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Bottom Quark Production Using PYTHIA and HERWIG

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Abstract
This note describes in general the procedure for generating all three significant mechanisms needed to model completely $b\bar{b}$ production at the Tevatron using HERWIG or PYTHIA in the CDF Run II framework. It also details the specific steps taken to generate Monte Carlo samples for the BVTX tag correlation analysis, which examines $b\bar{b}$ angular correlations, including details of the B decay model and detector simulation applied to the Monte Carlo to allow a direct comparison with the data.

1 Introduction

The difficulty in obtaining agreement between measurement of the b quark cross section and theoretical predictions has led to an increased interest in other characteristics of $b\bar{b}$ production, such as the angular correlation between the b quarks. Angular correlations provide a useful probe of $b\bar{b}$ production because they offer feedback on the effective size of the contribution from the different QCD production mechanisms detailed below. The BVTX tag correlation analysis is one of several analyses from CDF involving $b\bar{b}$ angular correlations. The details of the analysis are described more fully in [1]. To briefly summarize, the BVTX tag correlation analysis measures the angular correlations between pairs of displaced secondary vertices reconstructed using the BVTX tagging algorithm. To relate this correlation measurement to theoretical predictions involving $b\bar{b}$ production, $b\bar{b}$ Monte Carlo is processed through a detector simulation to generate a theoretical prediction for the tag angular correlation distributions. This note describes the process of generating a suitable Monte Carlo sample for the BVTX tag angular correlation analysis.

The dominant source of b quarks at the Tevatron is QCD. The contributions to the total b quark cross section from electroweak processes like $W \to tb$ or $Z \to b\bar{b}$ (not to mention $H \to b\bar{b}$) are small enough that these processes can generally be neglected. QCD $b\bar{b}$ production can be modeled using three processes:

- **Flavor Creation**, also known as direct production, occurs when quark-antiquark annihilation or gluon fusion results in the pair production of b quarks. Both b quarks are part of the hard scatter in this case.
- **Flavor Excitation** occurs when a b quark present in initial state of one of the beam particles is scattered into the final state through a hard interaction with a parton from the other beam particle. For this mechanism, only one b quark participates in the hard scatter.
- **Gluon Splitting**, sometimes called shower/fragmentation, happens when the $b\bar{b}$ pair is created as part of the fragmentation and showering process in the event. No b quarks participate in the hard scatter.

Figure 1 below shows the lowest order Feynman diagrams characteristic of each of these three processes.

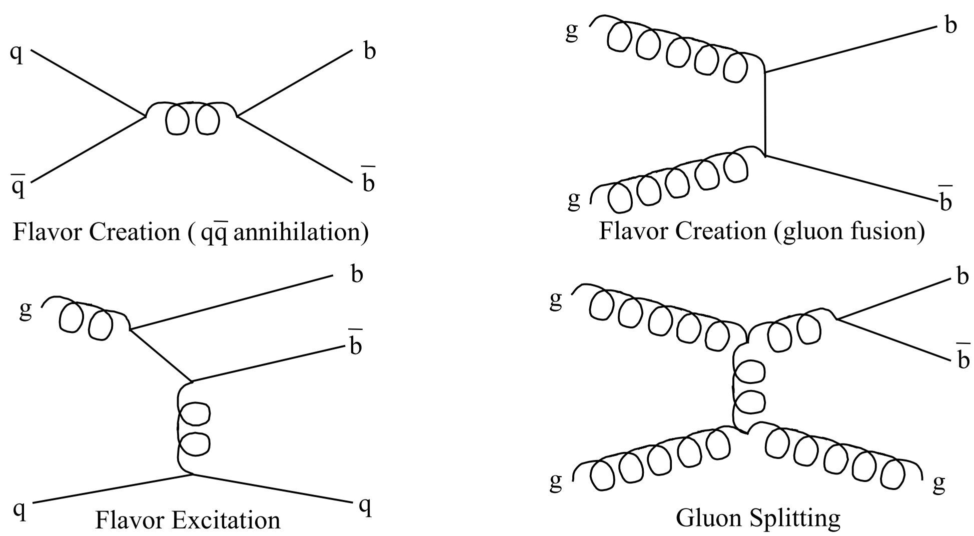

Figure 1 The lowest order contributions to $b\bar{b}$ production.

There are currently two methods available for calculating $b\bar{b}$ production: next-to-leading order (NLO) perturbation theory and the parton shower or leading-log (LL) model. The NLO calculation accounts for all terms to a fixed order α_s^3 but does not explicitly include fragmentation effects. On the other hand, the parton shower model, implemented in such Monte Carlo programs as PYTHIA [2], HERWIG [3], and ISAJET [4], always includes one or more models for fragmentation. However, this model is not exact to any order in perturbation theory. Rather, it bases its calculations on leading-order matrix elements and incorporates higher order effects by using a probabilistic model for initial and final state radiation. This probabilistic approach captures the leading-log characteristics of multiple-parton emission.

Each approach has its advantages and drawbacks, but in the regime of $b\bar{b}$ production, one would generally expect that both models would be reasonably successful in describing the data. Because of the way fragmentation is handled in the two approaches, it is far more straightforward to use the parton shower Monte Carlo programs. To generate the theoretical predictions for the BVTX tag correlations, we need hadron level Monte Carlo events suitable for use in our detector simulation. The parton shower Monte Carlo programs provide this by default. On the other hand, the NLO Monte Carlo programs generate weighted parton level events. In certain regions of phase space, the result relies on the cancellation of events with large negative weights by those with large positive weights. Applying a fragmentation model directly to the weighted, parton-level events can disturb this delicate cancellation and lead to erroneous results. Consequently, it becomes non-trivial to use a NLO Monte Carlo program to generate hadron level events. For this reason, we restrict ourselves to parton shower Monte Carlo programs for this analysis.

In the rest of this note, we describe the individual steps taken to produce suitable Monte Carlo samples using PYTHIA and HERWIG. Sections 2 through 4 give general information about generating QCD $b\bar{b}$ samples with PYTHIA or HERWIG. Sections 5 through 9 give information specific to the generation of the Monte Carlo sample for the BVTX tag correlation analysis.

