mode for a supersymmetric Higgs boson at large values of $\tan\beta$ [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 33, 26, 27, 28, 29, 30, 31, 32].[1] This background process is also a benchmark for this Higgs discovery channel. The search for a supersymmetric Higgs boson via this mode is underway at the Tevatron [33, 34, 35], and will be vigorously pursued at the CERN Large Hadron Collider (LHC) [36, 37].

When one considers the production of a heavy quark at a hadron collider, ones first thought is usually of a virtual gluon splitting into a final-state $Q\overline{Q}$ pair, as shown in Fig. 1(a), or via gluon fusion, as shown in Fig. 1(b). However, initial gluons splitting into a $Q\overline{Q}$ pair is just as important a source at the Tevatron, and even more important at the LHC, when only one heavy quark is observed at high transverse momentum (p_T). In that situation, it is advantageous to think of the initial gluon as splitting into a collinear $Q\overline{Q}$ pair, with one heavy quark remaining at low p_T while the other heavy quark participates in the hard scattering and emerges at high p_T. The heavy quark that participates in the hard scattering can be treated as part of the proton sea, with a parton distribution function that is calculated perturbatively from the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations [5, 6]. The production of a Z boson with two jets, one of which contains a heavy quark, then proceeds as shown in Fig. 2.

The reasons for using a heavy-quark distribution function are twofold. First, it resums collinear logarithms of the form $\ln Q/m_Q$ to all orders, where Q is the scale of the hard scattering. Second, it simplifies the leading-order process, which makes a higher-order calculation tractable.

This paper completes the NLO calculation of Z+jets, with one or more heavy quarks, up to two jets [40]. The production of a Z plus one jet, with one or more heavy quarks, was presented in Ref. [41], and agrees well with data from the Tevatron [42]. The inclusive production of a Z with one or more heavy quarks was presented in Ref. [43].

---

[1] The minimal supersymmetric standard model requires two Higgs doublets; the ratio of their vacuum expectation values is $\tan\beta \equiv v_2/v_1$.

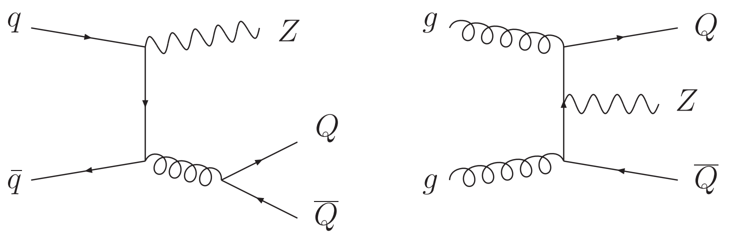

Figure 1: Diagrams contributing to the associated production of a Z boson and two high-p_T heavy quarks ($Q = c, b$).

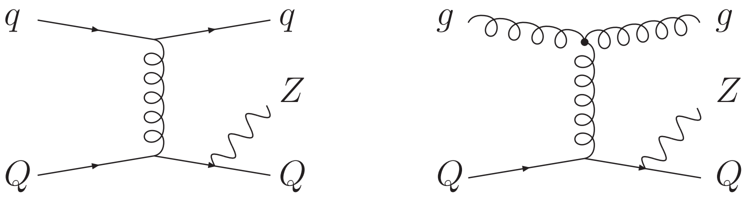

Figure 2: Diagrams contributing to the associated production of a Z boson and two high-p_T jets, one of which contains a heavy quark ($Q = c, b$).

2 ZQj at NLO

The leading-order (LO) processes for Z plus two jets, one or more of which contains a heavy quark, are $q\bar{q}(gg) \to ZQ\overline{Q}$ (Fig. 1) and $Qq(g) \to ZQq(g)$ (Fig. 2). The LO cross sections are given in Table 1, with the jets satisfying the conditions $p_T > 15$ GeV, $|\eta| < 2$ (2.5 at the LHC), and $\Delta R_{jj} > 0.7$. At the Tevatron, the leading-order cross sections for these two classes of processes are comparable; at the LHC, the latter dominates. The processes $Qq(g) \to ZQq(g)$ are relatively more important at the LHC than at the Tevatron because they are initiated by a heavy sea quark, whose distribution function rises at small values of x. Furthermore, $Qg \to ZQg$ is larger than $Qq \to ZQq$ at the LHC, while they are comparable at the Tevatron, since the former involves the gluon distribution function, which is large at small values of x. For the same reason, $gg \to ZQ\overline{Q}$ is dominant at the LHC compared with $q\bar{q} \to ZQ\overline{Q}$, while the latter is more important at the Tevatron.

As is often the case, the distinction between the various processes is lost once one goes beyond leading order. Fig. 2(a) shows a Feynman diagram which ostensibly contributes to the NLO correction to $q\bar{q} \to ZQ\overline{Q}$, while the Feynman diagram in Fig. 2(b) ostensibly contributes to the NLO correction to $Qq \to ZQq$, and the diagram in Fig. 2(c) to the NLO correction to $gg \to ZQ\overline{Q}$. However, all three diagrams contribute to the same amplitude, and therefore interfere. Thus one cannot uniquely identify them with any of the leading-order processes.

The next-to-leading-order calculations in this paper were performed with the Monte-Carlo code MCFM [46]. The leading-order calculations were performed both with this code and with MadEvent [47]. The NLO corrections are included in the code MCFM by implementing the virtual helicity amplitudes of Ref. [48]. These are given in the four-dimensional helicity scheme, which is used throughout the calculation. The real corrections are adapted from

Table 1: Leading-order cross sections (pb) for Z boson plus two jets, one or two of which contains a heavy quark, at the Tevatron ($\sqrt{s} = 1.96$ TeV $p\bar{p}$) and the LHC ($\sqrt{s} = 14$ TeV pp). A jet lies in the range $p_T > 15$ GeV and $|\eta| < 2$ (2.5 at the LHC), with $\Delta R_{jj} > 0.7$. No branching ratios or tagging efficiencies are included. The labels on the columns have the following meaning: ZQj = exactly two jets, one of which contains a heavy quark; $ZQ\overline{Q}$ = exactly two jets, both of which contain a heavy quark. The CTEQ6L1 parton distribution functions are used [7], with the factorization and renormalization scales chosen as $\mu_F = \mu_R = M_Z$. Also given, in square brackets, is the LO cross section obtained without using a heavy-quark distribution function, from $gq(g) \to ZQ\overline{Q}q(g)$.

