The Sources of b-Quarks at the Tevatron and their Correlations

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(Dated: October 30, 2018)

The leading-log order QCD hard scattering Monte-Carlo models of HERWIG, ISAJET, and PYTHIA are used to study the sources of b-quarks at the Tevatron. The reactions responsible for producing b and \( \bar{b} \) quarks are separated into three categories; flavor creation, flavor excitation, and parton-shower/fragmentation. Flavor creation corresponds to the production of a \( b\bar{b} \) pair by gluon fusion or by annihilation of light quarks, while flavor excitation corresponds to a \( b \) or \( \bar{b} \) quark being knocked out of the initial-state by a gluon or a light quark or antiquark. The third source occurs when a \( b\bar{b} \) pair is produced within a parton-shower or during the fragmentation process of a gluon or a light quark or antiquark (includes gluon splitting). The QCD Monte-Carlo models indicate that all three sources of b-quarks are important at the Tevatron and when combined they qualitatively describe the inclusive cross-section data. Correlations between the \( b \) and \( \bar{b} \) quark are very different for the three sources and can be used to isolate the individual contributions.

I. INTRODUCTION

It is important to have good leading order (or leading-log order) estimates of hadron-hadron collider observables. Of course, precise comparisons with data require beyond leading order calculations. If the leading order estimates are within a factor of two of the data, higher order calculations might be expected to improve the agreement. On the other hand, if the leading order estimates are off by more than about a factor of two of the data, one cannot expect higher order calculations to improve the situation. In this case, even if the higher order corrections were large enough to bring agreement, one could not trust a perturbative series in which the second term is greater than the first. If a leading order estimate is off by more than a factor of two, it usually means that one has overlooked some important physics. For this reason good leading-log order estimates are important.

FIG. 1: Illustration of a proton-antiproton collision in which the QCD hard 2-to-2 reaction results in the creation of a \( b\bar{b} \) pair via the subprocess \( q + \bar{q} \rightarrow b + \bar{b} \) or \( g + g \rightarrow b + \bar{b} \). The event also contains possible initial and final-state radiation and particles that result from the break-up of the initial proton and antiproton (i.e., “beam-beam remnants”).

In this analysis the leading-log order QCD hard scattering Monte-Carlo models of HERWIG, ISAJET, and PYTHIA are used to study the sources of b-quarks at the Tevatron. The reactions responsible of producing b-quarks are separated into three categories; flavor creation, flavor excitation, and shower/fragmentation. Flavor creation corresponds to the production of a \( b\bar{b} \) pair by gluon fusion or by the annihilation of light quarks via the two 2-to-2 parton subprocesses, \( q + \bar{q} \rightarrow b + \bar{b} \), and \( g + g \rightarrow b + \bar{b} \), and is illustrated in FIG. 1. The data from CDF and D0 for the integrated inclusive \( b \)-quark cross section for \( |y| < 1 \) at 1.8 TeV are compared with the QCD Monte-Carlo model predictions for flavor creation in FIG. 2, where \( y \) is the rapidity of the \( b \)-quark. Here

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FIG. 2: Data from CDF and D0 [4, 5, 6, 7] for the integrated inclusive $b$-quark total cross section ($p_T > p_T(\text{min})$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of HERWIG 5.9, PYTHIA 6.115, and ISAJET 7.32 for the “flavor creation” subprocesses illustrated in FIG. 1. All three Monte-Carlo models were generated using the parton distribution functions CTEQ3L and $p_T(\text{hard}) > 3\text{ GeV/c}$.

The parton distribution functions CTEQ3L have been used for all three Monte-Carlo models and, as is well know, the leading order predictions are roughly a factor of four below the data. The leading order estimates of the flavor creation contribution to $b$-quark production at the Tevatron are so far below the data that higher order corrections (even though they may be important) cannot be the whole story.

An additional source of $b$-quarks at the Tevatron comes from the scattering of a $b$ or $\bar{b}$ quark out of the initial-state into the final-state by a gluon or by a light quark or light antiquark via the subprocess $g + b \rightarrow g + b$, $q + b \rightarrow q + b$, or $\bar{q} + b \rightarrow \bar{q} + b$. These subprocesses together with the corresponding $\bar{b}$ terms are referred to as “flavor excitation”. Flavor excitation is, of course, very sensitive to the number of $b$ and $\bar{b}$ quarks within the proton (i.e., “beam-beam remnants”).

