B-Quark Production at Hadron Colliders

S. Riemersma
Department of Physics,
Southern Methodist University,
Fondren Science Building,
Dallas, TX 75275-0175, USA

and

Ruibin Meng
High Energy Physics Division,
Argonne National Laboratory,
Argonne, IL 60439

Abstract

Results for b-quark production at hadron colliders, both current and proposed, are presented. Distributions in $p_t$ are presented for the TeVatron and SSC. Confirmation of agreement between the $\mathcal{O}(\alpha_s^3)$ calculations and UA1 data is presented, and the discrepancy between the $\mathcal{O}(\alpha_s^3)$ calculations and the CDF results is updated with the most recent data.
1 Introduction

Studying B-physics at hadron accelerators requires a good understanding of the total and differential cross sections for b-quark production. This knowledge gives those involved in B ¯B mixing, rare B decays, and those trying to determine the CKM angles α, β, and γ an idea of how many events they can expect, given the luminosity and the branching ratios. It is particularly important for those studying rare B decays as they set limits on where we can hope to see new physics. For these reasons and others, the complete $O(\alpha_s^3)$ corrections to heavy-quark production at hadron accelerators were calculated in [1] and [2]. Also three groups [3], [4], [5] have attempted to calculate heavy-quark production using resummation techniques in the small-x kinematic region. These techniques are necessary since the b-quark mass $m_b$ is small relative to the center-of-mass energies $\sqrt{s}$ of the TeVatron and the SSC. While these techniques offer some hope of obtaining reasonable predictions for b-production at these machines, the current results can best be considered as preliminary.

Thus we must turn to perturbative QCD for guidance, as we have no other real choice at this point. However, let us submit a caveat here: fixed-order perturbative QCD works best when all the scales are roughly comparable, i.e. $\sqrt{s} \approx m_b \approx p_t$, $\sqrt{s}$ being the partonic center-of-mass energy. When we are not in this regime, for example at the TeVatron and the SSC, our predictions will then be less reliable. Bearing this in mind, let us continue to the results section.

2 Results

A number of fixed-target pp experiments have been proposed for HERA, LHC, and SSC. The cross sections given in Table 1. are total cross sections without any cuts applied. The purpose is to give an idea of the overall rate of b-production at these proposed experiments. Note that these cross sections are for inclusive b-production, so if one wants to calculate rates for b- or $\bar{b}$-production, one needs to multiply these results by a factor of two.
Table 1. Cross Sections for Proposed Fixed-Target Experiments.

| $\sqrt{S}$ (GeV) | Born   | $\mathcal{O}(\alpha^3_S)$ |
|------------------|--------|---------------------------|
| 43               | 8.3 nb | 17 nb                     |
| 124              | 0.32 $\mu$b | 0.58 $\mu$b               |
| 200              | 0.89 $\mu$b | 1.6 $\mu$b                |

These cross sections were generated using programs created by [2] with the following inputs: $m_b$ was chosen to be 4.75 GeV/$c^2$, the mass factorization scale $M^2$ was chosen to be $m_b^2$, and the parton distribution set used was CTEQ1M [6]. We would also like to mention here that similar results have been obtained earlier in in [7] using a similar parton distribution set and our numbers in Table 1. as well as in Table 2. below agree with theirs. From Table 1., we see that the corrections even at these low energies are sizeable. For $\sqrt{S} = 43$ GeV, one should probably take into account resummation effects at large-$x$ (see [8]). However, at these energies, we expect that the results are fairly accurate.

The situation for $b$-production at the TeVatron, LHC, and SSC is more problematic. We are no longer in a region where we expect fixed-order perturbative QCD to give experimentally valid results. Nevertheless, the predictions made are worth noting, to get a quantitative idea of which regions in phase space our predictions are lacking and how much of an improvement needs to be made. Having given sufficient warning, we present Table 2., cross sections for the TeVatron, LHC, and SSC.