2 Event Classification

In the parton shower approach to $b\bar{b}$ production, each event can be broken down into several stages: initial state showers, hard 2-to-2 scatter, final state showers, additional semi-hard parton scatters, and finally non-perturbative physics involving beam remnants and hadronization. For each event, there will be only one hardest 2-to-2 parton interaction, so the details of this interaction can be used to uniquely divide the events into different categories. One such classification scheme, relevant to $b\bar{b}$ production, is shown below [5]:

2.1 Categories

In this scheme, the identities of the incoming and outgoing partons in the hardest 2-to-2 parton scatter, plus the number of *b* quarks in the final state, are used to divide the events into the following categories

0. **Non-$b\bar{b}$ event:** These events do not have any *b* quarks in the final state, regardless of the details of the hard scatter.
1. **Gluon fusion** $(g+g \to b+\bar{b})$ **:** In these events, two gluons participate in the hard scatter to create a $b\bar{b}$ pair.
2. **Quark Annihilation** $(q+\bar{q} \to b+\bar{b})$ **:** In these events, a quark and an antiquark annihilate in the hard scatter to produce a $b\bar{b}$ pair. This process includes $b+\bar{b} \to b+\bar{b}$.
3. **Gluon-Initiated Flavor Excitation** ($g+b \to g+b$ or $g+\bar{b} \to g+\bar{b}$)**:** In these events, the hardest scatter involves a gluon and *b* quark in the initial state going to a gluon and *b* quark in the final state. To preserve bottom quantum number, there is a second *b* quark in the event of the opposite flavor as part of the additional activity in the event.
4. **Quark-Initiated Flavor Excitation** ($q+b \to q+b$, $\bar{q}+b \to \bar{q}+b$, $q+\bar{b} \to q+\bar{b}$, or $\bar{q}+\bar{b} \to \bar{q}+\bar{b}$, where *q* is any quark except *b*). The hardest parton scatter in these events contains one non-*b* quark and

one b quark in both the initial state and the final state. Like the process above, there is a second b quark generated by the rest of the activity in the event.

5. **Bottom-Quark-Initiated Flavor Excitation** ($b+b \rightarrow b+b$ or $\bar{b}+\bar{b} \rightarrow \bar{b}+\bar{b}$). In these events, both incoming and outgoing partons in the hardest scatter are b quarks of the same flavor. The opposite flavor case is part of quark annihilation above. In this class of event, there will always be four b quarks in the final state: two from the hard scatter, and two from the rest of the activity in the event.
6. **Gluon Splitting (two gluon final state):** The b quarks in this class of events do not come from the hard scatter. The two outgoing partons from the hardest scatter in this event are both gluons.
7. **Gluon Splitting (one gluon final state):** The b quarks in this class of events do not come from the hard scatter. One of the two outgoing partons from the hard scatter is a gluon. The other is a quark of some flavor other than bottom.
8. **Gluon Splitting (no gluon final state):** In this class of events, the b quark does not participate in the hardest scatter in the event. Neither of the outgoing partons from the hardest scatter are gluons.
9. **Error:** This category is reserved for situations that should not arise from normal QCD processes, like events with only one b quark or events containing two b quarks but no $\bar{b}$ quarks. These events should only result from bugs in the generator program or generation of non-QCD events.

Events from categories **1** and **2** make up **flavor creation**. Categories **3**, **4**, and **5** combine to yield **flavor excitation**, while **gluon splitting** is made up from events from categories **6**, **7**, and **8**.

2.2 Classification in PYTHIA

The first step to classifying $b\bar{b}$ events generated by PYTHIA is to loop through the HEPEVT [6] event record and count the number of b and $\bar{b}$ quarks. In the CDF Run II software framework, the HEPEVT event record may be accessed through the `HEPG_StorableBank` object that is part of the `SimulationObjects` package. In PYTHIA, entries with status code `ISTHEP` > 2 are comment lines and b quarks on those lines should not be counted. For a given event, if the number of b quarks plus the number of $\bar{b}$ quarks is zero, then the event belongs to category **0**. If the number of b quarks plus the number of $\bar{b}$ quarks is greater than zero, but the number of b quarks is not equal to the number of $\bar{b}$ quarks, then the event should be labeled as category **9**. If neither of these situations apply—in other words if the number of b quarks is non-zero and the number of b quarks equals the number of $\bar{b}$ quarks—then information about the hard scatter is required to classify the event.

Information about the hard scatter in PYTHIA is contained in the `MSTI` array from the `PYPARS` common block. `MSTI(15)` and `MSTI(16)` hold the identities of the two incoming partons for the hard scatter, while `MSTI(21)` and `MSTI(22)` contain the identities of the two outgoing partons. In the Run II framework, the `PYPARS` common block is accessible as a member object of the `Pythia` class from the `pythia_i` package. For example, to access `MSTI(15)`, one would use the following code:

```
Pythia *p = Pythia::Instance();
int id1 = p->pypars().msti(15); //Incoming hard scatter parton 1
```

Alternatively, if access to the PYTHIA common blocks is impossible—for example, if one is working with events in an output file, rather than as the events are generated—information about the hard scatter can also be gotten from PYTHIA comment lines in the HEPEVT record. These comment lines are the first 8 entries in the HEPEVT record for the event and have `ISTHEP` =3. Typically, the first two lines contain the ID of the two incoming beam particles. The next two lines should contain the partons selected from each beam particle to start the initial state showers. The following two lines record the partons selected from the initial state showers to participate in the hard scatter. The last two lines should list the two outgoing partons from the hard scatter. So, the fifth and sixth lines list the incoming partons for the hard scatter while the seventh and eighth lines list the two outgoing partons.

Once the identities of the incoming and outgoing hard scatter partons have been determined, it is straightforward to categorize the event. If both outgoing partons in an event are *b* quarks of opposite flavor, then it is a flavor creation event and the identity of the incoming partons determines if it is category **1** or **2**. If only one outgoing parton is a *b* quark, or if they are both *b* quarks of the same flavor, then the event should be classified as flavor excitation, with the exact category being determined again by the incoming hard scatter partons. Finally, if neither outgoing parton is a *b* quark, then the event comes from the gluon splitting processes. In this case, the number of gluons among the outgoing hard scatter partons determines the exact category. For this analysis, the classification scheme described above was implemented as a filter module that ran after event generation and used the `Pythia` and the `HEPG_StorableBank` objects to access the pertinent event information.

2.3 Classification in HERWIG

The basic procedure for categorizing events in HERWIG is the same as for PYTHIA with a few minor differences. As for PYTHIA data, the first step is to count the number of *b* quarks in the HEPEVT event record, skipping those with `ISTHEP` > 2, to determine whether the event belongs to category **0**, **9**, or one of the $b\bar{b}$ event categories. However, in HERWIG in the CDF Run II software framework, the hard scatter information is not conveniently available through common variables. Instead, the hard scatter information must be determined from the event record. The relevant entries are marked by the first entry in the event record with the following status codes (`ISTHEP`):

- **`ISTHEP` = 121:** The first incoming parton for the hard scatter.
- **`ISTHEP` = 122:** The second incoming parton for the hard scatter.
- **`ISTHEP` = 123:** The first outgoing parton from the hard scatter.
- **`ISTHEP` = 124:** The second outgoing parton from the hard scatter.

Once the partons in the hard scatter are identified from the event record, event classification proceeds just as for PYTHIA.

3 PYTHIA Generation

For this analysis, we used PYTHIA 6.203 in conjunction with release 4.6.0int1 of the Run II CDF software. Release 4.6.0int1 was chosen because it was the first release available on the machines where the generation would take place that had the full PYTHIA functionality required and no significant bugs. Releases early than 4.6.0int1 should not be used, as PYTHIA tended to crash frequently during $b\bar{b}$ generation. Releases after 4.6.0int1 in principle should be fine although we have not tested them.