FIG. 3: Illustration of a proton-antiproton collision in which the QCD hard 2-to-2 reaction corresponds to the scattering of a $b$-quark out of the initial-state into the final-state by a gluon or a light quark or light antiquark via the subprocess $g + b \rightarrow g + b$, $q + b \rightarrow q + b$, or $\bar{q} + b \rightarrow \bar{q} + b$. These subprocesses together with the corresponding $\bar{b}$ terms are referred to as “flavor excitation”. The event also contains possible initial and final-state radiation and particles that result from the break-up of the initial proton and antiproton (i.e., “beam-beam remnants”).
The $b\bar{b}$ pair content within the proton is generated entirely through the $Q^2$ evolution of the structure functions.

FIG. 4: Illustration of a proton-antiproton collision in which a $b\bar{b}$ pair is created within a parton-shower or during the fragmentation process of a gluon or a light quark or antiquark. Here the QCD hard 2-to-2 subprocess involves only gluons and light quarks and antiquarks (no heavy quarks in the 2-to-2 hard scattering subprocess). The event also contains possible initial and final-state radiation and particles that result from the break-up of the initial proton and antiproton (i.e., “beam-beam remnants”).

Another source of $b$-quarks at the Tevatron comes from reactions which have a $b\bar{b}$ in the final-state but with only gluons and light quarks and light antiquarks participating in the 2-to-2 hard parton scattering subprocess (i.e., no heavy quarks in the 2-to-2 hard scattering subprocess). This is referred to as “shower/fragmentation” and is illustrated in FIG. 4. Here the subprocesses are all QCD 2-to-2 gluon, light quark, and light antiquark subprocesses. The “shower/fragmentation” contribution comes from $b\bar{b}$ pairs produced within parton-showers or during the fragmentation process. This category includes the “gluon splitting” subprocess, $g + g \rightarrow g + (g \rightarrow b\bar{b})$, as modeled by the QCD leading-log Monte-Carlo models.

Section II discusses methods of generating the three sources of $b$-quarks: flavor creation, flavor excitation, and shower/fragmentation. In Section III the leading-log QCD Monte-Carlo model predictions are compared with data on the $b$-quark inclusive cross section at the Tevatron. Correlations between the $b$ and $\bar{b}$ quark are very different for the three sources and in Section IV we study ways to isolate the individual contributions using $b\bar{b}$ correlations. Section V is reserved for summary and conclusions.

II. MONTE-CARLO GENERATION

It is not easy to arrive at the QCD Monte-Carlo model predictions for $b$-quark production at the Tevatron. Some of the plots presented here contain 8 million generated events. In addition, one must handle each of the Monte-Carlo models differently in order to get all three contributions; flavor creation, flavor excitation, and shower/fragmentation.

A. Flavor Creation

The flavor creation contribution to $b$-quark production at the Tevatron is the easiest to generate. ISAJET, HERWIG, and PYTHIA all allow the user to select and generate separately the flavor creation contribution. For ISAJET if one runs all QCD and then selects the flavor creation terms by monitoring the 2-to-2 subprocess, one gets the same answer as running the flavor creation contribution separately. However, this is not true for HERWIG and PYTHIA. These two Monte-Carlo models only include the $b\bar{b}$-quark mass when one runs the flavor creation terms separately (i.e., heavy quark production). For HERWIG and PYTHIA, when one runs all QCD the $b$-quark mass is set to zero. ISAJET always includes the $b$-quark mass in the flavor creation subprocesses. Setting the $b$-quark mass equal to zero increases the $b$-quark inclusive flavor creation cross section for $p_T > 5$ GeV/c and $|y| < 1$ by roughly 40% at 1.8 TeV.

