

The Sources of b-quarks at the Tevatron

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Abstract

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-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 $q\bar{q}$ 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 final 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.

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 not within roughly 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 order estimated are crucial.

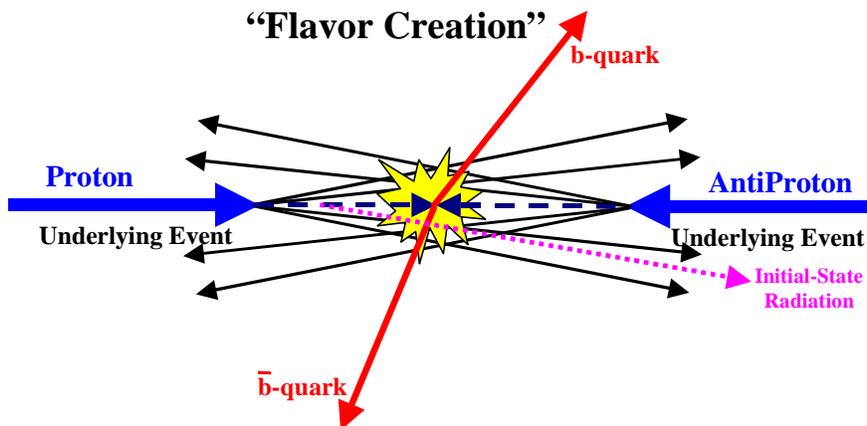


Fig. 1. Illustration of a proton-antiproton collision in which the QCD hard 2-to-2 reaction corresponds to the creation of a $b\bar{b}$ pair via the subprocess $g + g \rightarrow b + \bar{b}$ or $q + \bar{q} \rightarrow b + \bar{b}$.

In this analysis the leading-log order QCD hard scattering Monte-Carlo models of HERWIG [1], ISAJET [2], and PYTHIA [3] 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 $q\bar{q}$ annihilation of light quarks via the following two 2-to-2 parton subprocesses

$$g + g \rightarrow b + \bar{b}$$

$$q + \bar{q} \rightarrow b + \bar{b}$$

and is illustrated in Fig. 1. The data from CDF and D0 [4-7] for the integrated b-quark total 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 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.

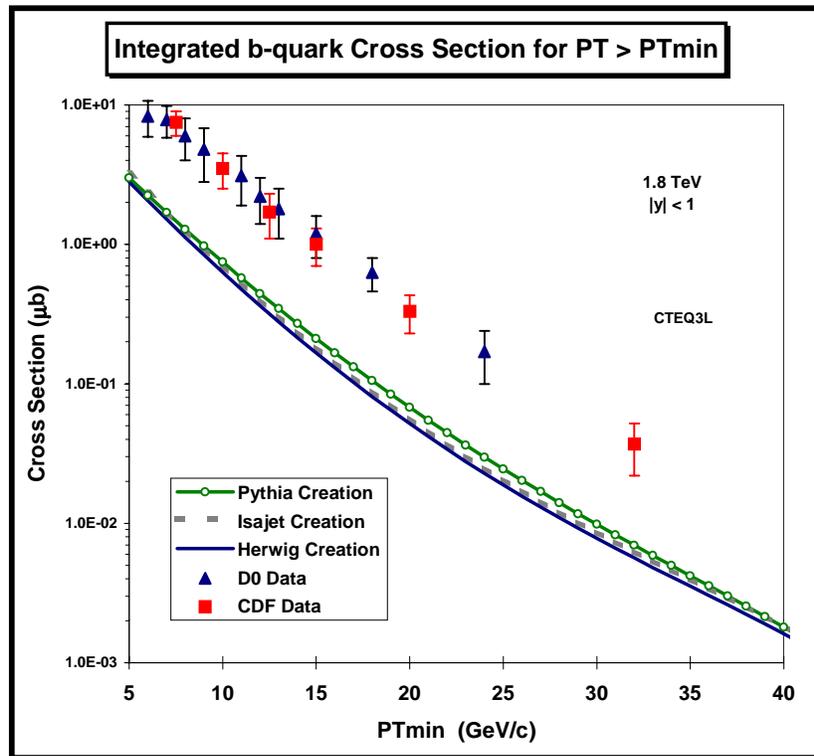


Fig. 2. Data from CDF and D0 for the integrated b-quark total cross section ($P_T > P_{T_{\min}}$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of HERWIG, PYTHIA, and ISAJET for the “flavor creation” subprocesses illustrated in Fig. 1. The parton distribution functions CTEQ3L have been used for all three Monte-Carlo models.

Another source of b-quarks comes 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 via the subprocesses

$$\begin{array}{ll}
g + b \rightarrow g + b & g + \bar{b} \rightarrow g + \bar{b} \\
q + b \rightarrow q + b & q + \bar{b} \rightarrow q + \bar{b} \\
\bar{q} + b \rightarrow \bar{q} + b & \bar{q} + \bar{b} \rightarrow \bar{q} + \bar{b}
\end{array}$$

This is referred to as “flavor excitation” and is illustrated in Fig. 3. Flavor excitation is, of course, very sensitive to the number of b-quarks within the proton (*i.e.* the structure functions).