Process	σ (pb)			
	Tevatron		LHC	
	ZQj	$ZQ\overline{Q}$	ZQj	$ZQ\overline{Q}$
$bq \to Zbq + bg \to Zbg$	0.89+1.29=2.18 [1.91]	–	76+276=352 [191]	–
$q\bar{q} \to Zb\bar{b} + gg \to Zb\bar{b}$	–	1.89+0.58=2.47	–	13+96=109
$cq \to Zcq + cg \to Zcg$	1.37+1.83=3.20 [3.26]	–	98+345=443 [271]	–
$q\bar{q} \to Zc\bar{c} + gg \to Zc\bar{c}$	–	1.89+0.45=2.34	–	12+75=87

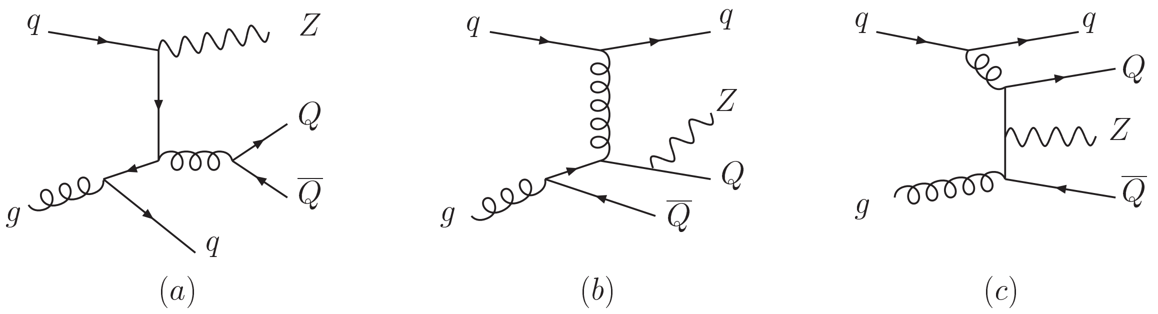

Figure 3: Diagrams contributing to the NLO correction to the associated production of a Z boson and two high-p_T jets, one or more of which contains a heavy quark ($Q = c, b$).

Ref. [49] and singularities are handled using the dipole subtraction method [4]. Since the matrix elements contain the decay of the gauge boson into massless particles, the code is general enough to provide results for final states from $\gamma^*, Z^* \to \ell^+\ell^-$ (including interference). For this paper we specialize to the case of a real Z boson.

The processes involved in the calculation are as follows:

- $q\bar{q} \to ZQ\overline{Q}$ at tree level (Fig. 1) and one loop
- $gg \to ZQ\overline{Q}$ at tree level (Fig. 1) and one loop
- $Qq \to ZQq$ at tree level (Fig. 2) and one loop
- $Qg \to ZQg$ at tree level (Fig. 2) and one loop
- $q\bar{q} \to ZQ\overline{Q}g$ at tree level
- $gg \to ZQ\overline{Q}g$ at tree level
- $Qg \to ZQgg$ at tree level
- $Qq \to ZQqg$ at tree level
- $gq \to ZQ\overline{Q}q$ at tree level (Fig. 2)
- $Qg \to ZQq\bar{q}$ at tree level

We also include the processes $QQ' \to ZQQ'$, $Q\overline{Q}' \to ZQ\overline{Q}'$, and $Q\overline{Q} \to ZQ'\overline{Q}'$ at LO. These processes are already small at LO, so it is safe to neglect their NLO corrections. For charm final states, we only take $Q = Q' = c$; for bottom, $Q, Q' = c, b$.

The results of our calculation are presented in Tables 2 and 3. The columns ZQj and $ZQ\overline{Q}$ contain the leading-order cross sections (in parentheses) for the processes $Qq(g) \to ZQq(g)$ and $q\bar{q}(gg) \to ZQ\overline{Q}$, respectively, taken from Table 1. We require the jets to satisfy the conditions $p_T > 15$ GeV, $|\eta| < 2$ (2.5 at the LHC), and $\Delta R_{jj} > 0.7$. The heavy-quark mass is neglected here and throughout the calculation (except where noted). To

Table 2: Cross sections (pb) for Z-boson plus two (or more) jets, one or more of which contains a heavy quark, at the Tevatron ($\sqrt{s} = 1.96$ TeV $p\bar{p}$). A jet lies in the range $p_T > 15$ GeV and $|\eta| < 2$. Two final-state partons are merged into a single jet if $\Delta R_{jj} < 0.7$. No branching ratios or tagging efficiencies are included. Numbers in parenthesis are leading-order results. The labels on the columns have the following meaning: ZQj = exactly two jets, one of which contains a heavy quark; $ZQ\overline{Q}$ = exactly two jets, both of which contain a heavy quark; $Z(Q\overline{Q})j$ = exactly two jets, one of which contains a heavy-quark pair; $ZQ\overline{Q}j$ = exactly three jets, two of which contain a heavy quark; $ZQjj$ = exactly three jets, one of which contains a heavy quark. For the last set of processes, the labels mean: Zjj = exactly two jets, including heavy quarks; $Zjjj$ = exactly three jets, including heavy quarks. For ZQj and $ZQ\overline{Q}$, both the leading-order (in parentheses) and next-to-leading-order cross sections are given. The CTEQ6M parton distribution functions are used throughout, except for the LO cross sections in parentheses, where CTEQ6L1 is used [7]. The factorization and renormalization scales are chosen as $\mu_F = \mu_R = M_Z$.

Tevatron	σ (pb)				
	ZQj	$ZQ\overline{Q}$	$Z(Q\overline{Q})j$	$ZQ\overline{Q}j$	$ZQjj$
bottom	(2.18) 5.23	(2.47) 3.07	0.634	0.672	0.326
charm	(3.20) 7.49	(2.34) 2.75	2.00	0.621	0.495
	Zjj			$Zjjj$	
Z+jets	(163) 182			22.9	

obtain the NLO cross sections for ZQj and $ZQ\overline{Q}$, which involve the radiation of additional partons (*e.g.*, Fig. 2), two partons are combined into a single jet by adding their four-momenta if $\Delta R_{jj} < 0.7$. If the combined partons are both heavy quarks, then the process contributes to the column labeled $Z(Q\overline{Q})j$. This is a $Z + 2j$ event in which one jet contains two heavy quarks, which changes the tagging probability for that jet [51]. It is calculated with a finite heavy-quark mass ($m_c = 1.4$ GeV, $m_b = 4.75$ GeV) in order to regulate the logarithmic divergence present when the heavy quarks are collinear. If all three partons are well separated, then the process contributes to either $ZQ\overline{Q}j$ or $ZQjj$.[2]

We checked that the effect of the heavy-quark mass is negligible by comparing $ZQ\overline{Q}$ at tree level with and without a finite quark mass. Similarly, we found that the heavy-quark mass is also negligible for $ZQ\overline{Q}j$ at tree level, as expected.

The NLO correction to ZQj is quite sizable at the Tevatron, more than 100%. One of the reasons is that the process $q\bar{q} \to ZQ\overline{Q}g$ (where one of the heavy quarks is outside the acceptance) makes a relatively large contribution. This is not really a NLO correction

---

[2] The matrix elements for both $Z(Q\overline{Q})j$ and $ZQ\overline{Q}j$ are calculated with a finite heavy-quark mass, but massive phase space is used only in the former. We checked that the quark mass is numerically irrelevant to the latter process.

Table 3: Same as Table 2, except at the LHC ($\sqrt{s}$ = 14 TeV pp). A jet lies in the range $p_T > 15$ GeV and $|\eta| < 2.5$.