In addition, it was recently discovered that PYTHIA contains a bug that directly affects the flavor excitation process [7]. Essentially this bug leads to an inconsistent treatment of the *b* mass during flavor excitation, with one class of events being handled as if the *b* quark were massless in the final state. The bug is caused by a missing line in the `PYSCAT` routine. The section of that code with the bug is shown below with the missing line in **bold**:

```
      ELSEIF(ISUB.EQ.28) THEN
C   f + g -> f + g; th = (p(f)-p(f))**2
        IF(MINT(15).EQ.21) JS=2
        KCC=MINT(2)+6
        IF(MINT(15).EQ.21) KCC=KCC+2
        IF(MINT(15).NE.21) KCS=ISIGN(1,MINT(15))
        IF(MINT(16).NE.21) KCS=ISIGN(1,MINT(16))
```

As of the time of this writing, this bug fix was not incorporated in any released version of PYTHIA and so must be implemented manually by code users.

In PYTHIA, it is best to generate each of the three contributions to $b\bar{b}$ production separately. Instructions for doing this in the CDF Run II software framework are given below:

3.1 Flavor Creation

Flavor creation is the easiest production mechanism to generate by itself in PYTHIA. To generate flavor creation events, one merely has to run PYTHIA with the heavy flavor process 5 (`MSEL` = 5) selected. In the Run II software framework, this can be specified by including the following line in the PYTHIA talk-to:

```
module talk Pythia
   PythiaMenu
      msel set 5
```

See appendix section 10.1.1 for the full PYTHIA flavor creation TCL file. In process 5, PYTHIA uses massive matrix elements to generate events in which the two outgoing partons from the hard scatter are always a $b\bar{b}$ pair. Since PYTHIA correctly accounts for the *b* mass in this calculation, the minimum parton-parton center of mass momentum, $\hat{p}_T(\text{min})$ can be set as low as 0 GeV/c. See section 9 for more information on choosing the right value for $\hat{p}_T(\text{min})$.

When PYTHIA is run in this configuration, every event generated should be a flavor creation $b\bar{b}$ event. To make sure everything is being done correctly, a filter module can be used to check that all events are classified as category **1** or **2** (flavor creation).

3.2 Flavor Excitation

It is also possible to configure a PYTHIA run so that almost all of the generated events are from the flavor excitation production mechanism; however, this requires more effort. The basic idea is to run the generic QCD jets process (`MSEL` = 1), but to limit the flavor content of one of the two incoming beam particles to just bottom. In this way, each collision generated will involve a *b* quark from one beam particle and any other parton from the other beam particle. To get the full flavor excitation contribution requires two runs: one in which all flavors but bottom are turned off in the proton beam, but the antiproton beam is left as normal, and one in which the proton beam is left normal and the all flavors but bottom are turned off in the antiproton beam. The two runs are then added together to yield the total contribution. For example, the total flavor excitation cross section is the sum of the cross sections from the individual runs.

In PYTHIA, the `KFIN` array from the `PYSUBS` common block is used to specify the allowed flavors in one of the beam particles. `KFIN` is a two dimension array where the first index specifies beam particle (1 = "beam side," typically the proton side at CDF, while 2 = "target side," which is the antiproton side by default at CDF), and the second index specifies beam flavor according to PYTHIA's `KF` particle codes. "`KFIN(I,J) = 1`" means that in beam `I`, flavor `J` is turned on, while a value of zero would indicate that flavor is turned off. Currently, the CDF interface to PYTHIA does not allow a direct manipulation of the `KFIN` array the PYTHIA talk-to, however, the user may specify settings for this array prior to a run using the `PYGIVE` facility. In the PYTHIA talk-to, the syntax for this is

```
module talk Pythia
   PythiaMenu
      pygiveFile set "pygive_file.txt"
```

where `pygive_file.txt` contains the settings for various PYTHIA common block variables. For example, the `PYGIVE` file to turn off all flavors in the proton (beam side) except bottom would contain the following:

```
KFIN(1,1)=0
KFIN(1,-1)=0
KFIN(1,2)=0
KFIN(1,-2)=0
KFIN(1,3)=0
KFIN(1,-3)=0
KFIN(1,4)=0
KFIN(1,-4)=0
KFIN(1,21)=0
```

To do the same for the antiproton (target side), change the first index from "1" to "2." For a full example of a PYTHIA flavor excitation TCL file, see section 10.1.2.

Run in this configuration, PYTHIA generates almost all flavor excitation events. However, a small number of the events generated will be of the type $b+\overline{b} \to b+\overline{b}$, which we categorize as flavor creation. Therefore, it is necessary to filter the generated events so that only events from categories **3**, **4**, and **5** are retained in the flavor excitation sample.

Finally, it should be noted that for generic QCD jets (`MSEL` = 1), PYTHIA uses a massless quark approximation to calculate the matrix elements. Thus, *b* quarks are treated as massless in the hard scatter. In the final state, to keep the kinematics consistent when the *b* quarks are given a non-zero mass, the *b* quark momentum vector is rescaled along its direction while keeping the energy constant. PYTHIA's massless treatment of *b* quarks in flavor excitation differs from HERWIG's approach, which is to account for the *b* quark mass in the matrix elements. This difference in approach leads to noticeable effects when flavor excitation data from the two generators are compared.

3.3 Gluon Splitting

The gluon splitting contribution to $b\overline{b}$ production is the most onerous of the three to generate. Just as for flavor excitation, PYTHIA should be set to generate generic QCD jets (`MSEL` = 1). However, unlike the flavor excitation case, there is no method for increasing the fraction of $b\overline{b}$ events generated by this process without introducing unrealistic biases. Instead, one must generate all possible QCD processes and accept only events in which at least one $b\overline{b}$ pair is produced. Depending on other PYTHIA settings—like $\hat{p}_T(\min)$, or the amount of initial state radiation—and given the kinematic region to which this analysis is sensitive, the ratio of the total number of events generated to number of usable gluon splitting events can be in the range of 1000 to one. Actually, all three contributions to $b\overline{b}$ production occur using this procedure, so it is necessary to use a filter so that only events from categories **6**, **7**, and **8** are present in the gluon splitting sample. The flavor creation events generated using this method are inferior to the events generated using the heavy flavor production process (`MSEL` = 5) because of the massless approximation used for the matrix elements. The flavor excitation events generated in this sample are equivalent to those generated using the procedure above, but the production is so much less efficient that it's hardly worth keeping the small number of events generated.

See section 10.1.3 for a full example PYTHIA gluon splitting TCL file.

3.4 Other PYTHIA Parameters

PYTHIA has a large number of parameters and switches that affect the character of the data regardless of the production mechanism generated. Some parameters have a direct effect on the hard scattering part of the event while others control features of the underlying event. These parameters must be carefully tuned depending on the level of agreement sought between Monte Carlo and data.

3.4.1 Initial State Radiation

One aspect of PYTHIA generation that has a marked effect on $b\bar{b}$ angular correlations is the amount of initial state radiation PYTHIA generates. Increasing the amount of initial state radiation has the effect of broadening peaks in the angular distributions, like the back-to-back peak from flavor creation. Increased initial state radiation can also lead to more detectable B hadrons because b quarks in the event can have a larger initial p_T. Finally, raising the amount of initial state radiation directly effects the gluon splitting portion of the $b\bar{b}$ cross section because more energetic gluons in the event leads to a greater probability of producing a $b\bar{b}$ pair from a gluon branching.