The final source of b-quarks comes from reactions resulting in a b or \bar{b} -quark in the final state but which have no b or \bar{b} -quark in the 2-to-2 hard scattering subprocess. This is referred to as “shower/fragmentation” and is illustrated in Fig. 4. The subprocesses contributing to fragmentation are all 2-to-2 gluon and light quark and antiquark subprocesses as follows

$$\begin{array}{lll}
g + g \rightarrow g + g & q + \bar{q} \rightarrow g + g & g + q \rightarrow g + q \\
g + \bar{q} \rightarrow g + \bar{q} & q + q \rightarrow q + q & q + \bar{q} \rightarrow q + \bar{q} \\
\bar{q} + \bar{q} \rightarrow \bar{q} + \bar{q} & &
\end{array}$$

Here the $b\bar{b}$ pair is produced within a parton shower or during the fragmentation process. This category includes the “gluon splitting” subprocess

$$g + g \rightarrow g + (g \rightarrow b + \bar{b})$$

as generated by the QCD Monte-Carlo models.

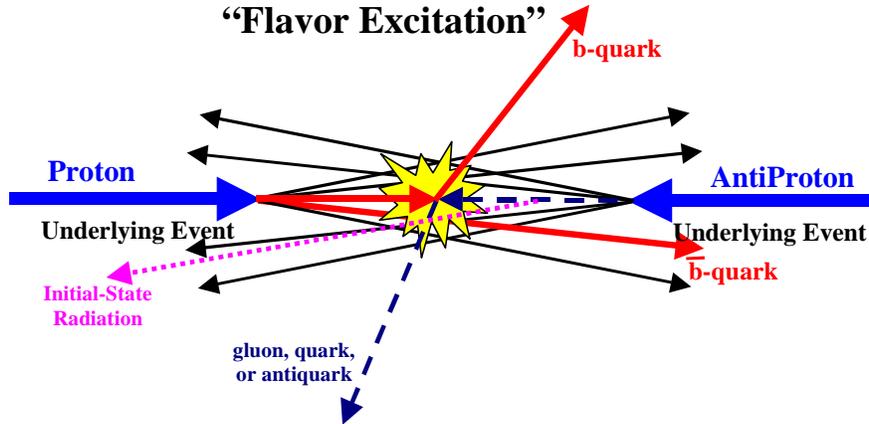


Fig. 3. Illustration of a proton-antiproton collision in which the QCD hard 2-to-2 reaction corresponds to the scattering of a b-quark out of the initial-state into the final-state by a gluon or a light quark via the subprocess $g + b \rightarrow g + b$, $q + b \rightarrow q + b$, or $\bar{q} + b \rightarrow \bar{q} + b$. These subprocesses are referred to as “flavor excitation”.

II. Monte-Carlo Generation

It is not easy to arrive at the QCD Monte-Carlo model predictions for b-quark production. Some of the plots presented here correspond to 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.

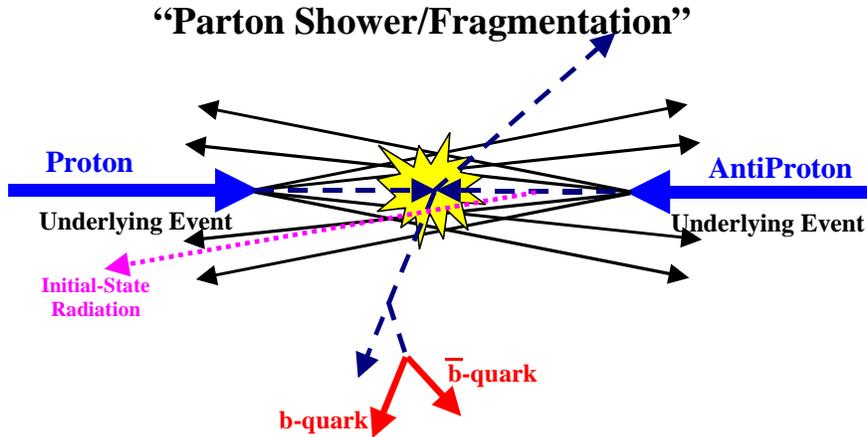


Fig. 4. Illustration of a proton-antiproton collision in which a $b\bar{b}$ pair is created within a parton shower or during the fragmentation process of a gluon or a light quark or antiquark. Here the QCD hard 2-to-2 subprocess involves gluons and light quarks and antiquarks (no heavy quarks in the 2-to-2 hard scattering subprocess). This includes what is referred to as “gluon splitting”.