In summary, one can produce the flavor creation contribution in two ways with ISAJET, either by running them separately or by running all QCD. For HERWIG and PYTHIA one must generate the flavor creation terms separately by running the heavy quark option (IPROC = 1705 or MSEL = 5). For PYTHIA this produces only the flavor creation contribution. However, for HERWIG the heavy quark option produces both the flavor creation terms and the flavor excitation terms and one must monitor the 2-to-2 subprocesses to separate them.
FIG. 5: Data on the integrated inclusive b-quark total cross section ($p_T > p_T(\text{min}), |y| < 1$) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of PYTHIA 6.115 (CTEQ3L, $p_T(\text{hard}) > 3 \text{ GeV}/c$). The four curves correspond to the contribution from flavor creation (FIG. [4]), flavor excitation (FIG. [3]), shower/fragmentation (FIG. [4]), and the resulting total.

B. Flavor Excitation

For ISAJET one can run the flavor excitation contribution separately or one can run all QCD and then select out the flavor excitation contribution (one gets the same answer either way). For HERWIG running the heavy quark option gets both the flavor creation and the flavor excitation contributions (with the b-quark mass included). For HERWIG, if one runs all QCD and then selects out the flavor excitation contribution one gets a different answer since here the b mass is set to zero. For PYTHIA the only way to get the flavor excitation contribution is to run all QCD and then select out the flavor excitation contribution, but here one only gets the massless approximation. Actually, in leading order it is not clear how to handle the b-quark mass in the flavor excitation subprocesses since one is going from an off-shell b (or b) quark in the initial state to an on-shell massive b (or b) quark in the final state. This limits the accuracy of the leading order estimate of this contribution.

C. Shower/Fragmentation

For all three Monte-Carlo models the only way to get the shower/fragmentation contribution to b-quark production is to run all QCD 2-to-2 subprocesses and then select out the shower/fragmentation contribution by monitoring the subprocesses, which requires producing large numbers of events. The shower/fragmentation contribution differs greatly among the Monte-Carlo models for two reasons. The first is due to different fragmentation schemes. ISAJET uses independent fragmentation, while HERWIG and PYTHIA do not. The second difference arises from the way the QCD Monte-Carlo produce parton showers. ISAJET uses a leading-log picture in which the partons within the shower are ordered according to their invariant mass. Kinematics requires that the invariant mass of daughter partons are less than the invariant mass of the parent. HERWIG and PYTHIA modify the leading-log picture to include “color coherence effects” which leads to “angle ordering” within the parton shower.

The flavor excitation and shower/fragmentation 2-to-2 subprocesses diverge as the parton transverse momentum, $p_T(\text{hard})$, goes to zero. To get a finite result one must regulate the divergences or specify a minimum value for $p_T(\text{hard})$. For HERWIG and ISAJET we take $p_T(\text{hard}) > 3 \text{ GeV}/c$. PYTHIA regulates the perturbative 2-to-2 parton scattering differential cross sections, which allow one to take $p_T(\text{hard}) > 0$. For PYTHIA b-quark predictions with $p_T(b\text{-quark}) > 5 \text{ GeV}/c$ are independent of the whether one takes $p_T(\text{hard}) > 3 \text{ GeV}/c$ or $p_T(\text{hard}) > 0$. 
III. THE INCLUSIVE CROSS-SECTION

The data from CDF and D0 \[4, 5, 6, 7\] on the integrated inclusive $b$-quark total cross-section are compared with the QCD Monte-Carlo model predictions in FIGS. \[5-7\], with the CTEQ3L structure functions and $p_T^{\text{hard}} > 3 \text{ GeV/c}$. The four curves in each of the plots correspond to the contribution to $b$-quark production from flavor creation, flavor excitation, shower/fragmentation, and the resulting overall total. After adding the contributions from all three sources PHOJET (CTEQ4L) agrees fairly well with the data. ISAJET (CTEQ3L) is a bit below the data because of a smaller shower/fragmentation contribution. HERWIG (CTEQ3L) is also slightly below the data due to a smaller flavor excitation component. One does not expect precise agreement from these leading-log estimates. However, the qualitative agreement indicates that probably nothing unusual is happening in $b$-quark production at the Tevatron.