LHC	σ (pb)				
	ZQj	$ZQ\overline{Q}$	$Z(Q\overline{Q})j$	$ZQ\overline{Q}j$	$ZQjj$
bottom	(352) 421	(109) 92.1	23.5	60.8	92.1
charm	(443) 623	(87) 75.2	58.6	49.3	123
	Zjj			$Zjjj$	
Z+jets	(6090) 4840			1810	

to $Qq(g) \to ZQq(g)$, but rather a new channel. This contribution is about 1.2 pb for both bottom and charm at the Tevatron. In contrast, this process makes a relatively small contribution to ZQj at the LHC, only 10 pb for bottom and 4 pb for charm.

We also list in Tables 2 and 3 the LO (in parentheses) and NLO cross sections for Zjj [40, 52, 53], and the LO cross section for $Zjjj$. In these cross sections we have included the contribution from light partons as well as heavy quarks. Thus, for example, the fraction of $Z + 2j$ events in which only one of the jets contains heavy quarks is given by $[ZQj + Z(Q\overline{Q})j]/Zjj$.

In Tables 4 and 5 we list the results in an inclusive manner, and also include the NLO result for Z plus one heavy-quark jet [41]. In addition, we give the NLO cross section for Zj [41], including both light and heavy partons. Thus $ZQ + X$ is the cross section for a Z plus at least one heavy-quark jet; it is the sum of the columns labeled ZQ, ZQj, and $ZQ\overline{Q}$ in Tables 1 and 2 of Ref. [41], including all contributing processes. $Z(Q\overline{Q})$ contains one jet which contains a heavy-quark pair. It is calculated at LO, including the heavy-quark mass in order to regulate the collinear divergence present in $q\bar{q} \to Z(Q\overline{Q})$. $ZQj + X$ has at least two jets, one of which contains a heavy quark; it is the sum of the columns labeled ZQj and $ZQjj$ in Tables 2 and 3. $ZQ\overline{Q} + X$ has at least two jets, two of which contain a heavy quark; it is the sum of the columns labeled $ZQ\overline{Q}$ and $ZQ\overline{Q}j$ in Tables 2 and 3. Finally, $Z(Q\overline{Q})j$ contains two jets, one of which contains a heavy-quark pair; it is calculated at LO with a finite quark mass.

We estimate the uncertainties in the NLO inclusive cross sections by varying the renormalization scale, the factorization scale, and the parton distribution functions independently. The renormalization scale is varied over $\mu_R = (0.5-2)M_Z$, with $\mu_F = M_Z$. Similarly, we vary $\mu_F = (0.5-2)M_Z$ with $\mu_R = M_Z$. The uncertainties due to scale variation are significantly reduced at NLO in comparison with the LO calculation. Significant renormalization-scale dependence remains since the process is $\mathcal{O}(\alpha_S^2)$. The parton distribution functions are varied over the 41 different sets contained in CTEQ6M [7, 45]. A symmetric uncertainty on the cross sections can be obtained from these sets by using Eq. (26) of Ref. [54]. In addition, we have studied the deviation of the cross section in each direction separately, as in Ref. [55].

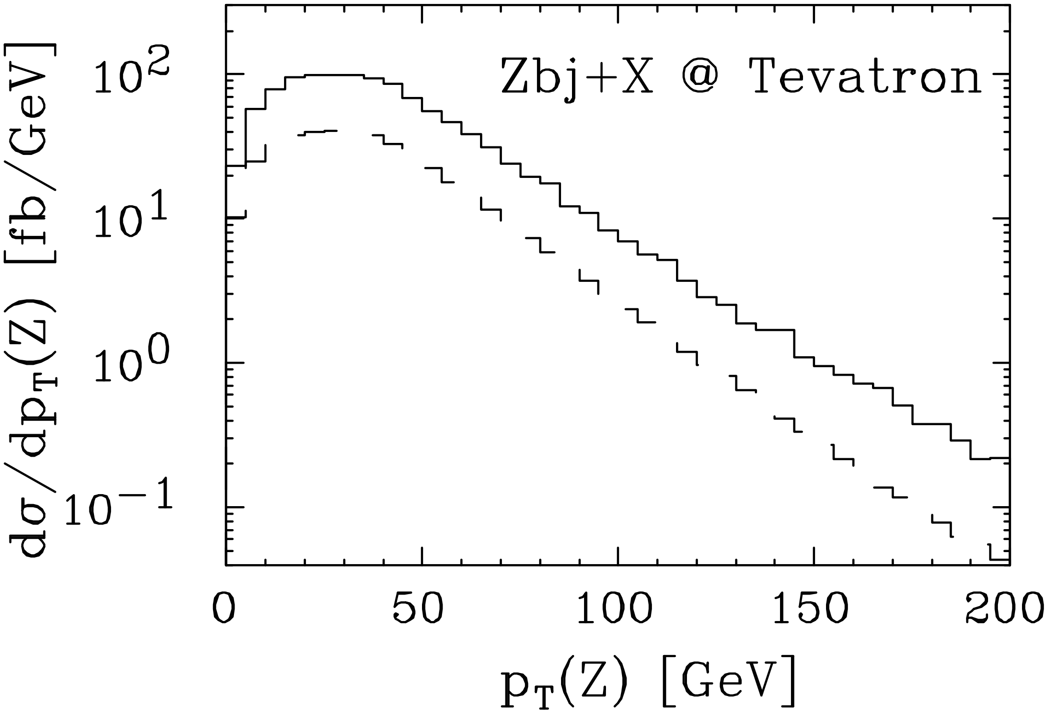

Figure 4: Transverse-momentum distribution of the Z boson in events with at least two jets, one of which contains a bottom quark, at the Tevatron ($\sqrt{s} = 1.96$ TeV $p\bar{p}$). The jets satisfy the conditions $p_T > 15$ GeV, $|\eta| < 2$, and $\Delta R_{jj} > 0.7$. Both LO (dashed) and NLO (solid) distributions are shown.

However, we find that the difference between the positive and negative deviations is not significant in any of the cases and thus we report only symmetric uncertainties.

As an example of the use of these tables, consider the inclusive cross section for $Z+$ 2 jets with one heavy-quark tag. This cross section is obtained from

$$\sigma = \epsilon_Q \sigma_{ZQj+X} + 2\epsilon_Q(1-\epsilon_Q)\sigma_{ZQ\overline{Q}+X} + \epsilon_{Q\overline{Q}}\sigma_{Z(Q\overline{Q})j} \tag{1}$$

where ϵ_Q is the tagging probability for a heavy-quark jet, and $\epsilon_{Q\overline{Q}}$ is the tagging probability for a jet containing a heavy-quark pair.

We show in Figures 4 and 5 the transverse-momentum spectrum of the Z boson in events with at least two jets, one of which contains a bottom quark, at the Tevatron and the LHC. Both the LO and NLO distributions are shown. The radiative corrections do not significantly change the shape of the distribution, as is often the case when the quantity plotted is not affected by the change in the kinematics due to additional radiation.