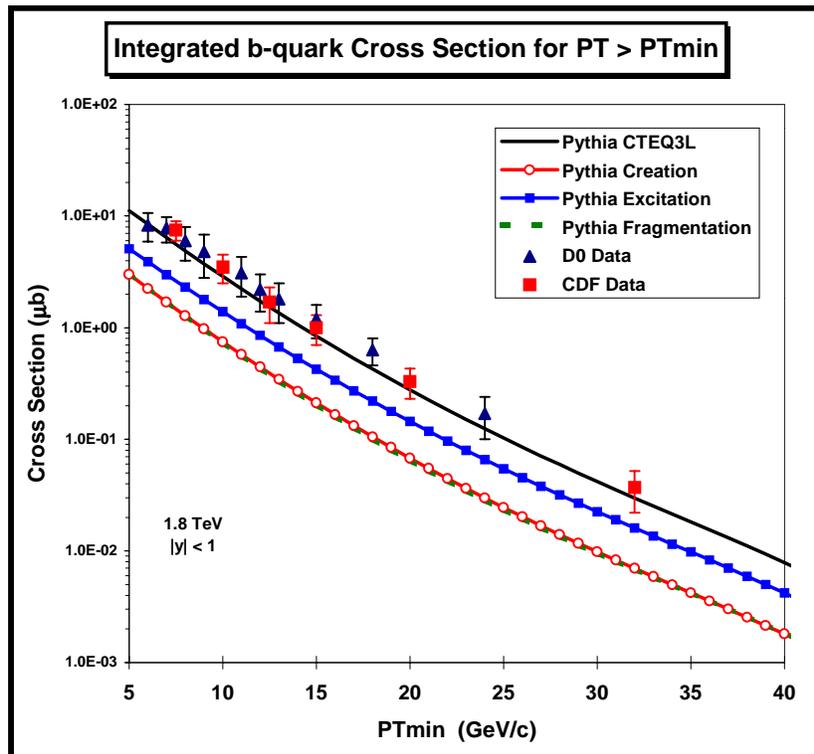


Fig. 5. Data on the integrated b-quark total cross section ($P_T > P_{Tmin}$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of PYTHIA (CTEQ3L). The four curves correspond to the contribution from flavor creation (Fig. 1), flavor excitation (Fig. 3), shower/fragmentation (Fig. 4), and the resulting total.

(a) Flavor Creation

The flavor creation contribution to b-quark production 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 2-to-2 reactions 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-quark mass when one runs the flavor creation terms separately (*i.e.* heavy quark production). For HERWIG and PYTHIA when one runs all QCD 2-to-2 subprocesses the b-quark mass is set to zero. ISAJET always puts in the b-quark mass for pair creation. For pair creation setting the b-quark mass equal to zero increases the b-quark 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 2-to-2 subprocesses. For HERWIG and PYTHIA one must generate the flavor creation terms separately by running the heavy quark option (IPROC = 1705, 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.

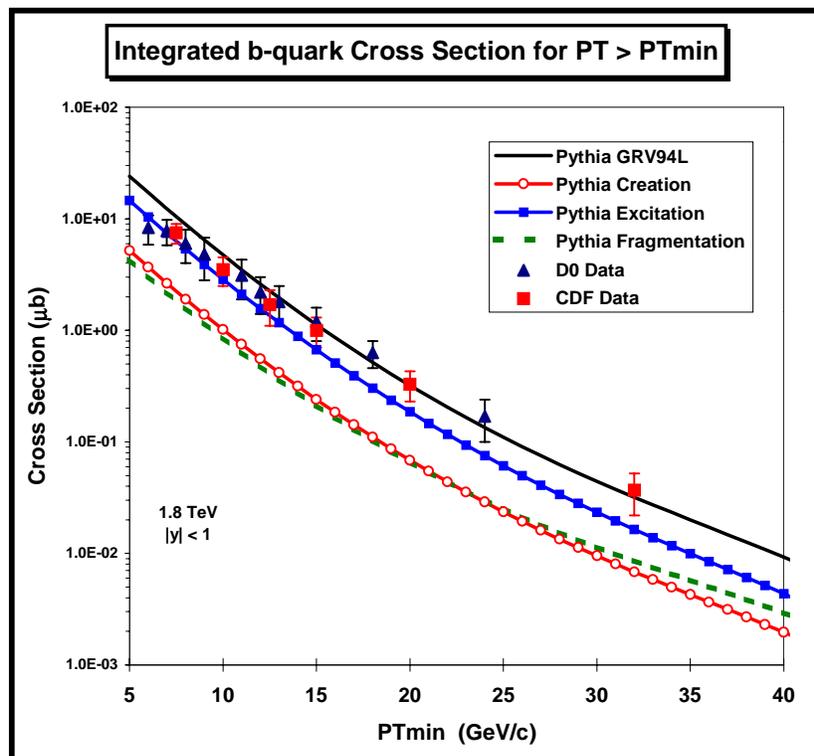


Fig. 6. Data on the integrated b-quark total cross section ($P_T > P_{T_{\min}}$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of PYTHIA (GRV94L)). The four curves correspond to the contribution from flavor creation (Fig. 1), flavor excitation (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 2-to-2 subprocesses 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 2-to-2 subprocesses and then select 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 2-to-2 subprocesses and then select out the flavor excitation contribution, but here one only gets the massless approximation.

(c) Shower/Fragmentation

For all three Monte-Carlo models the only way to get the parton-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 2-to-2 subprocesses, which requires producing a large number of events. This 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 be 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.