FIG. 8 and FIG. 9 show the differential inclusive $b$-quark $p_T$ cross section and the integrated total cross section, respectively, from PYTHIA (CTEQ4L), with $p_T^{\text{hard}} > 0$. PYTHIA regulates the divergences in the perturbative 2-to-2 parton scattering differential cross sections and these plots show a smooth behavior down to $p_T (b$-quark) equal to zero.

FIG. 10 shows the predictions of HERWIG (DO1.1), HERWIG (CTEQ3L), ISAJET (CTEQ3L), PHOJET (CTEQ3L), PYTHIA (CTEQ4L), and PYTHIA (GRV94L) for the integrated $b$-quark total cross section ($p_T > 5 \text{ GeV/c}, |y| < 1$) at 1.8 TeV. The contributions from flavor creation, flavor excitation, and shower/fragmentation are shown together with the overall resulting sum (overall height of box). The DO1.1 structure functions include only four flavors and the probability of finding a $b$ (or $\bar{b}$) quark within the proton is set identically equal to zero. Thus, running with the DO1.1 structure functions results in no flavor excitation. The differences among the Monte-Carlo models for flavor excitation are due to the different ways the models handle the $b$-quark mass in this subprocess.

The Monte-Carlo model predictions for the shower/fragmentation contribution differ considerably. This is not surprising since ISAJET uses independent fragmentation, while HERWIG and PYTHIA do not; and HERWIG and PYTHIA modify the leading-log picture of parton showers to include “color coherence effects”, while ISAJET does not.

The flavor creation contribution to inclusive $b$-quark production ($p_T > 5 \text{ GeV/c}, |y| < 1$) is predicted by HERWIG (CTEQ3L) and PYTHIA (CTEQ3L) to be about 25% of the overall $b$-quark production rate from all three sources at 1.8 TeV, while for ISAJET (CTEQ3L) it is about 35% of the total.
FIG. 7: Data on the integrated inclusive $b$-quark total cross section ($p_T > p_T(\text{min}), |y| < 1$) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of HERWIG 5.9 (CTEQ3L, $p_T(\text{hard}) > 3$ GeV/$c$). The four curves correspond to the contribution from flavor creation (FIG. 1), flavor excitation (FIG. 3), shower/fragmentation (FIG. 4), and the resulting total.

FIG. 8: The inclusive $b$-quark differential cross section, $d\sigma/dp_T$, for $|y| < 1$ for proton-antiproton collisions at 1.8 TeV resulting from PYTHIA 6.158 (CTEQ4L, $p_T(\text{hard}) > 0$). The four curves correspond to the contribution from flavor creation (FIG. 1), flavor excitation (FIG. 3), shower/fragmentation (FIG. 4), and the resulting total.

IV. CORRELATIONS

Clearly the three sources of $b$-quarks: flavor creation, flavor excitation, and shower/fragmentation have quite different topological structures and the correlations between the $b$ and $\bar{b}$ quarks are quite different.
FIG. 9: Data on the integrated inclusive $b$-quark total cross section ($p_T > p_T(\text{min})$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of PYTHIA 6.158 (CTEQ4L, $p_T(\text{hard}) > 0$). The four curves correspond to the contribution from flavor creation (FIG. 1), flavor excitation (FIG. 3), shower/fragmentation (FIG. 4), and the resulting total.

FIG. 10: Predictions of HERWIG 5.9 (DO1.1), HERWIG 5.9 (CTEQ3L), ISAJET 7.32 (CTEQ3L), PYTHIA 6.115 (CTEQ3L), PYTHIA 6.158 (CTEQ4L), and PYTHIA 6.115 (GRV94L) for the integrated inclusive $b$-quark total cross section ($p_T > 5 \text{ GeV/c}$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV. The contributions from flavor creation (FIG. 1), flavor excitation (FIG. 3), shower/fragmentation (FIG. 4) are shown together with the resulting sum (overall height of box).