In PYTHIA, the amount of initial state radiation is controlled by the variable `PARP(67)` from the `PYPARS` common block. The value of `PARP(67)` is multiplied by the Q^2 of the hard scatter to determine the maximum virtuality of the initial state shower. Higher values of `PARP(67)` lead to more initial state radiation. The correct amount of initial state radiation is not known from first principles. The default value of `PARP(67)=1.0` for the latest versions of PYTHIA (any after 6.138) comes from studies involving heavy quark production [8]. However, the versions of PYTHIA used during Run I (for example, PYTHIA 5.6), had a higher amount of initial state radiation, with a default value of `PARP(67) = 4.0`. In all likelihood, the best value lies somewhere between 1.0 and 4.0. We have generated samples using both values and will compare to data.

3.4.2 Parton Distribution Functions

The choice of parton distribution function primarily effects the amount of flavor excitation predicted in PYTHIA. Changing the parton distribution set can yield higher or lower contributions from flavor excitation to the total amount of $b\bar{b}$ production. For this analysis, we use the CTEQ5L parton distribution functions. This choice was motivated by [9], which uses the CTEQ parton distributions to obtain reasonable agreement between the PYTHIA predictions for the inclusive b quark cross section and experimental measurements.

3.4.3 Underlying Event

The term "underlying event" refers to all the other activity associated with a proton-antiproton collision beyond the hardest parton-parton scatter. At a minimum, this activity includes the breakup of the proton and antiproton remnants after the hard scatter, and any initial and final state radiation in the event. There is also good evidence that additional semi-hard parton interactions contribute to the underlying event [9]. In PYTHIA, this contribution is labeled "multiple parton interactions" (MPI), or frequently, just "multiple interactions," not to be confused with the term "multiple interactions" referring to multiple proton-antiproton collisions in the same event. (In the PYTHIA documentation, events containing multiple proton-antiproton collisions are referred to as "pile-up events." PYTHIA has a number of parameters that allow one to tune the underlying event to match the data. The default PYTHIA settings do not match CDF data very well. For this analysis, we have used PYTHIA settings determined by [9] from studying minimum-bias and underlying event data from CDF.

The exact tuning of the underlying event in PYTHIA depends on the amount of initial state radiation, as determined by `PARP(67)`, and the choice of pdf set, in this case CTEQ5L. Table 1 shows the parameters used to tune the underlying event for the two different initial state radiation settings used to generate the PYTHIA samples. It is important to realize that a change in either the initial state radiation or the pdf set used requires completely different values of the these PYTHIA parameters to match the underlying event.

4 HERWIG Generation

This analysis uses version HERWIG 6.400 within release 4.6.0int1 of the Run II CDF software. Release 4.6.0int1 was chosen to match the release used for PYTHIA generation. No other releases or versions of HERWIG were tested.

Also, there was a minor bug discovered in version HERWIG 6.4 that, as of this writing, had not been fixed in any released HERWIG version [7]. The fix is to add a set of parentheses around an expression in `HWSBRN.F`. Specifically, one must change the lines

```
          IF (SUDORD.EQ.1.AND.HWUALF(2,QLAM).LT.HWRGEN(0) .OR.
     &        (2.-XI)*QLAM**2.GT.EMSCA**2.AND..NOT.FORCE) THEN
```

Add parentheses here

to

```
          IF ((SUDORD.EQ.1.AND.HWUALF(2,QLAM).LT.HWRGEN(0) .OR.
     &        (2.-XI)*QLAM**2.GT.EMSCA**2).AND..NOT.FORCE) THEN
```

Implementing this change reduces the number of events killed by HERWIG during generation because of HWARN error messages.

Parameter	**Meaning**	**`PARP(67) = 4.0`**	**`PARP(67) = 1.0`**
`MSTP(81)`	Multiple-parton interaction switch	1 (Multiple Parton Interactions ON)	
`MSTP(82)`	Model of multiple parton interactions	3 (Varying impact parameter assuming a single Gaussian matter distribution)	
`PARP(82)`	p_T turn-off when using single Gaussian model of multiple interactions	1.7	1.6
`PARP(85)`	Probability that a multiple parton interaction produces two gluons with color connections to the "nearest neighbors"	1.0	
`PARP(86)`	Probability that an MPI produces two gluons either as described above or as a closed gluon loop. The rest of the MPIs produce quark-antiquark pairs	1.0	
`PARP(89)`	Determines the reference energy E_0	1800.	

Table 1 The table above shows the **PYTHIA** setting used to tune the underlying event to data for the CTEQ5L parton distribution set and two different initial state radiation settings. For more details consult the **PYTHIA** manual[2].

4.1 Flavor Creation and Flavor Excitation

HERWIG contains an option to run a heavy quark process which includes contributions from flavor creation and flavor excitation. For *b* quarks, this is process 1705 (`IPROC` = 1705). In the CDF Run II software framework, this option can be selected from the HERWIG talk-to as follows:

```
module talk herwig
   Process set 1705
```

Because process 1705 generates both flavor creation and flavor excitation, it is necessary to filter the output to separate these two contributions. For this analysis, this was done by cloning the hard process filter and setting up two paths, one that used a version of the filter that selected category **1** and **2** events, and one that used a version of the filter that selected category **3**, **4**, and **5** events. These two paths were associated with separate streams, so the job output different files for the flavor creation and flavor excitation samples. A full example of this TCL file is given in section 10.2.1.

For its heavy flavor production process, HERWIG uses matrix elements which take into account the b quark mass. This means, unlike PYTHIA flavor excitation, which is calculated in the massless approximation, HERWIG flavor excitation explicitly includes the b mass. This difference in approach leads to different results for the flavor excitation contribution to $b\bar{b}$ production. Also, since the b quark mass provides a natural cut-off to regulate any divergences in the hard scattering, p_T(min) can be set as low as 0 GeV/c for both flavor creation and flavor excitation in HERWIG.

4.2 Gluon Splitting

As in PYTHIA, the only way to generate the gluon splitting contribution to $b\bar{b}$ production in HERWIG is to run all QCD 2-to-2 hard processes and to select events which happen to contain a $b\bar{b}$ pair as part of the shower and fragmentation activity. This is accomplished in HERWIG by running process 1500. Most of the events generated this way will not be $b\bar{b}$ events, and of the $b\bar{b}$ generated, only some will come from gluon. Therefore, it is necessary to use a filter to select only events from categories **6**, **7**, and **8**. Also, because process 1500 uses massless matrix elements for the hard scatter, it is necessary to select a p_T(min) greater than zero. For gluon splitting, p_T(min) should be set to 5 GeV/c or higher, depending on the region of kinematic sensitivity for the given analysis.

An example of a complete gluon splitting TCL file is given in section 10.2.2.

4.3 Other HERWIG Parameters

HERWIG does not contain as many options for tuning the event generation as PYTHIA does. For this analysis, we chose to use the CTEQ5L parton distributions just as we did for PYTHIA. HERWIG does not automatically chose a Λ_{QCD} appropriate for the structure function in use, so we had to set it manually to the appropriate value of 0.192 GeV. Finally, in order to get HERWIG to produce B baryons in addition to B mesons, it is necessary to change the default value of the `CLPOW` parameter to the CDF default of 1.26.