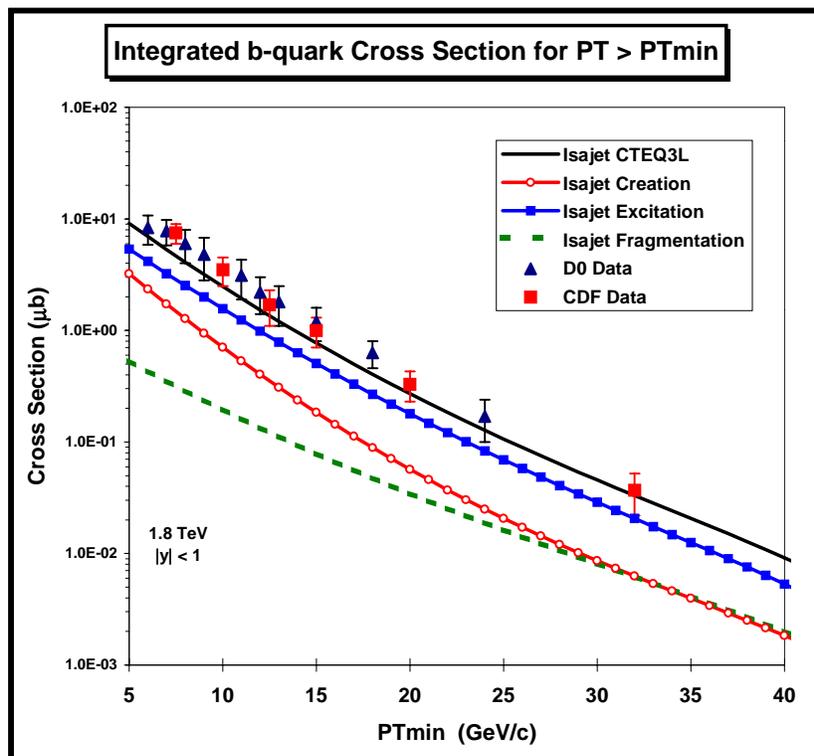


Fig. 7. Data on the integrated b -quark total cross section ($P_T > P_{Tmin}$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of ISAJET (CTEQ3L). The four curves correspond to the contribution from flavor creation (Fig. 1), flavor excitation (Fig. 3), shower/fragmentation (Fig. 4), and the resulting total.

III. The b-quark Cross-Section

The data from CDF and D0 on the integrated b-quark total cross section for $|y| < 1$ at 1.8 TeV are compared with the QCD Monte-Carlo model predictions in Fig. 5 – Fig. 8. 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. Fig. 5 and Fig. 6 show the predictions of PYTHIA with two different structure functions; CTEQ3L and GRV94L. Fig. 7 and Fig. 8 show the predictions of ISAJET and HERWIG, respectively, using CTEQ3L. After adding the contributions from all three sources the Monte-Carlo models are in qualitative agreement with the data. PYTHIA (GRV94L) is slightly above the data and PHYTHIA (CTEQ3L) 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.

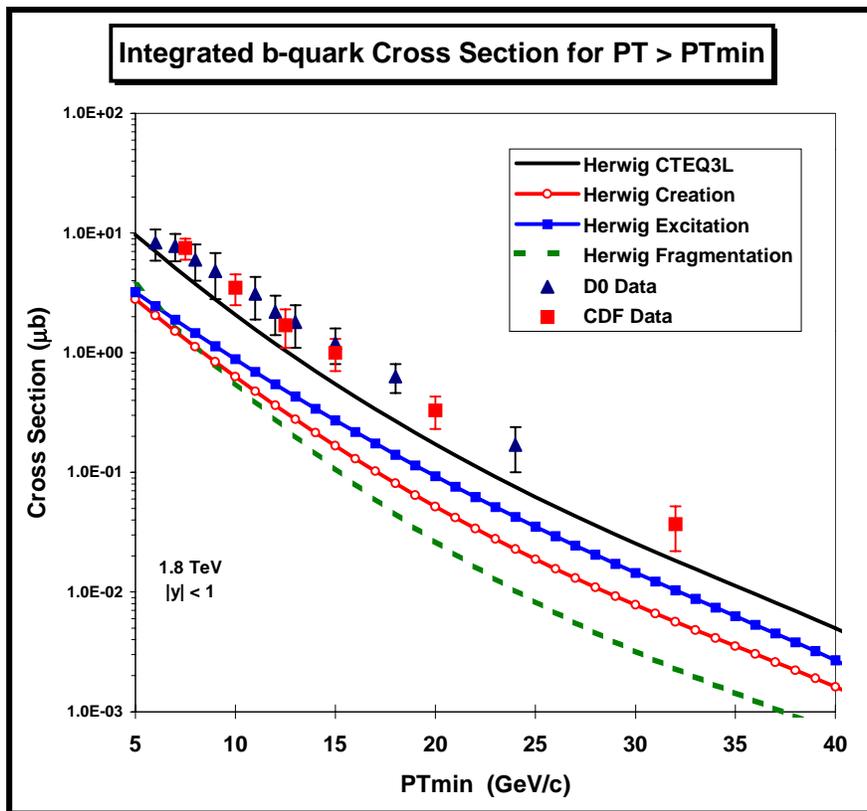


Fig. 8. Data on the integrated b-quark total cross section ($P_T > P_{Tmin}$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of HERWIG (CTEQ3L). The four curves correspond to the contribution from flavor creation (Fig. 1), flavor excitation (Fig. 3), shower/fragmentation (Fig. 4), and the resulting total.

Fig. 9 and Fig. 10 compare the predictions of the flavor excitation and shower/fragmentation contributions to b-quark production, respectively, from HERWIG, PYTHIA, and ISAJET. Here the parton distribution functions CTEQ3L have been used for all three Monte-Carlo models. The Monte-Carlo models 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.