3 Conclusions

In this paper we present a NLO calculation of the production of a Z boson plus two jets, one or more of which contains a heavy quark. This greatly improves the accuracy with which

Table 4: Inclusive cross sections (pb) for Z boson plus one or two jets, one or two of which contains a heavy quark, at the Tevatron ($\sqrt{s} = 1.96$ TeV $p\bar{p}$). A jet lies in the range $p_T > 15$ GeV and $|\eta| < 2$. Two final-state partons are merged into a single jet if $\Delta R_{jj} < 0.7$. No branching ratios or tagging efficiencies are included. Numbers in parenthesis are leading-order results. The labels on the columns have the following meaning: $ZQ + X$ = at least one jet, at least one of which contains a heavy quark; $Z(Q\overline{Q})$ = one jet which contains a heavy-quark pair; $ZQj + X$ = at least two jets, one of which contains a heavy quark; $ZQ\overline{Q} + X$ = at least two jets, two of which contain a heavy quark; $Z(Q\overline{Q})j$ = two jets, one of which contains a heavy-quark pair. The last row gives the inclusive cross section for jets containing both light and heavy partons. The CTEQ6M parton distribution functions are used throughout, except for the LO cross sections in parentheses, where CTEQ6L1 is used [7]. The factorization and renormalization scales are chosen as $\mu_F = \mu_R = M_Z$. The uncertainties are from the variation of the renormalization scale, the factorization scale, and the parton distribution functions, respectively.

Tevatron	σ (pb)				
	$Z + 1$ jet $+X$		$Z + 2$ jets $+X$		
	$ZQ + X$	$Z(Q\overline{Q})$	$ZQj + X$	$ZQ\overline{Q} + X$	$Z(Q\overline{Q})j$
bottom	(8.23) 18.1	2.1	(2.19) $5.56^{+1.2}_{-0.9}{}^{+0.07}_{-0.05}{}^{+0.5}_{-0.5}$	(2.49) $3.74^{+0.45}_{-0.45}{}^{+0.12}_{-0.12}{}^{+0.15}_{-0.15}$	$0.63^{+0.26}_{-0.16}{}^{+0.06}_{-0.06}{}^{+0.05}_{-0.05}$
charm	(11.3) 27.5	6.6	(3.21) $8.23^{+1.7}_{-1.4}{}^{+0.15}_{-0.26}{}^{+0.8}_{-0.8}$	(2.35) $3.47^{+0.44}_{-0.37}{}^{+0.0}_{-0.87}{}^{+0.14}_{-0.14}$	$2.08^{+0.85}_{-0.53}{}^{+0.22}_{-0.16}{}^{+0.15}_{-0.15}$
all jets	(898) 1070		(163) $205^{+19}_{-19}{}^{+7}_{-2}{}^{+5}_{-5}$		

Table 5: Same as Table 4, except at the LHC ($\sqrt{s} = 14$ TeV pp). A jet lies in the range $p_T > 15$ GeV and $|\eta| < 2.5$.

LHC	σ (pb)				
	$Z + 1$ jet $+X$		$Z + 2$ jets $+X$		
	$ZQ + X$	$Z(Q\overline{Q})$	$ZQj + X$	$ZQ\overline{Q} + X$	$Z(Q\overline{Q})j$
bottom	(826) 1060	25	(353) $513^{+84}_{-58}{}^{+44}_{-35}{}^{+25}_{-25}$	(111) $153^{+20}_{-20}{}^{+2}_{-2}{}^{+9}_{-9}$	$24^{+10}_{-6}{}^{+0.3}_{-0.3}{}^{+1.2}_{-1.2}$
charm	(989) 1430	50	(443) $746^{+110}_{-110}{}^{+0}_{-46}{}^{+45}_{-45}$	(90) $125^{+17}_{-17}{}^{+2}_{-2}{}^{+8}_{-8}$	$59^{+23}_{-15}{}^{+2}_{-2}{}^{+3}_{-3}$
all jets	(15300) 18400		(6090) $6650^{+470}_{-500}{}^{+170}_{-50}{}^{+240}_{-240}$		

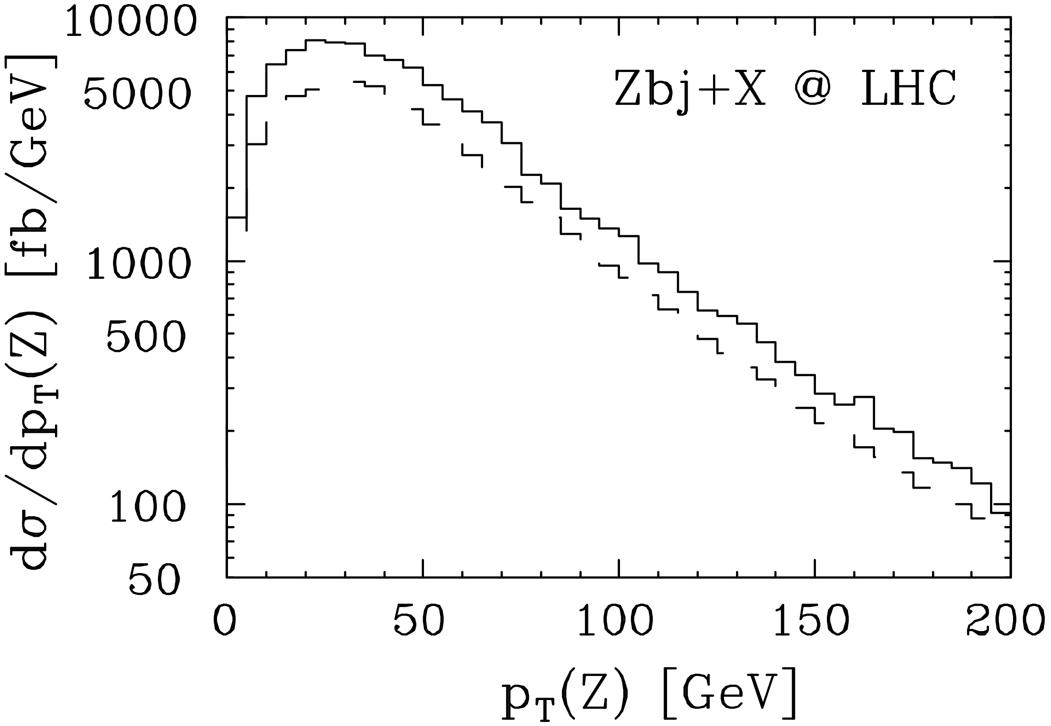

Figure 5: Same as Fig. 4, but at the LHC ($\sqrt{s} = 14$ TeV pp). The jets satisfy the conditions $p_T > 15$ GeV, $|\eta| < 2.5$, and $\Delta R_{jj} > 0.7$.

this fundamental background is known at the Tevatron and the LHC. We provide our results in both an exclusive (Tables 2 and 3) and an inclusive manner (Tables 4 and 5). The NLO cross section is significantly greater than the LO cross section for the default scale choice $\mu_F = \mu_R = M_Z$.