It is worth noting that, as shown in [9], HERWIG does a poor job of modeling the underlying event at the Tevatron. This is mainly because HERWIG does not include a model of multiple parton interactions as PYTHIA does. As a result, HERWIG does not produce enough hard tracks in the underlying event. This analysis is not terribly sensitive to details of the underlying event. In situations where the underlying event must be modeled correctly, one might do better to use JIMMY, which is an extension to HERWIG that adds multiple parton interactions [10].

5 Redecaying with QQ

For this analysis, B hadrons are decayed using a modified version of the Cleo B decay program QQ, run in the Run II CDF software framework. The version of QQ used is based on version 9.1 from the Run I CDF software framework, modified so that B_c decays are also included. In addition, changes have been made to the default QQ decay tables to fix some mistakes and to give B baryons more realistic semileptonic branching fractions.

In order to enhance the statistics of the Monte Carlo samples, each $b\bar{b}$ event from PYTHIA or HERWIG is decayed multiple times. In addition, some of the B hadrons are forced to decay semileptonically to increase the fraction of the events with a lepton passing the necessary electron or muon trigger. For both PYTHIA and HERWIG flavor creation and flavor excitation samples, we redecay each event ten times forcing the "b-flavored" hadrons to decay semileptonically, and then ten times forcing the "$\bar{b}$ -flavored" hadrons to decay semileptonically. This gives a total of twenty decays for each flavor creation and flavor excitation event. We redecay the gluon splitting samples from both Monte Carlos twenty times for each flavor of semileptonic decay, for a total of forty decays for each event.

An example TCL file used to redecay events for this analysis is given in section 10.3

6 Detector Simulation: QFL′

After the Monte Carlo is generated and redecayed in the Run II framework, the sequential root output files are converted to Run I YBOS files so that the Monte Carlo can be processed through the Run I detector simulation, reconstruction and analysis code. For this analysis, we use the Run I fast detector simulation, QFL′ [11] from version 7.12 of the Run I offline software. The "prime" in QFL′ indicates that this version of the code includes a simulation of the Run Ib silicon detector. We keep the standard QFL′ defaults for most settings (see section 10.4 for the full UIC file used). In the analysis of the data, we assumed a beam spot size of 25μm in *x* and *y*; therefore, we set the beam spot size to 25μm in QFL′. Also, since we require the SVX for this analysis, we limited the *z* vertex of the generated events to ±35cm from the center of the detector.

QFL′ does not retain a link between Monte Carlo particles and their corresponding tracks from the tracking simulation. However, for various studies, Monte Carlo particle to track matching is useful. We associate Monte Carlo particles with tracks after QFL′ based on the closest match between the momentum vectors of the particles and tracks. For a Monte Carlo particle to be associated with a track, it must be a charged, final state particle (e, μ, π, K, or p), and the difference between the Monte Carlo particle's momentum and the closest-matching track momentum must be less than 80% of the Monte Carlo particle's p_T. Only Monte Carlo particles with $|\eta| < 1$ and $p_T > 0.2$ GeV/c are considered for matching.

7 Trigger Simulation

The data for this analysis are required to pass certain electron or muon trigger requirements. In order to account for the effects of the trigger on lepton momentum distribution, a trigger simulation was applied to the Monte Carlo data. For the electron trigger simulation, we implemented the algorithm from [12]. For the muons, we used the standard Bottom group muon simulation code DIMUTG [13], version 2.1, which has been modified to handle single CMUP muon triggers. In neither case do we try to account for trigger prescales. We consider only the kinematic effects of the relevant triggers. Figure 1 demonstrates how well the Monte Carlo lepton distributions match the data after the simulation.

8 Event Reconstruction and Analysis

Once the Monte Carlo has been passed through the detector simulation, it is treated as much as possible like the actual data. This includes running it through the standard event reconstruction sequence using version 7.12 of the Run I offline code. SVX reconstruction is handled by the modules `SVXCLU` and `DO_SVX_PAD`.

After the Monte Carlo events are reconstructed, they are passed through a modified version of the BVTX tagging algorithm used for the time dependent *B* mixing analysis, as well as the same analysis code used to identify doubly-tagged events in the data. A full description of this procedure as applied to data can be found in [1]. The full UIC file used to analyze the Monte Carlo is given in section 10.4.