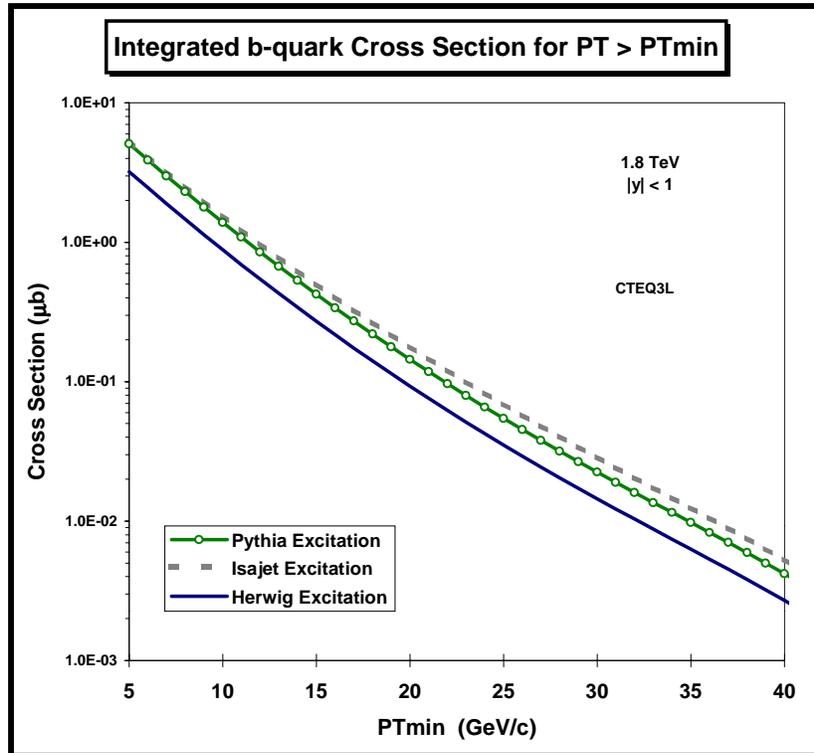


Fig. 9. Predictions of HERWIG, PYTHIA, and ISAJET for the integrated b-quark total cross section ($P_T > P_{Tmin}$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV resulting from the “flavor excitation” subprocesses illustrated in Fig. 3. The parton distribution functions CTEQ3L have been used for all three Monte-Carlo models.

The differences in the flavor excitation contribution seen in Fig. 9 are due to the different ways the models handle the b-quark mass in this subprocess. For the flavor creation diagrams inserting the b-quark mass is straightforward. One uses massless incoming partons, which then produce the massive $b\bar{b}$ pair. For the flavor excitation diagrams it is not so clear on how to proceed. In this case one has an off-shell b-quark in the initial state being knocked on-shell by a massless parton. It is not clear what the QCD Monte-Carlo models are doing. I believe that ISAJET and PYTHIA take the b-quark to be massless in the initial and final-state for the flavor excitation diagrams and that HERWIG assigns a mass to the b-quark in the final-state. This would explain why the HERWIG flavor excitation contribution lies below ISAJET and PYTHIA.

Fig. 11 shows the predictions of ISAJET (CTEQ3L), HERWIG (CTEQ3L), PYTHIA (CTEQ3L), HERWIG (DO1.1), and PYTHIA (GRV94L) for the integrated b-quark total cross section ($P_T > 5$ GeV/c, $|y| < 1$) for proton-antiproton collisions 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 structure functions DO1.1 are older and the probability of finding a b quark within the proton is set identically equal to zero. Thus, running with the DO1.1 structure functions results in no flavor excitation contribution.

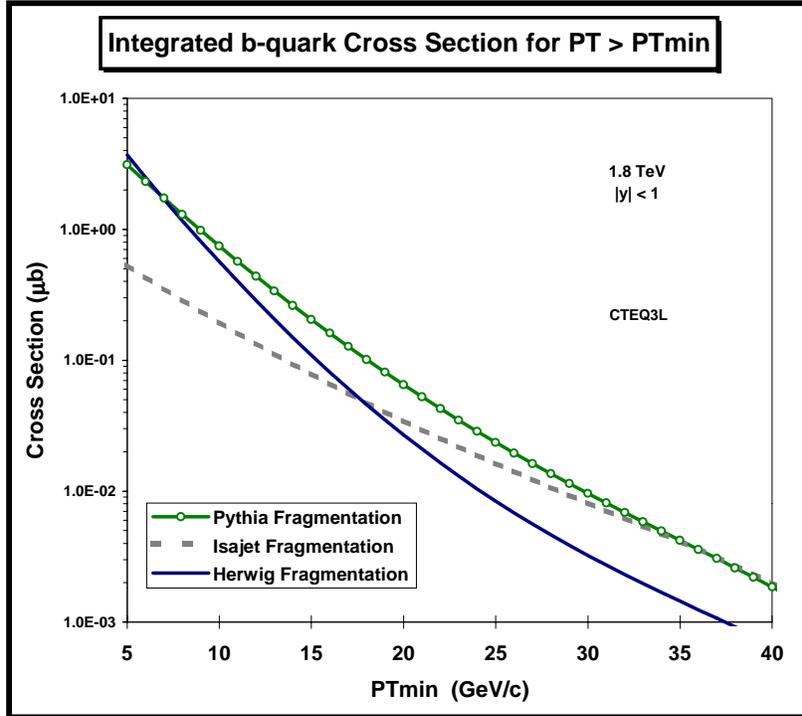


Fig. 10. Predictions of HERWIG, PYTHIA, and ISAJET for the integrated b-quark total cross section ($P_T > P_{Tmin}$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV resulting from the “shower/fragmentation” subprocesses illustrated in Fig. 4. The parton distribution functions CTEQ3L have been used for all three Monte-Carlo models.