A. Simple “Toward” and “Away” Probabilities

FIGS. 11 - 13 show the QCD Monte-Carlo model predictions for some simple correlations. Here one requires a $b$-quark to be in the region $p_T > 5 \text{ GeV/c}$ and $|y| < 1$ and then asks for the probability of finding a $\bar{b}$-quark in the same region, $p_T > 5 \text{ GeV/c}$ and $|y| < 1$. Furthermore, one breaks this probability into two terms, “toward” and “away”. The “toward” region corresponds to $|\Delta \phi| < 90^\circ$ and the “away” region has $|\Delta \phi| > 90^\circ$, where $\Delta \phi$ is the azimuthal angle between the $b$ and $\bar{b}$ quark. The models predict that for flavor creation the probability that both the $b$ and $\bar{b}$ quark lie in the region $p_T > 5 \text{ GeV/c}$ and $|y| < 1$ is about 40%, with the $b$-quark almost always on the “away-side” of the
FIG. 11: Predictions of PYTHIA 6.115 (CTEQ3L, $p_T^\text{hard} > 3 \text{ GeV}/c$) for the probability of finding a $\bar{b}$-quark with $p_T > 5 \text{ GeV}/c$ and $|y| < 1$ in an event with a $b$-quark with $p_T > 5 \text{ GeV}/c$ and $|y| < 1$ for proton-antiproton collisions at 1.8 TeV. The contribution from the “toward” ($|\Delta \phi| < 90^\circ$) and the “away” ($|\Delta \phi| > 90^\circ$) region of the $b$-quark are shown for flavor creation (FIG. 1), flavor excitation (FIG. 3), and shower/fragmentation (FIG. 4), where $|\Delta \phi|$ is the azimuthal angle between the $b$ and $\bar{b}$-quark.

FIG. 12: Predictions of HERWIG 5.9 (CTEQ3L, $p_T^\text{hard} > 3 \text{ GeV}/c$) for the probability of finding a $\bar{b}$-quark with $p_T > 5 \text{ GeV}/c$ and $|y| < 1$ in an event with a $b$-quark with $p_T > 5 \text{ GeV}/c$ and $|y| < 1$ for proton-antiproton collisions at 1.8 TeV. The contribution from the “toward” ($|\Delta \phi| < 90^\circ$) and the “away” ($|\Delta \phi| > 90^\circ$) region of the $b$-quark are shown for flavor creation (FIG. 1), flavor excitation (FIG. 3), and shower/fragmentation (FIG. 4), where $|\Delta \phi|$ is the azimuthal angle between the $b$ and $\bar{b}$-quark.

$b$-quark.

The QCD Monte-Carlo models differ considerably on the correlations for the shower/fragmentation contribution. For this contribution all three models predict that both the $b$ and $\bar{b}$ quark lie in the region $p_T > 5 \text{ GeV}/c$ and $|y| < 1$ around 30%-40% of the time, which is comparable to the flavor creation contribution. However, ISAJET predicts that for the shower/fragmentation contribution that the $\bar{b}$-quark is almost always on the “toward-side” of the $b$-quark, while HERWIG and PYTHIA predict about equal amounts of “toward” and “away” for this contribution.

As one would expect, all the models predict that it is not very likely to find both the $b$ and $\bar{b}$-quark in the region $p_T > 5 \text{ GeV}/c$ and $|y| < 1$ for the flavor excitation contribution. For flavor excitation either the $b$-quark or the $\bar{b}$-quark is part of the “underlying” event (see FIG. 3). The models differ greatly on the correlations for the flavor excitation contribution. For this contribution PYTHIA predicts that both the $b$ and $\bar{b}$-quark lie in the region $p_T > 5 \text{ GeV}/c$ and $|y| < 1$ around 20% of the time, while ISAJET predicts 13% and HERWIG gives 5% for this probability. All three models predict that for flavor excitation when both the $b$ and $\bar{b}$-quark are found in the region $p_T > 5 \text{ GeV}/c$ and $|y| < 1$
that the $\bar{b}$-quark is about equally likely to be on “toward” or “away” side of the $b$-quark.

FIG. 14: Predictions of PYTHIA 6.158 (CTEQ4L, $p_T(\text{hard}) > 0$) for the azimuthal angle, $\Delta \phi$, between a $b$-quark with $p_T > 5 \text{ GeV}/c$ and $|y| < 1$ and a $\bar{b}$-quark with $p_T > 0$ and $|y| < 1$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/d\Delta \phi (\mu \text{b/sr})$ for flavor creation (FIG. 14a), flavor excitation (FIG. 14b), shower/fragmentation (FIG. 14c), and the resulting total. The “toward” ($|\Delta \phi| < 90^\circ$) and the “away” ($|\Delta \phi| > 90^\circ$) region of the $b$-quark are labeled. (Note the logarithmic scale.)