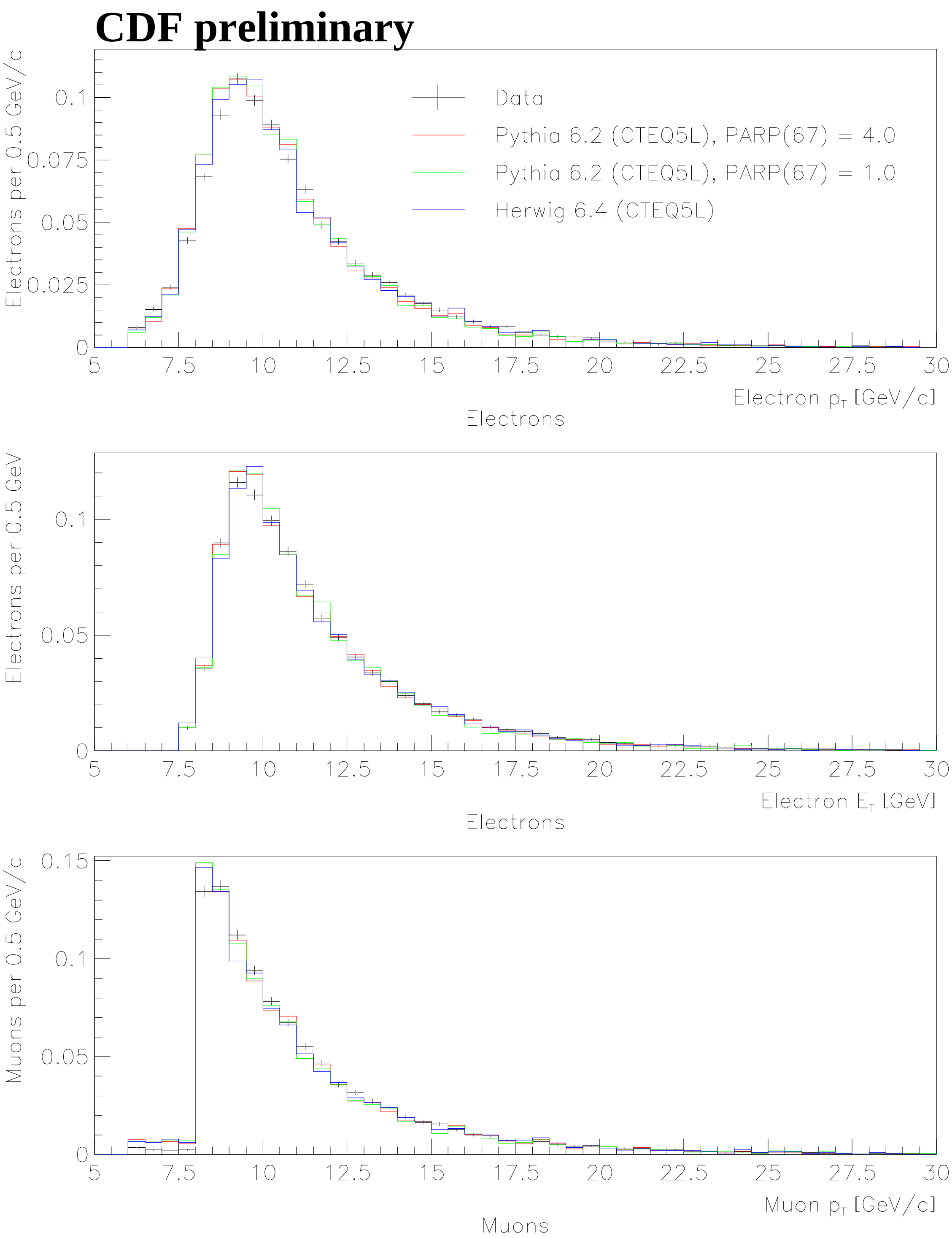

Figure 2 shows a comparison between Monte Carlo and data for the p_T and E_T spectra of electrons and the p_T spectrum of muons. The distributions are normalized to unit area. For the Monte Carlo spectra, contributions from the three production mechanisms are added normalized according to the Monte Carlo cross section predictions.

9 Choosing $\hat{p}_T$(min)

In PYTHIA, $\hat{p}_T$ is defined as the p_T of the 2-to-2 hard scatter in the parton-parton center of mass reference frame. PYTHIA allows one to specify a minimum value of $\hat{p}_T$ to be generated. HERWIG has a similar concept with its parameter, p_T(min), which specifies the minimum p_T in hadronic jet production. The primary purpose for the parameter $\hat{p}_T(\text{min})$ is to provide a cutoff for processes in which the cross section diverges as $\hat{p}_T$ approaches zero. Processes calculated with massive matrix elements, like flavor creation in PYTHIA and HERWIG, and flavor excitation in HERWIG, have a natural cutoff through the quark masses. So, for these processes, one may safely set $\hat{p}_T(\text{min}) = 0$ GeV/c . In addition, PYTHIA makes an effort to regulate divergent cross sections, regardless of the value of $\hat{p}_T(\text{min})$. In principle, it should always be safe to take $\hat{p}_T(\text{min})$ down to zero for any process in PYTHIA and the cross section produced should remain below the total inelastic proton-antiproton cross section. In practice, this assumption should be checked, especially with older versions of PYTHIA as the implementation of the cutoff was not perfect and in certain $\hat{p}_T(\text{min})$ ranges, unreasonably high cross sections may be generated. HERWIG does not regulate divergent cross sections, so it is always necessary to set a reasonable p_T(min) in HERWIG to guarantee that processes with no natural cutoffs—like those calculated with massless matrix elements—do not diverge.

In addition to regulating divergent cross sections, $\hat{p}_T(\text{min})$ can be used to improve the efficiency with which certain events are generated. For example, in PYTHIA, flavor excitation and gluon splitting do not become significant until $\hat{p}_T(\text{min}) \sim m_b$. Studies have shown that for PYTHIA, there is no significant difference in flavor excitation and gluon splitting between $\hat{p}_T(\text{min}) = 0$ GeV/c and $\hat{p}_T(\text{min}) = 5$ GeV/c . The same is true for gluon splitting in HERWIG. Thus for these processes, there is little motivation for using a $\hat{p}_T(\text{min}) < 5$ GeV/c . The table below summarizes the lowest sensible $\hat{p}_T(\text{min})$ for each process in each generator:

Process	**PYTHIA**	**HERWIG**
flavor creation	0 GeV/c	0 GeV/c
flavor excitation	5 GeV/c	0 GeV/c
gluon splitting	5 GeV/c	5 GeV/c

Table 2 The lowest sensible $\hat{p}_T(\text{min})$ for generating each contribution to $b\bar{b}$ production. Higher values may be used if the particular analysis that will use the Monte Carlo has no sensitivity to lower p_T b quarks.

Higher values than shown in Table 2 may be reasonable depending on the analysis. For example, in the flavor creation subprocess, ignoring initial state and final state radiation, $\hat{p}_T(\text{min})$ essentially sets the minimum p_T for the b quarks produced. Flavor excitation and gluon splitting have similar trends although $\hat{p}_T(\text{min})$ and b p_T are not so tightly correlated. Because the gain in efficiency for producing events within the acceptance of an analysis can be large, it is worthwhile to investigate whether higher $\hat{p}_T(\text{min})$ values would be suitable for a given analysis. However, care must be taken since effects like initial state radiation can change the correlation between b p_T and $\hat{p}_T(\text{min})$.

For this analysis, we determined suitable values for $\hat{p}_T(\text{min})$ as follows. We began with some trial runs at relatively low $\hat{p}_T(\text{min})$ in order to get an idea of the lower limit of our sensitivity to B p_T. From this study, we concluded that the B that decays leptonically must have a p_T of at least 13 GeV/c to have a reasonable chance of producing a lepton that would satisfy the trigger requirements. For the other B to have a chance of being tagged, we estimated that it should have a p_T of at least 6 GeV/c. We then looked at the generator level data on the events to estimate the minimum $\hat{p}_T(\text{min})$ necessary to create an event containing $b\bar{b}$ within our kinematic acceptance. Figure 3 through Figure 5 show the $\hat{p}_T(\text{min})$ spectra for events in which the B hadrons are both in the central region ($|\eta| < 1$), and in which one B hadron has $p_T >$ 13 GeV/c and the other has $p_T >$ 6 GeV/c for each Monte Carlo sample. Because our trial samples were small and because in some cases—particularly for gluon splitting—a small increase in $\hat{p}_T(\text{min})$ could lead to a large increase in the number of accepted events, some of our choices for $\hat{p}_T(\text{min})$ may have been somewhat aggressive. The table below shows the $\hat{p}_T(\text{min})$ we used to generate each Monte Carlo sample for this analysis:

Process	PYTHIA, PARP(67) = 1.0	PYTHIA, PARP(67) = 4.0	HERWIG
flavor creation	8 GeV/c	8 GeV/c	8 GeV/c
flavor excitation	10 GeV/c	8 GeV/c	8 GeV/c
gluon splitting	15 GeV/c	12 GeV/c	10 GeV/c

Table 3 The actual $\hat{p}_T(\text{min})$ used to generate Monte Carlo for this analysis. The values are lower for the PYTHIA case with more initial state radiation because the *b* quarks get an additional p_T kick over the case with less initial state radiation.

Figure 6 through Figure 9 show the *B* hadron and *b* quark p_T spectra from the Pythia sample with `PARP(67) = 4.0`. The other Monte Carlo samples have similar distributions. From these distributions, we can deduce the 90% cut-offs for the *B* hadron that decays semi-leptonically and for the other *B*. The 90% p_T cut-offs for each Monte Carlo sample are presented in Table 4 through Table 6.