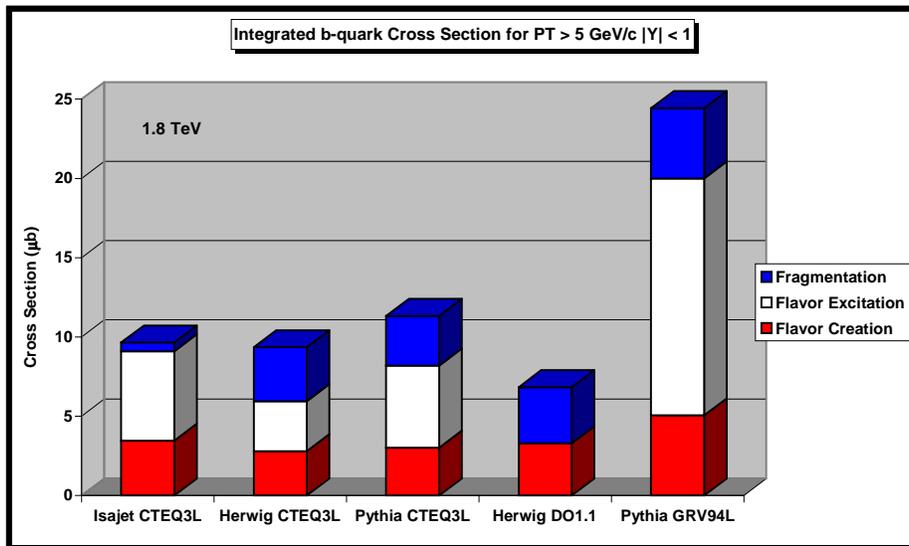


Fig. 11. Predictions of ISAJET (CTEQ3L), HERWIG (CTEQ3L), PYTHIA (CTEQ3L), HERWIG (DO1.1), and PYTHIA (GRV94L) for the integrated b-quark total cross section ($P_T > 5$ GeV/c, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV. The contributions from flavor creation (Fig. 1), flavor excitation (Fig. 3), and shower/fragmentation (Fig. 4) are shown together with the resulting sum (overall height of box).

Fig. 12 and Fig 13 show the predictions of ISAJET (CTEQ3L), HERWIG (CTEQ3L), and PYTHIA (CTEQ3L) for the integrated b-quark $|y| < 1$ total cross section for $P_T > 5$ GeV/c and for $P_T > 10$ GeV/c, respectively. The flavor creation contribution to b-quark production is

predicted by HERWIG and PYTHIA to be about 25% of the total b-quark production rate from all sources at the Tevatron ($P_T > 5 \text{ GeV}/c$, $|y| < 1$). For ISAJET it is about 35% of the total.

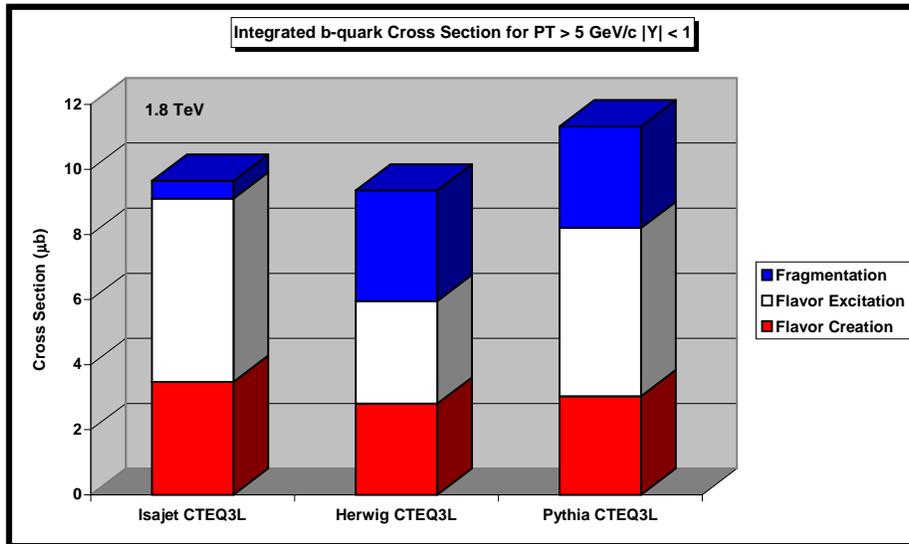


Fig. 12. Predictions of ISAJET (CTEQ3L), HERWIG (CTEQ3L), and PYTHIA (CTEQ3L) for the integrated b-quark total cross section ($P_T > 5 \text{ GeV}/c$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV. The contributions from flavor creation (Fig. 1), flavor excitation (Fig. 3), and shower/fragmentation (Fig. 4) are shown together with the resulting sum (overall height of box).