B. $\Delta \phi$ Distribution

FIG. 14 shows the predictions of PYTHIA for the azimuthal angle, $\Delta \phi$, between a $b$-quark with $p_T > 5 \text{ GeV}/c$ and $|y| < 1$ and a $\bar{b}$-quark with $p_T > 0$ and $|y| < 1$. FIG. 15 is the same as FIG. 14 except both the $b$ and $\bar{b}$ quark are required to have $p_T > 5 \text{ GeV}/c$. Notice that the relative amounts of flavor excitation and shower/fragmentation decrease compared to flavor creation when one demands that both the $b$ and $\bar{b}$ quarks to have $p_T > 5 \text{ GeV}/c$. Integrating the curves in FIG. 14 over the “toward” and “away” regions correspond to the simple probabilities discussed in Section IV(a). Clearly, the “toward” region is very sensitive to the presence of the flavor excitation and shower/fragmentation terms.
FIG. 15: Predictions of PYTHIA 6.158 (CTEQ4L, \( p_T \) (hard) > 0) for the azimuthal angle, \( \Delta \phi \), between a \( b \)-quark with \( p_T > 5 \text{ GeV}/c \) and \( |y| < 1 \) and a \( \bar{b} \)-quark with \( p_T > 5 \text{ GeV}/c \) and \( |y| < 1 \) in proton-antiproton collisions at 1.8 TeV. The curves correspond to \( d\sigma/d\Delta \phi (\mu \text{b}) \) for flavor creation (FIG. 1), flavor excitation (FIG. 3), shower/fragmentation (FIG. 4), and the resulting total. The “toward” (\(|\Delta \phi| < 90^\circ\)) and the “away” (\(|\Delta \phi| > 90^\circ\)) region of the \( b \)-quark are labeled. (Note the logarithmic scale.)

C. Distance “R”

FIG. 16 shows the predictions of PYTHIA for the distance, \( R \), in \( \eta-\phi \) space between a \( b \)-quark with \( p_T > 5 \text{ GeV}/c \) and \( |y| < 1 \) and a \( \bar{b} \)-quark with \( p_T > 5 \text{ GeV}/c \) proton-antiproton collisions at 1.8 TeV. The curves correspond to \( d\sigma/dR (\mu \text{b}) \) for flavor creation (FIG. 1), flavor excitation (FIG. 3), shower/fragmentation (FIG. 4), and the resulting total. (Note the logarithmic scale.)

D. Rapidity Correlations

FIG. 17 shows the predictions of PYTHIA for the rapidity, \( y_1 \) of a \( b \)-quark with \( p_T > 5 \text{ GeV}/c \) for events with a \( \bar{b} \)-quark with \( p_T > 5 \text{ GeV}/c \) and \( |y_2| < 0.5 \). Here the flavor excitation contribution behaves much differently than the
other two terms. However, the resulting sum of the three contributions looks similar to the flavor creation term.

FIG. 17: Predictions of PYTHIA 6.158 (CTEQ4L, \( p_T(\text{hard}) > 0 \)) for the rapidity, \( y_1 \), of a \( b \)-quark with \( p_{T1} > 5 \text{ GeV/c} \) for events with a \( b \)-quark with \( p_{T2} > 5 \text{ GeV/c} \) and \( |y_2| < 0.5 \) in proton-antiproton collisions at 1.8 TeV. The curves correspond to \( d\sigma/dy_1 (\mu b) \) for flavor creation (FIG. 1), flavor excitation (FIG. 3), shower/fragmentation (FIG. 4), and the resulting total.