Our calculation makes use of the heavy quarks present in the proton sea, which are perturbatively calculable. This makes the LO calculation simpler, thus allowing a higher-order calculation to be tractable. We showed that the processes $Qq(g) \to ZQq(g)$ are a significant source of ZQj events at the Tevatron, and the dominant source at the LHC.

Alternatively, one could eschew the heavy quarks in the proton sea, and regard the proton as containing only light quarks and gluons. In that approach, the LO processes for ZQj are $gq(g) \to ZQ\overline{Q}q(g)$, where one of the heavy quarks is outside the acceptance of the detector. We give the results of this calculation in square brackets in Table 1, using CTEQL1 with $\mu_F = \mu_R = M_Z$. The results are quite consistent with the LO results of the heavy-quark approach at the Tevatron, but at the LHC they lie somewhat below, though within a factor of two. In any case, the most accurate cross sections are the NLO results presented in this paper, based on the heavy-quark approach.

An important application of these results is to the search for the Higgs boson via $q\bar{q} \to Zh$, followed by $h \to b\bar{b}$, where the signal is $Z + 2j$ with one or two b tags [8]. We provide NLO results for the backgrounds with either one or two heavy-quark jets. We have shown that the majority of such events have only one heavy-quark jet. We see from Tables 4 and 5 that

$Zbj + X$ is nearly twice as big as $Zb\bar{b} + X$ at the Tevatron, and more than three times as large at the LHC. Similarly, $Zcj + X$ is about thrice $Zc\bar{c} + X$ at the Tevatron, and about six times as large at the LHC.

Acknowledgments

We are grateful for conversations with C. Ciobanu, T. Junk, T. Liss, S. Lowette, B. Mellado, K. Pitts, P. Venlaer, and C. Weiser. J. C. and S. W. thank the Aspen Center for Physics for hospitality. This work was supported in part by the U. S. Department of Energy under contracts Nos. DE-AC02-76CH03000 and DE-FG02-91ER40677.

References

[1] F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **74**, 2626 (1995) [arXiv:hep-ex/9503002].

[2] S. Abachi *et al.* [D0 Collaboration], Phys. Rev. Lett. **74**, 2632 (1995) [arXiv:hep-ex/9503003].

[3] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. D **65**, 052007 (2002) [arXiv:hep-ex/0109012].

[4] V. M. Abazov *et al.* [D0 Collaboration], arXiv:hep-ex/0505063.

[5] A. Stange, W. J. Marciano and S. Willenbrock, Phys. Rev. D **49**, 1354 (1994) [arXiv:hep-ph/9309294].

[6] A. Stange, W. J. Marciano and S. Willenbrock, Phys. Rev. D **50**, 4491 (1994) [arXiv:hep-ph/9404247].

[7] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. D **71**, 012005 (2005) [arXiv:hep-ex/0410058].

[8] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. Lett. **95**, 051801 (2005) [arXiv:hep-ex/0503039].

[9] D. A. Dicus and S. Willenbrock, Phys. Rev. D **39**, 751 (1989).

[10] Z. Kunszt and F. Zwirner, Nucl. Phys. B **385**, 3 (1992) [arXiv:hep-ph/9203223].

[11] C. Kao and N. Stepanov, Phys. Rev. D **52**, 5025 (1995) [arXiv:hep-ph/9503415].

[12] J. Dai, J. F. Gunion and R. Vega, Phys. Lett. B **345**, 29 (1995) [arXiv:hep-ph/9403362].

[13] J. Dai, J. F. Gunion and R. Vega, Phys. Lett. B **387**, 801 (1996) [arXiv:hep-ph/9607379].

[14] E. Richter-Was and D. Froidevaux, Z. Phys. C **76**, 665 (1997) [arXiv:hep-ph/9708455].

[15] V. D. Barger and C. Kao, Phys. Lett. B **424**, 69 (1998) [arXiv:hep-ph/9711328].

[16] D. Choudhury, A. Datta and S. Raychaudhuri, arXiv:hep-ph/9809552.

[17] C. S. Huang and S. H. Zhu, Phys. Rev. D **60**, 075012 (1999) [arXiv:hep-ph/9812201].

[18] M. Drees, M. Guchait and P. Roy, Phys. Rev. Lett. **80**, 2047 (1998) [Erratum-ibid. **81**, 2394 (1998)] [arXiv:hep-ph/9801229].

[19] M. Carena, S. Mrenna and C. E. M. Wagner, Phys. Rev. D **60**, 075010 (1999) [arXiv:hep-ph/9808312].

[20] J. L. Diaz-Cruz, H. J. He, T. Tait and C. P. Yuan, Phys. Rev. Lett. **80**, 4641 (1998) [arXiv:hep-ph/9802294].

[21] C. Balazs, J. L. Diaz-Cruz, H. J. He, T. Tait and C. P. Yuan, Phys. Rev. D **59**, 055016 (1999) [arXiv:hep-ph/9807349].

[22] C. Balazs, H. J. He and C. P. Yuan, Phys. Rev. D **60**, 114001 (1999) [arXiv:hep-ph/9812263].

[23] D. Dicus, T. Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. D **59**, 094016 (1999) [arXiv:hep-ph/9811492].

[24] ATLAS Collaboration, Technical Design Report, CERN-LHCC-99-15.

[25] M. Carena *et al.*, "Report of the Tevatron Higgs working group," arXiv:hep-ph/0010338.

[26] J. Campbell, R. K. Ellis, F. Maltoni and S. Willenbrock, Phys. Rev. D **67**, 095002 (2003) [arXiv:hep-ph/0204093].

[27] F. Maltoni, Z. Sullivan and S. Willenbrock, Phys. Rev. D **67**, 093005 (2003) [arXiv:hep-ph/0301033].

[28] R. V. Harlander and W. B. Kilgore, Phys. Rev. D **68**, 013001 (2003) [arXiv:hep-ph/0304035].

[29] S. Dittmaier, M. Kramer and M. Spira, Phys. Rev. D **70**, 074010 (2004) [arXiv:hep-ph/0309204].

[30] S. Dawson, C. B. Jackson, L. Reina and D. Wackeroth, Phys. Rev. D **69**, 074027 (2004) [arXiv:hep-ph/0311067].

[31] S. Dawson, C. B. Jackson, L. Reina and D. Wackeroth, Phys. Rev. Lett. **94**, 031802 (2005) [arXiv:hep-ph/0408077].

[32] J. Campbell *et al.*, in *Les Houches 2003: Physics at TeV Colliders*, arXiv:hep-ph/0405302.

[33] T. Affolder *et al.* [CDF Collaboration], Phys. Rev. Lett. **86**, 4472 (2001) [arXiv:hep-ex/0010052].

[34] D. Acosta *et al.* [CDF Collaboration], arXiv:hep-ex/0506042.

[35] V. M. Abazov *et al.* [D0 Collaboration], arXiv:hep-ex/0504018.

[36] S. Abdullin *et al.*, Eur. Phys. J. C **39S2**, 41 (2005).

[37] M. Schumacher, arXiv:hep-ph/0410112.

[38] M. A. G. Aivazis, J. C. Collins, F. I. Olness and W. K. Tung, Phys. Rev. D **50**, 3102 (1994) [arXiv:hep-ph/9312319].