Electron Monte Carlo (All numbers in GeV/c):

	***B* (leptonic)**		***B* (non-leptonic)**		***b* quark (leptonic)**		***b* quark (non-leptonic)**	
	Ave.	**90%**	**Ave**	**90%**	**Ave**	**90%**	**Ave**	**90%**
fc	20.4	14.0	17.7	10.1	21.9	14.6	19.5	10.6
fe	21.2	14.4	15.0	7.5	22.9	15.2	16.4	8.1
gs	21.8	14.6	15.0	7.4	23.7	15.4	16.5	8.1

Muon Monte Carlo (All numbers in GeV/c):

	***B* (leptonic)**		***B* (non-leptonic)**		***b* quark (leptonic)**		***b* quark (non-leptonic)**	
	Ave.	**90%**	**Ave**	**90%**	**Ave**	**90%**	**Ave**	**90%**
fc	22.0	14.0	19.1	10.4	23.6	14.6	20.8	11.1
fe	23.0	14.6	15.6	7.6	24.8	15.3	17.2	8.3
gs	23.7	14.7	15.8	7.6	25.5	15.7	17.4	8.3

Table 4 shows the average and the 90% threshold for the *B* hadron and *b* quark p_T distributions from PYTHIA Monte Carlo with `PARP(67) = 4.0`. "Leptonic" *B* hadrons are *B* hadrons that decay semileptocnically. "Leptonic" *b* quarks hadronize into *B* hadrons which decay semileptonically. "Non-leptonic" *B* hadrons and *b* quarks are associated with *B* hadrons that don't decay semileptonically.

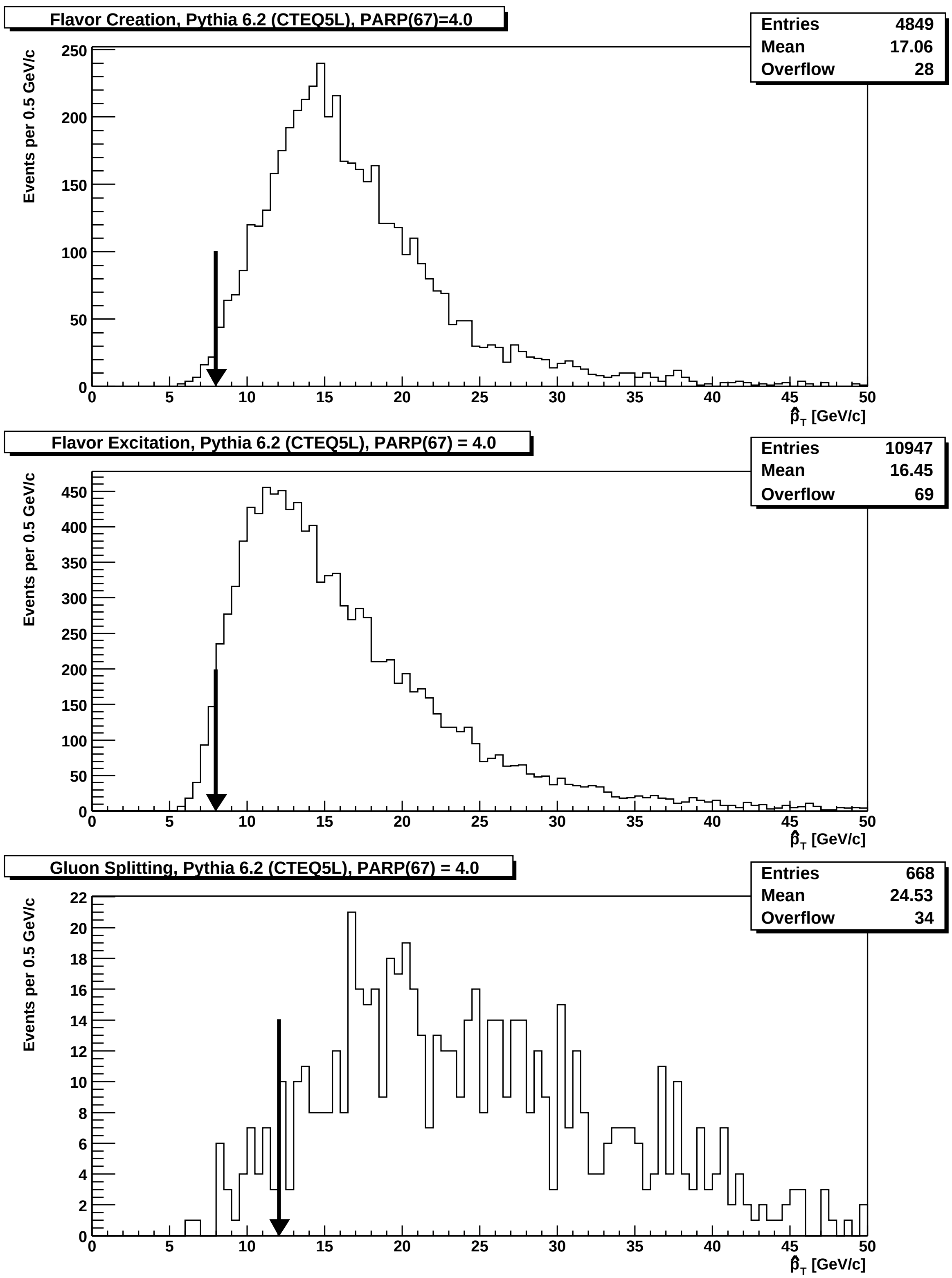

Figure 3 shows $\hat{p}_T$ for events from PYTHIA with `PARP(67) = 4.0` that have one B hadron having $p_T >$ 13 GeV/c and another B hadron with $p_T >$ 6 GeV/c. These distributions were generated using the lowest reasonable $\hat{p}_T$(min) for each production mechanism. The arrows show the $\hat{p}_T$(min) values used to generate the large samples used with the detector simulation.