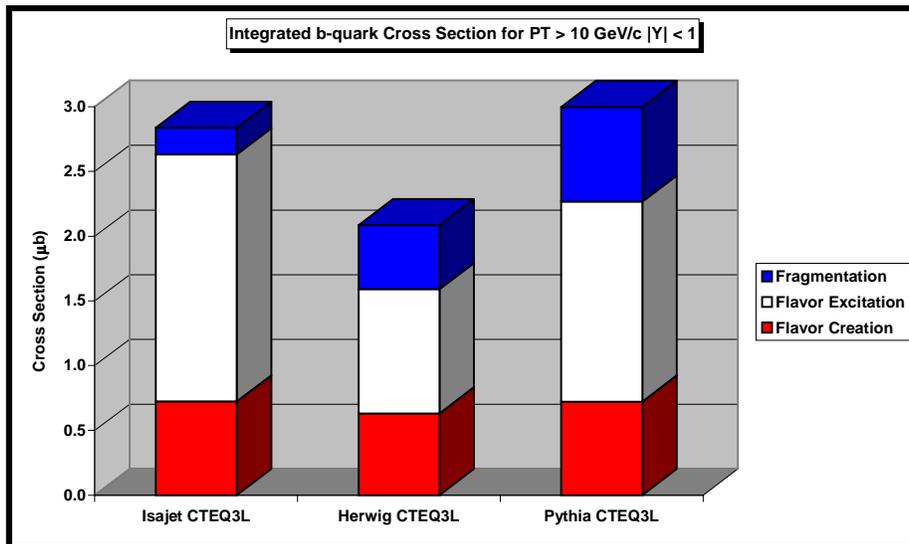


Fig. 13. Predictions of ISAJET (CTEQ3L), HERWIG (CTEQ3L), and PYTHIA (CTEQ3L) for the integrated b-quark total cross section ($P_T > 10 \text{ GeV}/c$, $|y| < 1$) for proton-antiproton collisions at 1.8 TeV. The contributions from flavor creation (Fig. 1), flavor excitation (Fig. 3), and shower/fragmentation (Fig. 4) are shown together with the resulting sum (overall height of box).

IV. b-quark 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} quark are quite different. Fig. 14 – Fig. 16 show the QCD Monte-Carlo model

predictions for some simple correlations. Here one requires a b-quark to be in the region $P_T > 5$ GeV/c and $|y| < 1$ and then asks for the probability of finding a \bar{b} -quark in the same region $P_T > 5$ 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 Monte-Carlo models predict that for flavor creation the probability that both the b and \bar{b} quark lie in the region $P_T > 5$ GeV/c and $|y| < 1$ is about 40%, with the \bar{b} -quark almost always on the “away-side” of the b-quark.

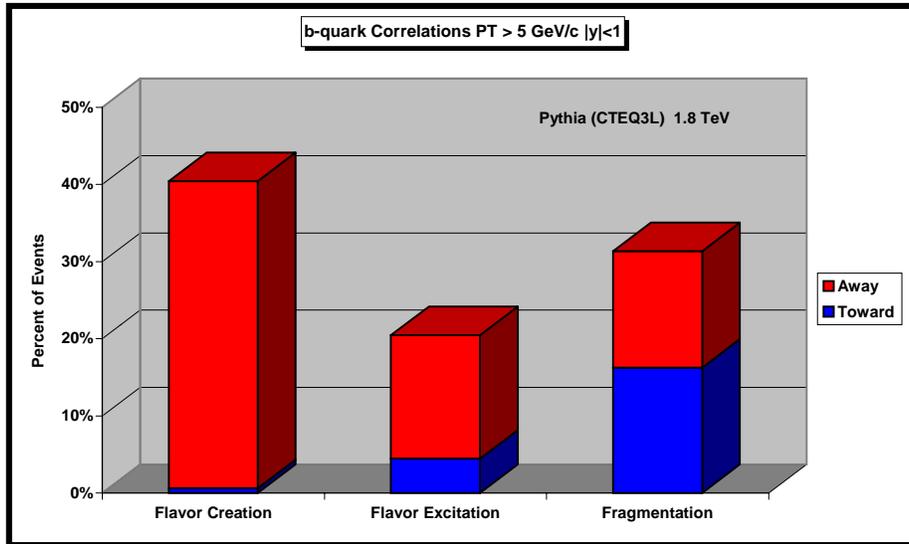


Fig. 14. Predictions of PYTHIA (CTEQ3L) for the probability of finding a \bar{b} quark with $P_T > 5$ GeV/c and $|y| < 1$ for events with a b-quark with $P_T > 5$ GeV/c and $|y| < 1$ for proton-antiproton collisions at 1.8 TeV. The contribution from the “toward” ($|\Delta\phi| < 90^\circ$) and the “away” ($|\Delta\phi| > 90^\circ$) region of the b-quark are shown for flavor creation (Fig. 1), flavor excitation (Fig. 3), and shower/fragmentation (Fig. 4).