FIG. 18: Prediction of PYTHIA 6.158 (CTEQ4L, \( p_T(\text{hard}) > 0 \)) for the \( p_T \) asymmetry, \( A = (p_{T1} - p_{T2})/(p_{T1} + p_{T2}) \), for events with a \( b \)-quark with \( p_{T1} > 0 \) and \( |y_1| < 1 \) and a \( b \)-quark with \( p_{T2} > 5 \text{ GeV/c} \) and \( |y_2| < 1 \) in proton-antiproton collisions at 1.8 TeV. The curves correspond to \( d\sigma/dA (\mu b) \) for flavor creation (FIG. 1), flavor excitation (FIG. 3), shower/fragmentation (FIG. 4), and the resulting total.

E. The Transverse Momentum Asymmetry

FIG. 18 shows the predictions of PYTHIA for the \( p_T \) asymmetry, \( A = (p_{T1} - p_{T2})/(p_{T1} + p_{T2}) \), for events with a \( b \)-quark with \( p_{T1} > 0 \) and \( |y_1| < 1 \) and a \( b \)-quark with \( p_{T2} > 5 \text{ GeV/c} \) and \( |y_2| < 1 \). If there were no initial-state radiation (see FIG. 1) and no “intrinsic” transverse momentum, the flavor creation terms would produce zero asymmetry. Also, as one would expect (FIG. 3), the flavor excitation terms have, on the average, a large transverse momentum asymmetry. Requiring \( p_T \) asymmetries with a magnitude greater than around 60% isolates the flavor excitation contribution.
FIG. 19: Prediction of PYTHIA 6.158 (CTEQ4L, $p_T$(hard) > 0) for the transverse momentum, $p_{T2}$, of a $b$-quark with $|y_2| < 1.0$ for events with a $b$-quark with $p_{T1} > 5\text{ GeV/c}$ and $|y_1| < 1.0$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/dp_{T2}$ (µb/GeV/c) for flavor creation (FIG. 1), flavor excitation (FIG. 3), shower/fragmentation (FIG. 4), and the resulting total. (Note the logarithmic scale.)

FIG. 20: Prediction of PYTHIA 6.158 (CTEQ4L, $p_T$(hard) > 0) for the integrated pair cross section for a $\bar{b}$-quark with $p_{T2} > p_{T2}(\text{min})$ and $|y_2| < 1.0$ and a $b$-quark with $p_{T1} > 5\text{ GeV/c}$ and $|y_1| < 1.0$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $\sigma$ (µb) for flavor creation (FIG. 1), flavor excitation (FIG. 3), shower/fragmentation (FIG. 4), and the resulting total. (Note the logarithmic scale.)

F. Double Differential Cross Section

FIG. 19 shows the predictions of PYTHIA for the transverse momentum, $p_{T2}$, of a $\bar{b}$-quark with $|y_2| < 1$ for events with a $b$-quark with $p_{T1} > 5\text{ GeV/c}$ and $|y_1| < 1$. As the transverse momentum asymmetry in FIG. 18 indicated, the flavor creation contribution peaks at $p_{T2} \approx 5\text{ GeV/c}$ (i.e., small $p_T$ asymmetry), while the flavor excitation and shower/fragmentation contributions peak at low $p_T$ (i.e., larger $p_T$ asymmetry).

FIG. 20 shows the predictions of PYTHIA for the integrated $b\bar{b}$ pair cross section for a $\bar{b}$-quark with $p_{T2} > p_{T2}(\text{min})$
and $|y_2| < 1$ and b-quark with $p_T > 5 \text{ GeV/c}$ and $|y_1| < 1$. Notice how the three terms contribute in different proportions to the $b\bar{b}$ pair cross section in FIG. [20] and the inclusive single $b$-quark cross section in FIG. [4]. Flavor excitation is a major contributor to the single inclusive cross section, while flavor creation dominates the pair cross section.

V. SUMMARY AND CONCLUSIONS

The leading-log order QCD hard scattering Monte-Carlo models of HERWIG, ISAJET, and PYTHIA have been used to study the sources of $b$-quarks at the Tevatron. The reactions responsible of producing $b$-quarks are separated into flavor creation, flavor excitation, and shower/fragmentation.