Table 2. Cross Sections for the Various Colliders.

| $\sqrt{S}$ (TeV) | Born   | $\mathcal{O}(\alpha^3_S)$ |
|------------------|--------|---------------------------|
| 1.8              | 17 $\mu$b | 37 $\mu$b                |
| 15.4             | 92 $\mu$b | 270 $\mu$b               |
| 40               | 170 $\mu$b | 550 $\mu$b               |

As in Table 1., no cuts were applied and the input parameters chosen were the same. We see rather large increases when the $\mathcal{O}(\alpha^3_S)$ corrections are included. The 'K-factors' are 2.2, 2.9, and 3.2 for the TeVatron, LHC, and SSC, respectively. The size of these 'K-factors' might give one cause to worry, however they are slightly misleading since the massless $t$-channel exchanges...
present in the $O(\alpha_s^3)$ corrections are absent in the Born approximation calculation. A better indication of the convergence should be found in comparing the $O(\alpha_s^4)$ results with the $O(\alpha_s^3)$ corrections. We were also presented with a list of cuts from various experimental groups, and what was settled upon was the following: for CDF, we were asked for pseudorapidities $|\eta| < 1$ and $p_t > 4 \text{ GeV}/c$ in the central region. The D0 cuts were $|\eta| < 3.4$ and $p_t > 5 \text{ GeV}/c$ in the central region. In the forward region at the TeVatron, the request was for $2.5 < |\eta| < 5.5$ and $p_t > 1.5 \text{ GeV}/c$. At the SSC, the central region was determined to be $|\eta| < 2.5$ and $p_t > 10 \text{ GeV}/c$, and the forward region given was $1.5 < |\eta| < 5.5$ and $p_t > 1.5 \text{ GeV}/c$. The calculations are done with cuts in rapidity not pseudorapidity, but the difference should be small. Table 3. shows the results for these cuts.

|       | CDF Central | D0 Central | TeVatron Forward | SSC Central | SSC Forward |
|-------|-------------|------------|-----------------|-------------|------------|
| Cross Section | 7.2 $\mu$b  | 13 $\mu$b  | 7.0 $\mu$b     | 62 $\mu$b   | 300 $\mu$b |

The forward region results include the sum of the positive and negative rapidity results. The result for the central SSC region seems low until one considers the large $p_t$-cut made. Also, the large rapidity coverage of D0 helps considerably in enlarging the cross section.

For additional enlightenment, we have plotted $d\sigma/dp_t$ versus $p_t$ for the central and forward regions for both the TeVatron and the SSC. Before we discuss the $d\sigma/dp_t$ plots we would also refer interested readers to [4] for rapidity distributions giving additional useful information. In Figure 1., we see that the expanded rapidity coverage of D0 makes the cross section larger by a factor of two over CDF rather uniformly over the entire $p_t$-range. Most of the cross section lies in the low-$p_t$ range. Therefore if one could lower the $p_t$-cut, the event increase would be sizeable. For these plots, we have chosen $M^2 = p_t^2 + m^2$. Also, these plots were produced by running the programs for the Born approximation $p_t$-distributions and multiplying by the 'K-factors' previously introduced: 2.2 for the TeVatron plots and 3.2 for the SSC plots. The justification for this was 1) time was of the essence and the higher-order calculations would have taken a day each to compute and 2) in discussions [4], it was revealed that the higher-order calculations generally raise the Born
approximation results by a fairly uniform amount across the entire \( p_t \)-range. Figure 2. shows a dramatic fall-off in the forward region as \( p_t \) increases, again with most of the cross section in the low-\( p_t \) region. In the low-\( p_t \) range, the cross section is reduced by a factor of three to five compared to the central region, depending on the cut made. Turning to the SSC, Figure 3. shows that by imposing a \( p_t \)-cut of 10 GeV/\( c \), most of the cross section is lost in the central region. At large \( p_t \), we find that the contribution is still appreciable. Finally, in the forward region, Figure 4. reveals the large-\( p_t \) region is again still significant, but again the majority of the cross section comes from the low-\( p_t \) region. The loss of cross section as \( p_t \) increases is not so dramatic as it is in the forward region at the TeVatron.

3 Conclusions

What can we conclude from these results? First, the fixed-target results are probably solid, since we can see from Figure 5. the results from UA1 \cite{10} are in good agreement with the \( \mathcal{O}(\alpha_3^2) \) results, and the energies for the fixed-target experiments are lower than that of UA1. Looking at Figure 6., we compare the \( \mathcal{O}(\alpha_3^2) \) calculations of \cite{1,2} with the 1988-89 and 1992-93 results of CDF \cite{11}. Some of these data are still preliminary, of course, but it appears that the data do not fit the calculation. From the figure caption we see that we are off by about a factor of 2.6. But we have some consolation because the shape is approximately correct, although a slightly steeper distribution as discussed in \cite{12} would fit better. This factor of 2.6 will only be magnified when we look at the results for the SSC. Clearly, we have a problem.