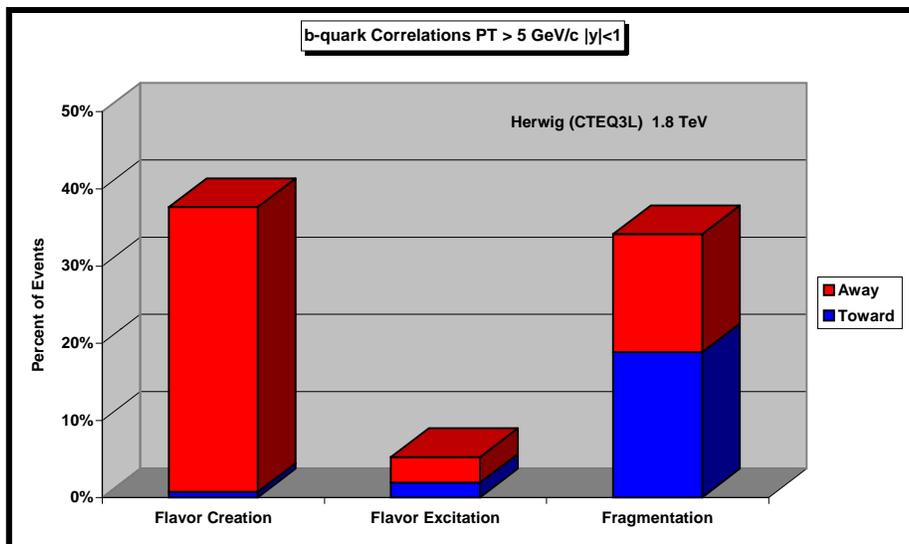


Fig. 15. Predictions of HERWIG (CTEQ3L) for the probability of finding a \bar{b} quark with $P_T > 5$ GeV/c and $|y| < 1$ for events with a b-quark with $P_T > 5$ GeV/c and $|y| < 1$ for proton-antiproton collisions at 1.8 TeV. The contribution from the “toward” ($|\Delta\phi| < 90^\circ$) and the “away” ($|\Delta\phi| > 90^\circ$) region of the b-quark are shown for flavor creation (Fig. 1), flavor excitation (Fig. 3), and shower/fragmentation (Fig. 4).

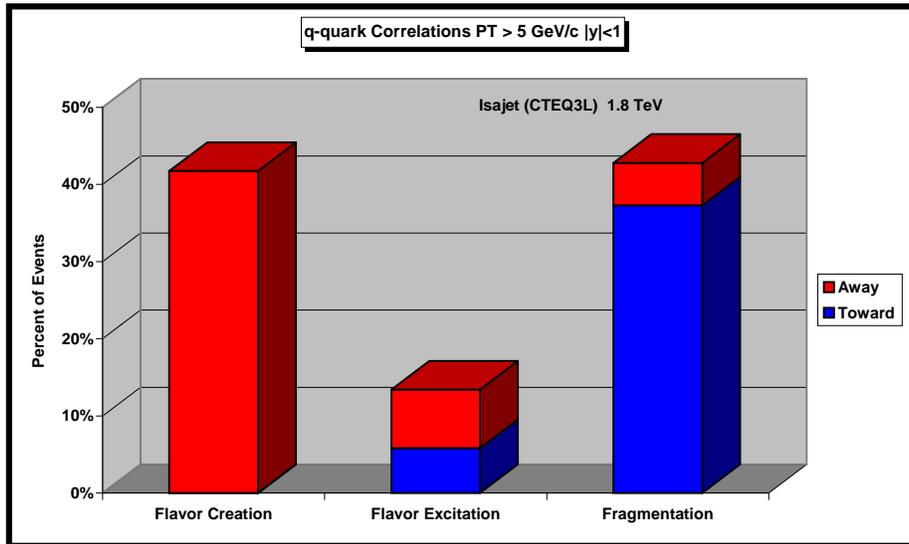


Fig. 16. Predictions of ISAJET (CTEQ3L) for the probability of finding a \bar{b} quark with $P_T > 5$ GeV/c and $|y| < 1$ for events with a b-quark with $P_T > 5$ GeV/c and $|y| < 1$ for proton-antiproton collisions at 1.8 TeV. The contribution from the “toward” ($|\Delta\phi| < 90^\circ$) and the “away” ($|\Delta\phi| > 90^\circ$) region of the b-quark are shown for flavor creation (Fig. 1), flavor excitation (Fig. 3), and shower/fragmentation (Fig. 4).

The QCD Monte-Carlo models differ considerably on the correlations for the shower/fragmentation contribution. For this contribution all three predict that both the b and \bar{b} quark lie in the region $P_T > 5$ 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.

All the QCD Monte-Carlo models predict that it is not very likely to find both the b and the \bar{b} -quark in the region $P_T > 5$ GeV/c and $|y| < 1$ for the flavor excitation contribution. For the flavor excitation terms 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 $P_T > 5$ 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 the flavor excitation contribution when both a b and a \bar{b} -quark are found in the region $P_T > 5$ GeV/c and $|y| < 1$ that the \bar{b} -quark is usually on the “away-side” of the b-quark.

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 $q\bar{q}$ annihilation of light quarks is easy to generate and all three Monte-Carlo models predict roughly the same cross section and similar $b\bar{b}$ correlations from these terms. However, 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 b-quark production rate from all sources for $P_T > 5 \text{ GeV}/c$ and $|y| < 1$.

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 models predictions for these terms differ somewhat, however, it seems likely that at the Tevatron the flavor excitation contribution to the b-quark cross section ($P_T > 5 \text{ GeV}/c$, $|y| < 1$) 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.

Parton Shower/Fragmentation

The production of b and \bar{b} -quarks 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 fragmentation contribution to the b-quark cross section ($P_T > 5 \text{ GeV}/c$, $|y| < 1$) might be comparable to the contribution from flavor creation.

Work needs to be done to improve the accuracy of the leading-log order estimates of the QCD Monte-Carlo models for the flavor excitation and the shower/fragmentation contributions to b-quark production. However, it seems likely that at the Tevatron all three sources of b-quarks; flavor creation, flavor excitation, and shower/fragmentation are important. In Run II we should be able experimentally to isolate the individual contributions to b-quark production by studying $b\bar{b}$ correlations in detail.

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