Flavor Creation

The production of a $b\bar{b}$ pair via gluon fusion or annihilation of light quarks is easy to generate and all three QCD Monte-Carlo models (with the same structure functions) predict roughly the same cross section and similar $b\bar{b}$ correlations from these terms. At the Tevatron all three Monte-Carlo models predict that the flavor creation contribution to $b$-quark production is less than 35% of the overall inclusive $b$-quark production rate ($p_T > 5 \text{ GeV/c}, |y| < 1$) from all three sources.

Flavor Excitation

The source of $b$-quarks resulting from the scattering of a $b$-quark or $\bar{b}$-quark out of the initial-state into the final-state by a gluon or by a light quark or antiquark is difficult to generate and depends sensitively on the parton distribution functions. The QCD Monte-Carlo model predictions differ somewhat, however, it seems likely that at the Tevatron the flavor excitation contribution to the inclusive $b$-quark cross section is comparable to or greater than the contribution from flavor creation. The $b\bar{b}$ correlations resulting from the flavor excitation term are much different than those arising from flavor creation. In particular, the distribution in the azimuthal angle, $\Delta \phi$, between the $b$ and the $b$-quark peaks sharply in the “backward” ($|\Delta \phi| > 90^\circ$) region for flavor creation, while flavor excitation produces an approximately flat $|\Delta \phi|$ distribution. Also, the flavor excitation terms have, on the average, a large transverse momentum asymmetry between the $b$ and $b$-quark, while the flavor creation terms produce a $p_T$ asymmetry near zero.

Shower/Fragmentation

The production of $b\bar{b}$ pairs within a parton-shower or during the fragmentation process of gluons and light quarks and antiquarks is an important source at the Tevatron. The QCD Monte-Carlo models predictions differ considerably for this contribution. However, at the Tevatron the shower/fragmentation contribution to the inclusive $b$-quark cross section might be comparable to the contribution from flavor creation. This source can be isolated by looking for $b\bar{b}$ pairs with $R < 1$, where $R$ is the distance in $\eta$-$\phi$ space between the $b$ and $b$-quark.

The QCD Monte-Carlo model leading-log estimates of the flavor excitation and the shower/fragmentation contributions to $b$-quark production are uncertain and should not be taken too seriously. However, it seems likely that at the Tevatron all three sources of $b$-quarks, flavor creation, flavor excitation, and shower/fragmentation are important [8]. One does not expect precise agreement from leading-log estimates. On the other hand, the qualitative agreement shown indicates that probably nothing unusual is happening in $b$-quark production at the Tevatron. Furthermore, in Run II at the Tevatron we should be able to isolate experimentally the individual contributions to $b$-quark production by studying $b\bar{b}$ correlations in detail.

Acknowledgments

I would like to thank the CDF B Group for several stimulating discussions. Also, I would like to thank Henry Frisch, Michelangelo Mangano, and Torbjörn Sjöstrand for helpful remarks.

[1] G. Marchesini and B. R. Webber, Nucl. Phys. B310, 461 (1988); I. G. Knowles, Nucl. Phys. B310, 571 (1988); S. Catani, G. Marchesini, and B. R. Webber, Nucl. Phys. B349, 635 (1991).
[2] F. Paige and S. Protopopescu, BNL Report, BNL38034, 1986 (unpublished), version 7.32.
[3] T. Sjostrand, Phys. Lett. 157B, 321 (1985); M. Bengtsson, T. Sjostrand, and M. van Zijl, Z. Phys. C32, 67 (1986); T. Sjostrand and M. van Zijl, Phys. Rev. D36, 2019 (1987).
[4] F. Abe et al., The CDF Collaboration, Phys. Rev. Lett. 71, 2396 (1993).
[5] F. Abe et al., The CDF Collaboration, Phys. Rev. Lett. 75, 1451 (1995).
[6] S. Abachi et al., The D0 Collaboration, Phys. Rev. Lett. 74, 3548 (1995).
[7] William Wester, B Physics at the Tevatron Run I, Workshop on B Physics at the Tevatron Run II and Beyond, Fermilab, September 23-25, 1999.
[8] The PYTHIA results presented here are consistent with the analysis performed by E. Norrbin and T. Sjöstrand; Phys. Lett. B442, 407 (1998); Eur. Phys. J. C17, 137 (2000).