What are the possible solutions? Calculate the \( \mathcal{O}(\alpha_4^4) \) corrections and see what difference that makes. That is an enormous endeavor and would take years. Try to make further headway on the small-\( x \) front. This is possible but large uncertainties remain. As an example, one interesting mechanism to accommodate the CDF data shown in Figure 6. is to alter the form of the gluon distribution in the small-\( x \) region \cite{12}. But for a 'ballpark estimate' that probably is not too bad, why not do the following: try

\[
\sigma_{\text{exp}} = \sigma_0 e^{(K-1)},
\]

(3.1)

where \( \sigma_0 \) is the Born cross section, \( K \) is the appropriate 'K-factor,' and \( \sigma_{\text{exp}} \) is the expected cross section. In the case of the TeVatron, \( \sigma_0 = 17 \)
microbarns and $K = 2.2$. We would get $\sigma_{exp} = 56$ microbarns. For the SSC, $\sigma_0 = 170$ microbarns and $K = 3.2$. Here $\sigma_{exp} = 1.5$ millibarns. The distributions would also have the factor $e^{(K-1)}$ multiplying the lowest-order distributions. This is of course rather ad hoc, but the results look reasonable. More theoretically valid calculations are still well off in the distance, and the numbers are needed now.

Finally, in the course of many discussions [13], it was decided that approximate cross section figures for each of the colliders, current and proposed, should be provided so that an estimate of B-physics event rates could be made. Toward that end, we present Table 4., a compilation of cross section figures that should be correct within a factor of two.

Table 4. Cross Section Figures for Reference.

| $\sqrt{S}$ | 43 GeV | 124 GeV | 200 GeV | 1.8 TeV | 15.4 TeV | 40 TeV |
|------------|--------|---------|---------|---------|---------|-------|
| $\sigma$   | 20 nb  | 0.5 $\mu$b | 2 $\mu$b | 100 $\mu$b | 0.5 mb  | 1 mb   |

The numbers for the lower energies were arrived at essentially by rounding the results of the $O(\alpha_3^3)$ calculation. The 1.8 TeV result was derived in the following way: we took the fact that the curve that fits the data of CDF is 2.6 times the $O(\alpha_3^3)$ result. Multiplying the 37 microbarns by the factor of 2.6, we get a convenient number of 100 microbarns for the TeVatron with no cuts. The numbers for the LHC and the SSC were based upon various estimates obtained using various parton distribution sets. They were also agreed upon in [13] and further detailed discussions about the uncertainties can be found in [7], [13].

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Fig. 1. $d\sigma/dp_t$ vs. $p_t$ for the kinematic cuts imposed for the CDF collaboration (solid line) and the D0 collaboration (dashed line) in the central region.

Fig. 2. $d\sigma/dp_t$ vs. $p_t$ for the kinematic cuts imposed in the forward region at the TeVatron.

Fig. 3. $d\sigma/dp_t$ vs. $p_t$ for the kinematic cuts imposed in the central region at the SSC.

Fig. 4. $d\sigma/dp_t$ vs. $p_t$ for the kinematic cuts imposed in the forward region at the SSC.

Fig. 5. $\sigma$ vs. $p_t^{\text{min}}$ for $\sqrt{S} = 630$ GeV with $|y| < 1.5$. The data are taken from Table 2. of [10]. The high curve was run with $m_b = 4.5$ GeV/$c^2$, and $M = m_b/2$. The middle curve was run with $m_b = 4.75$ GeV/$c^2$, and $M = m_b$. The low curve was run with $m_b = 5.0$ GeV/$c^2$, and $M = 2m_b$. CTEQ1M distribution functions were used.

Fig. 6. $\sigma$ vs. $p_t^{\text{min}}$ for $\sqrt{S} = 1.8$ TeV with $|y| < 1$. The high solid curve was run with $m_b = 4.5$ GeV/$c^2$, and $M = m_b/2$. The middle solid curve was run with $m_b = 4.75$ GeV/$c^2$, and $M = m_b$. The low solid curve was run with $m_b = 5.0$ GeV/$c^2$, and $M = 2m_b$. CTEQ1M distribution functions were used. The data with the thick error bars are taken from the 88-89 and the thin error bars from the 92-93 runs of CDF [11]. The dashed curve is the middle solid curve multiplied by a factor of 2.6.