[39] J. C. Collins, Phys. Rev. D **58**, 094002 (1998) [arXiv:hep-ph/9806259].

[40] J. M. Campbell and R. K. Ellis, Phys. Rev. D **62**, 114012 (2000) [arXiv:hep-ph/0006304].

[41] J. Campbell, R. K. Ellis, F. Maltoni and S. Willenbrock, Phys. Rev. D **69**, 074021 (2004) [arXiv:hep-ph/0312024].

[42] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **94**, 161801 (2005) [arXiv:hep-ex/0410078].

[43] F. Maltoni, T. McElmurry and S. Willenbrock, arXiv:hep-ph/0505014.

[44] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky and W. K. Tung, JHEP **0207**, 012 (2002) [arXiv:hep-ph/0201195].

[45] J. Huston, J. Pumplin, D. Stump and W. K. Tung, JHEP **0506**, 080 (2005) [arXiv:hep-ph/0502080].

[46] K. Ellis *et al.* [QCD Tools Working Group], arXiv:hep-ph/0011122.

[47] F. Maltoni and T. Stelzer, JHEP **0302**, 027 (2003) [arXiv:hep-ph/0208156].

[48] Z. Bern, L. J. Dixon and D. A. Kosower, Nucl. Phys. B **513**, 3 (1998) [arXiv:hep-ph/9708239].

[49] Z. Nagy and Z. Trocsanyi, Phys. Rev. D **59**, 014020 (1999) [Erratum-ibid. D **62**, 099902 (2000)] [arXiv:hep-ph/9806317].

[50] S. Catani and M. H. Seymour, Nucl. Phys. B **485**, 291 (1997) [Erratum-ibid. B **510**, 503 (1997)] [arXiv:hep-ph/9605323].

[51] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. D **71**, 092001 (2005) [arXiv:hep-ex/0412006].

[52] J. Campbell and R. K. Ellis, Phys. Rev. D **65**, 113007 (2002) [arXiv:hep-ph/0202176].

[53] J. Campbell, R. K. Ellis and D. L. Rainwater, Phys. Rev. D **68**, 094021 (2003) [arXiv:hep-ph/0308195].

[54] J. Pumplin *et al.*, Phys. Rev. D **65**, 014013 (2002) [arXiv:hep-ph/0101032].

[55] P. M. Nadolsky and Z. Sullivan, eConf **C010630**, P510 (2001) [arXiv:hep-ph/0110378].

February 2, 2008

Erratum: Production of a Z Boson and Two Jets with One Heavy-Quark Tag

J. Campbell[1], **R. K. Ellis**[2], **F. Maltoni**[3], and **S. Willenbrock**[4]

[1]Department of Physics and Astronomy, University of Glasgow
Glasgow G12 8QQ, United Kingdom

[2]Theoretical Physics Department, Fermi National Accelerator Laboratory
P. O. Box 500, Batavia, IL 60510

[3]Institut de Physique Théorique and
Centre for Particle Physics and Phenomenology (CP3)
Université Catholique de Louvain
Chemin du Cyclotron 2
B-1348 Louvain-la-Neuve, Belgium

[4]Department of Physics, University of Illinois at Urbana-Champaign
1110 West Green Street, Urbana, IL 61801

We recently presented a next-to-leading-order (NLO) calculation of $Z + 2$ jets, with one or more heavy-quarks ($Q = c, b$), at hadron colliders [1]. This process is a background to numerous searches at hadron colliders, in particular the search for the Higgs boson: it is the principal irreducible background to $q\bar{q} \to Zh$, followed by $h \to b\bar{b}$, and a significant reducible background to $gg \to h \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ when both jets contain heavy quarks that decay semi-leptonically. We neglected the heavy-quark mass throughout that calculation, except when two heavy quarks were produced from a virtual gluon, $g^* \to Q\bar{Q}$, in which case it is mandatory to keep the quark mass nonzero when the heavy quarks are collinear. This occurs when two heavy quarks are contained in the same jet. More generally, one cannot neglect the quark mass if the invariant mass of the quark pair coming from $g^* \to Q\bar{Q}$ is not large compared with the quark mass.

In a subsequent NLO calculation of $W + 2$ jets, with one or more b quarks, we learned that this can also occur in another situation [2], which we overlooked in Ref. [1]. If both heavy quarks are at large transverse momentum (p_T) compared to their mass, then the mass may be safely neglected [3]. However, there are NLO processes in which one heavy quark is at high p_T while another is at low p_T (and is missed by the detector), yet their invariant mass is not large compared to their mass. If this heavy-quark pair comes from a virtual gluon splitting to a heavy-quark pair, $g^* \to Q\bar{Q}$, then one cannot neglect the quark mass. This can occur in the NLO processes $q\bar{q} \to ZQ\bar{Q}g$ (Fig. 1) and $gq \to ZQ\bar{Q}q$ (Fig. 2), both of which contribute to ZQj when one heavy quark is missed.

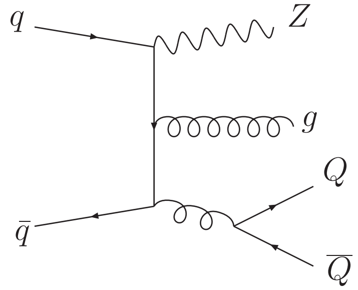

Figure 1: Diagram contributing to the NLO correction to the associated production of a Z boson and two high-p_T jets, one or more of which contains a heavy quark ($Q = c, b$).

To demonstrate this, we show in Fig. 3 the invariant-mass distribution of the heavy-quark pair from $q\bar{q} \to Zb\bar{b}g$ when it contributes to the final state Zbj, with the other heavy quark outside the acceptance of the detector (taken to be $p_T > 15$ GeV, $|\eta| < 2$, $\Delta R_{jj} > 0.7$), at the Fermilab Tevatron ($\sqrt{S} = 1.96$ TeV $p\bar{p}$). There are two curves, one with (solid, blue) and one without (dashed, red) the quark mass included. It is clear that the quark mass has a large influence on the cross section (the area under the curves).

In the case of the process $gq \to ZQ\bar{Q}q$, which involves the splitting $g \to Q\bar{Q}$ in the initial state [Fig. 2(b)] as well as the final state [Fig. 2(a)], this requires that we abandon the dipole subtraction method [4] in favor of subtracting the mass singularity via the truncated Q distribution function [5, 6]

$$\tilde{Q}(x, \mu) = \frac{\alpha_S(\mu)}{2\pi} \ln\left(\frac{\mu^2}{m_Q^2}\right) \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y, \mu) \tag{2}$$

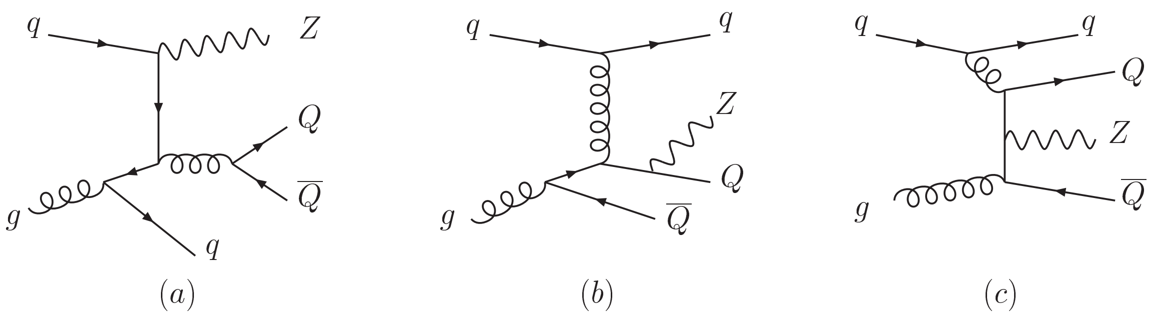

Figure 2: Diagrams contributing to the NLO correction to the associated production of a Z boson and two high-p_T jets, one or more of which contains a heavy quark ($Q = c, b$).

where $P_{qg}(z) = \frac{1}{2}[z^2 + (1-z)^2]$ is the DGLAP splitting function. The counterterm is constructed by calculating $\tilde{Q}q \to ZQq$; this cancels the initial-state logarithmic dependence on the heavy-quark mass in $gq \to ZQ\bar{Q}q$, and yields a cross section in the $\overline{\rm MS}$ factorization scheme. This technique was developed in Ref. [2].

We have revisited our NLO calculation of $Z + 2$ jets, with one or more heavy quarks, and corrected this omission. Specifically, we recalculated the NLO processes[3]

- $q\bar{q} \to ZQ\overline{Q}g$ at tree level [Fig. 1]
- $gq \to ZQ\overline{Q}q$ at tree level [Fig. 2]

using a finite heavy-quark mass throughout ($m_c = 1.4$ GeV, $m_b = 4.75$ GeV).

The results for the exclusive and inclusive cross sections at the Fermilab Tevatron and the CERN Large Hadron Collider (LHC) are presented in Tables II-V. These should replace the corresponding tables in Ref. [1]. While there are small changes throughout the tables, the only significant change is in the NLO cross section for Zbj at the Tevatron in Table 2 (as well as the inclusive cross section $Zbj + X$ in Table 4), which was reduced by 16% by including the b-quark mass (5.23 pb → 4.37 pb). The dominant effect of the b-quark mass was on the subprocess $q\bar{q} \to ZQ\bar{Q}g$ [Fig. 1], which was reduced by more than 50% (1.16 pb → 0.50 pb). A similar percentage reduction occurs at the LHC (9 pb → 4 pb), but this subprocess is so small at that machine that it hardly affects the total result for Zbj.

We raised the p_T threshold on the acceptance for b jets to greater than 15 GeV, and found that the effect of the b mass became less. This is consistent with our findings that the effect of the c mass is smaller than that of the b mass for the same p_T threshold.

---

[3] It is not necessary to recalculate $gg \to ZQ\overline{Q}g$, since there is no contribution from a virtual gluon splitting to a heavy-quark pair, $g^* \to Q\bar{Q}$. We recalculated it nevertheless, and found that the effect of the heavy-quark mass is about -6% at the Tevatron and -12% at the LHC. However, since this subprocess makes a relatively small contribution to the cross section, this change is negligible.

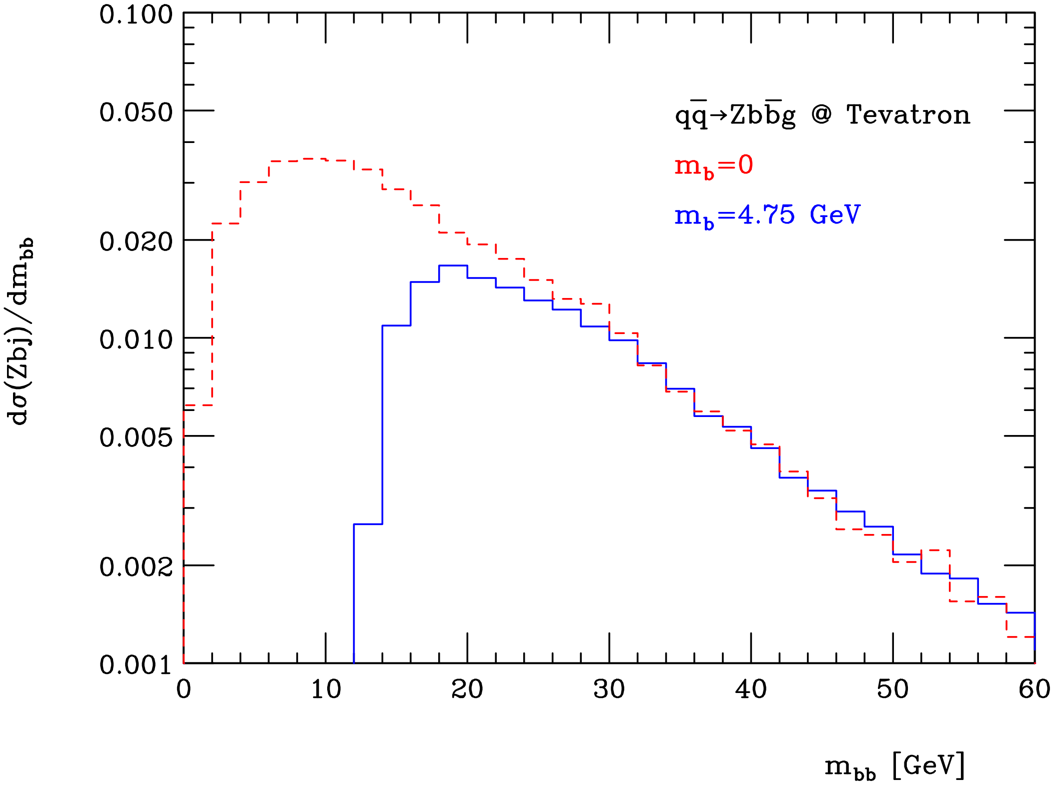

Figure 3: The differential cross section for Z plus two jets, one of which contains a b quark, vs. the invariant mass of the b quark and another b quark that lies outside the acceptance of the detector (taken to be $p_T > 15$ GeV, $|\eta| < 2$, $\Delta R_{jj} > 0.7$), at the Fermilab Tevatron ($\sqrt{S} = 1.96$ TeV $p\bar{p}$). Only the contribution from the subprocess $q\bar{q} \to Zb\bar{b}g$ is shown. The (solid, blue) curve includes the b quark mass, while the (dashed, red) curve does not.

Acknowledgments

We are grateful for conversations with Gavin Salam. This work was supported in part by the U. S. Department of Energy under contracts Nos. DE-AC02-76CH03000 and DE-FG02-91ER40677.

References

[1] J. Campbell, R. K. Ellis, F. Maltoni and S. Willenbrock, Phys. Rev. D **73**, 054007 (2006) [arXiv:hep-ph/0510362].

[2] J. Campbell, R. K. Ellis, F. Maltoni and S. Willenbrock, Phys. Rev. D **75**, 054015 (2007) [arXiv:hep-ph/0611348].

[3] F. Febres Cordero, L. Reina and D. Wackeroth, Phys. Rev. D **74**, 034007 (2006) [arXiv:hep-ph/0606102].

Table 2: Cross sections (pb) for Z-boson plus two (or more) jets, one or more of which contains a heavy quark, at the Tevatron ($\sqrt{s} = 1.96$ TeV $p\bar{p}$). A jet lies in the range $p_T > 15$ GeV and $|\eta| < 2$. Two final-state partons are merged into a single jet if $\Delta R_{jj} < 0.7$. No branching ratios or tagging efficiencies are included. Numbers in parenthesis are leading-order results. The labels on the columns have the following meaning: ZQj = exactly two jets, one of which contains a heavy quark; $ZQ\overline{Q}$ = exactly two jets, both of which contain a heavy quark; $Z(Q\overline{Q})j$ = exactly two jets, one of which contains a heavy-quark pair; $ZQ\overline{Q}j$ = exactly three jets, two of which contain a heavy quark; $ZQjj$ = exactly three jets, one of which contains a heavy quark. For the last set of processes, the labels mean: Zjj = exactly two jets, including heavy quarks; $Zjjj$ = exactly three jets, including heavy quarks. For ZQj and $ZQ\overline{Q}$, both the leading-order (in parentheses) and next-to-leading-order cross sections are given. The CTEQ6M parton distribution functions are used throughout, except for the LO cross sections in parentheses, where CTEQ6L1 is used [7]. The factorization and renormalization scales are chosen as $\mu_F = \mu_R = M_Z$.

Tevatron	σ (pb)				
	ZQj	$ZQ\overline{Q}$	$Z(Q\overline{Q})j$	$ZQ\overline{Q}j$	$ZQjj$
bottom	(2.18) 4.37	(2.47) 3.07	0.634	0.672	0.326
charm	(3.20) 7.35	(2.34) 2.75	2.00	0.621	0.495
	Zjj			$Zjjj$	
Z+jets	(163) 182			22.9	

[4] S. Catani and M. H. Seymour, Nucl. Phys. B **485**, 291 (1997) [Erratum-ibid. B **510**, 503 (1997)] [arXiv:hep-ph/9605323].

[5] M. A. G. Aivazis, J. C. Collins, F. I. Olness and W. K. Tung, Phys. Rev. D **50**, 3102 (1994) [arXiv:hep-ph/9312319].

[6] J. C. Collins, Phys. Rev. D **58**, 094002 (1998) [arXiv:hep-ph/9806259].

[7] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky and W. K. Tung, JHEP **0207**, 012 (2002) [arXiv:hep-ph/0201195].

Table 3: Same as Table 2, except at the LHC ($\sqrt{s} = 14$ TeV pp). A jet lies in the range $p_T > 15$ GeV and $|\eta| < 2.5$. (This table is nearly identical to Table III of Ref. [1].)

LHC	σ (pb)				
	ZQj	$ZQ\overline{Q}$	$Z(Q\overline{Q})j$	$ZQ\overline{Q}j$	$ZQjj$
bottom	(352) 418	(109) 92.1	23.5	60.8	92.1
charm	(443) 624	(87) 75.2	58.6	49.3	123
	Zjj			$Zjjj$	
Z+jets	(6090) 4840			1810	

Table 4: Inclusive cross sections (pb) for Z boson plus one or two jets, one or two of which contains a heavy quark, at the Tevatron ($\sqrt{s} = 1.96$ TeV $p\bar{p}$). A jet lies in the range $p_T > 15$ GeV and $|\eta| < 2$. Two final-state partons are merged into a single jet if $\Delta R_{jj} < 0.7$. No branching ratios or tagging efficiencies are included. Numbers in parenthesis are leading-order results. The labels on the columns have the following meaning: $ZQ + X$ = at least one jet, at least one of which contains a heavy quark; $Z(Q\overline{Q})$ = one jet which contains a heavy-quark pair; $ZQj + X$ = at least two jets, one of which contains a heavy quark; $ZQ\overline{Q} + X$ = at least two jets, two of which contain a heavy quark; $Z(Q\overline{Q})j$ = two jets, one of which contains a heavy-quark pair. The last row gives the inclusive cross section for jets containing both light and heavy partons. The CTEQ6M parton distribution functions are used throughout, except for the LO cross sections in parentheses, where CTEQ6L1 is used [7]. The factorization and renormalization scales are chosen as $\mu_F = \mu_R = M_Z$. The uncertainties are from the variation of the renormalization scale, the factorization scale, and the parton distribution functions, respectively.

Tevatron	σ (pb)				
	$Z + 1$ jet $+X$		$Z + 2$ jets $+X$		
	$ZQ + X$	$Z(Q\overline{Q})$	$ZQj + X$	$ZQ\overline{Q} + X$	$Z(Q\overline{Q})j$
bottom	(8.23) 18.1	2.1	(2.18) $4.70^{+1.2\ +0.07\ +0.5}_{-0.9\ -0.05\ -0.5}$	(2.47) $3.74^{+0.45\ +0.12\ +0.15}_{-0.45\ -0.12\ -0.15}$	$0.63^{+0.26\ +0.06\ +0.05}_{-0.16\ -0.06\ -0.05}$
charm	(11.3) 27.5	6.6	(3.20) $7.85^{+1.7\ +0.15\ +0.8}_{-1.4\ -0.26\ -0.8}$	(2.34) $3.37^{+0.44\ +0.0\ +0.14}_{-0.37\ -0.87\ -0.14}$	$2.00^{+0.85\ +0.22\ +0.15}_{-0.53\ -0.16\ -0.15}$
all jets	(898) 1070		(163) $205^{+19\ +7\ +5}_{-19\ -2\ -5}$		

Table 5: Same as Table 4, except at the LHC ($\sqrt{s} = 14$ TeV pp). A jet lies in the range $p_T > 15$ GeV and $|\eta| < 2.5$. (This table is nearly identical to Table V of Ref. [1].)

LHC	σ (pb)				
	$Z + 1$ jet $+X$		$Z + 2$ jets $+X$		
	$ZQ + X$	$Z(Q\overline{Q})$	$ZQj + X$	$ZQ\overline{Q} + X$	$Z(Q\overline{Q})j$
bottom	(826) 1060	25	(352) $510^{+84\,+44\,+25}_{-58\,-35\,-25}$	(109) $153^{+20\,+2\,+9}_{-20\,-2\,-9}$	$24^{+10\,+0.3\,+1.2}_{-6\,-0.3\,-1.2}$
charm	(989) 1430	50	(443) $747^{+110\,+0\,+45}_{-110\,-46\,-45}$	(87) $125^{+17\,+2\,+8}_{-17\,-2\,-8}$	$59^{+23\,+2\,+3}_{-15\,-2\,-3}$
all jets	(15300) 18400		(6090) $6650^{+470\,+170\,+240}_{-500\,-50\,-240}$		