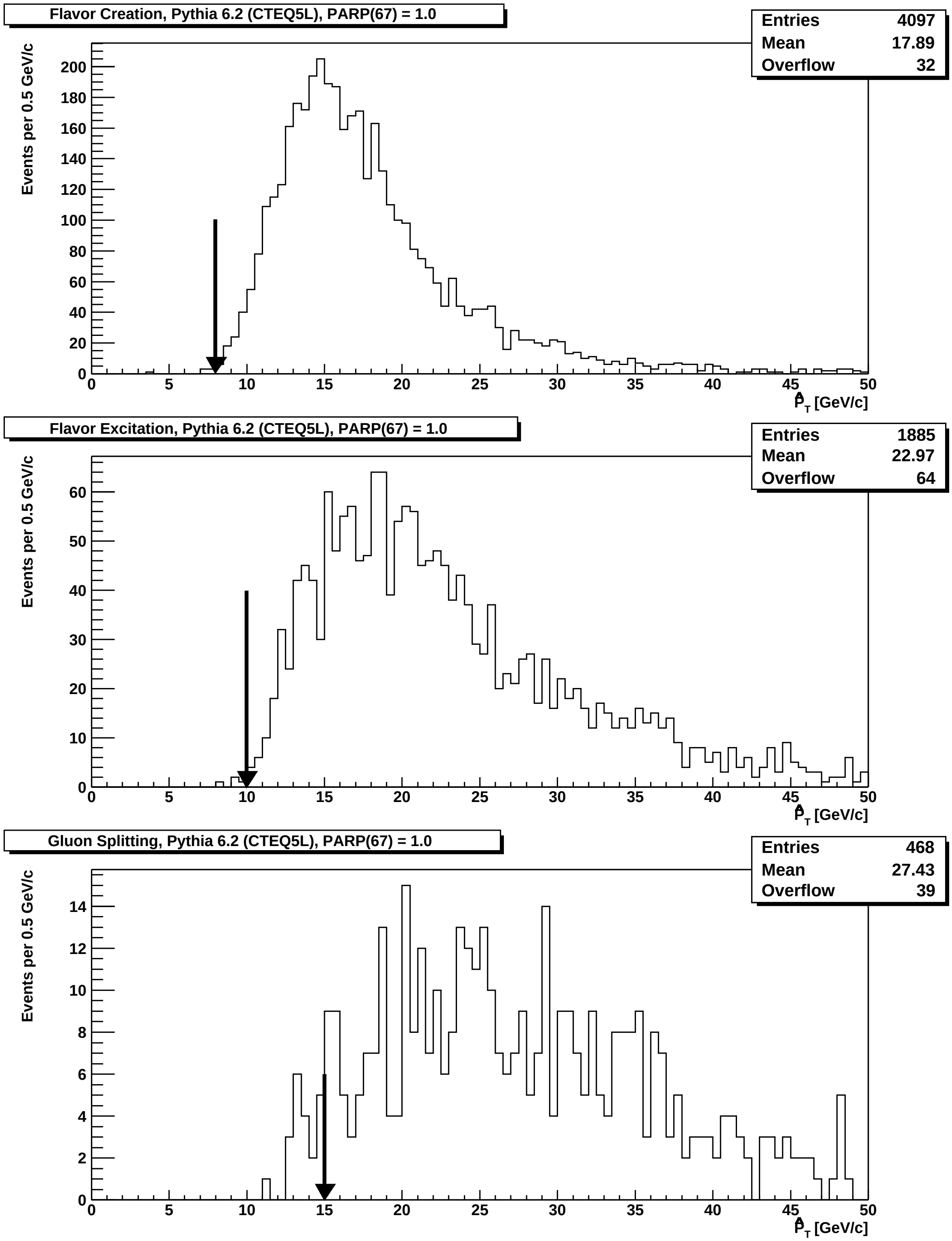

Figure 4 shows $\hat{p}_T$ for events from PYTHIA with `PARP(67) = 1.0` that have one *B* hadron having $p_T >$ 13 GeV/c and another *B* hadron with $p_T >$ 6 GeV/c. These distributions were generated using the lowest reasonable $\hat{p}_T$(min) for each production mechanism. The arrows show the $\hat{p}_T$(min) values used to generate the large samples used with the detector simulation.

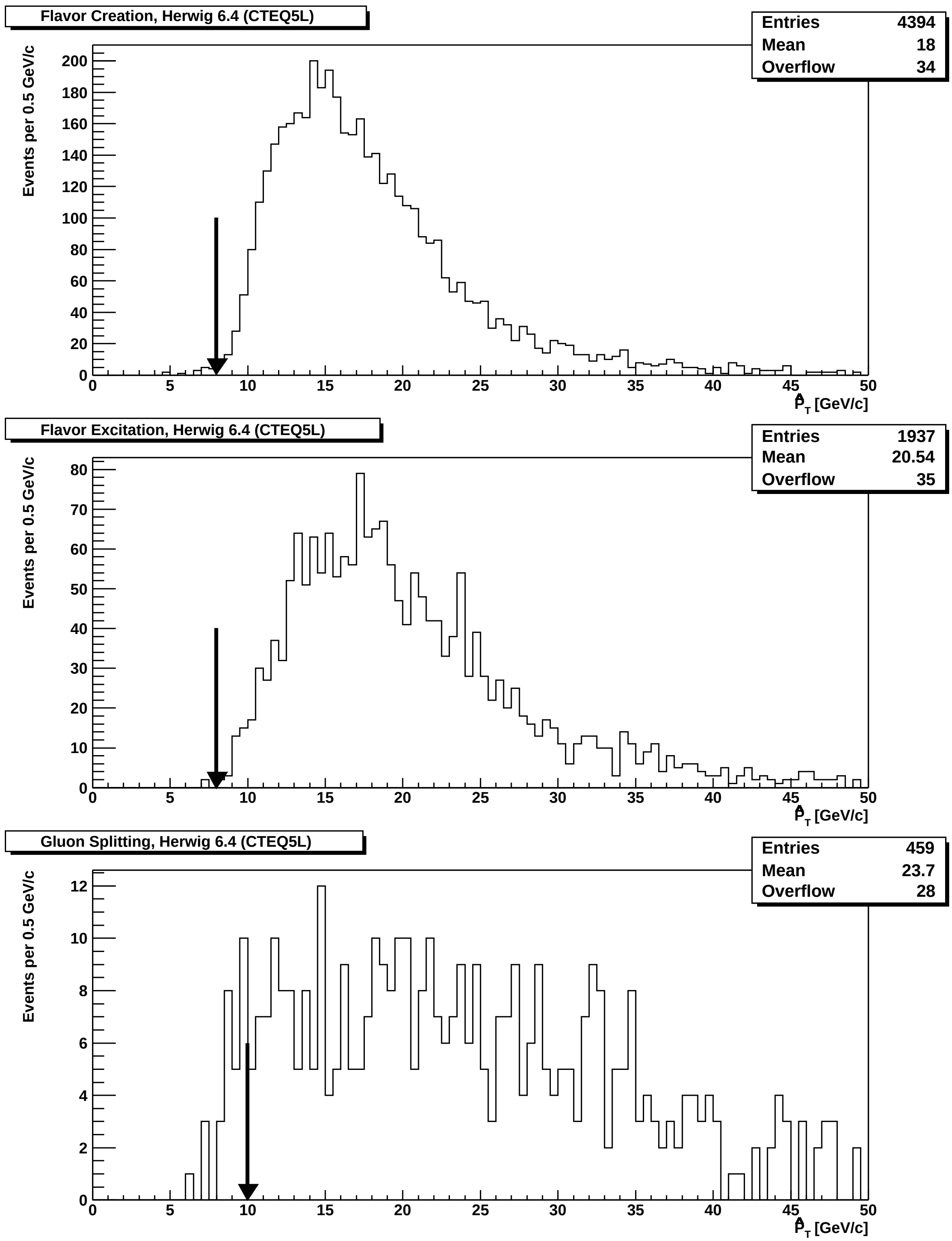

Figure 5 shows $\hat{p}_T$ for events from HERWIG that have one B hadron having $p_T > 13$ GeV/c and another B hadron with $p_T > 6$ GeV/c. These distributions were generated using the lowest reasonable $\hat{p}_T$(min) for each production mechanism. The arrows show the $\hat{p}_T$(min) values used to generate the large samples used with the detector simulation.

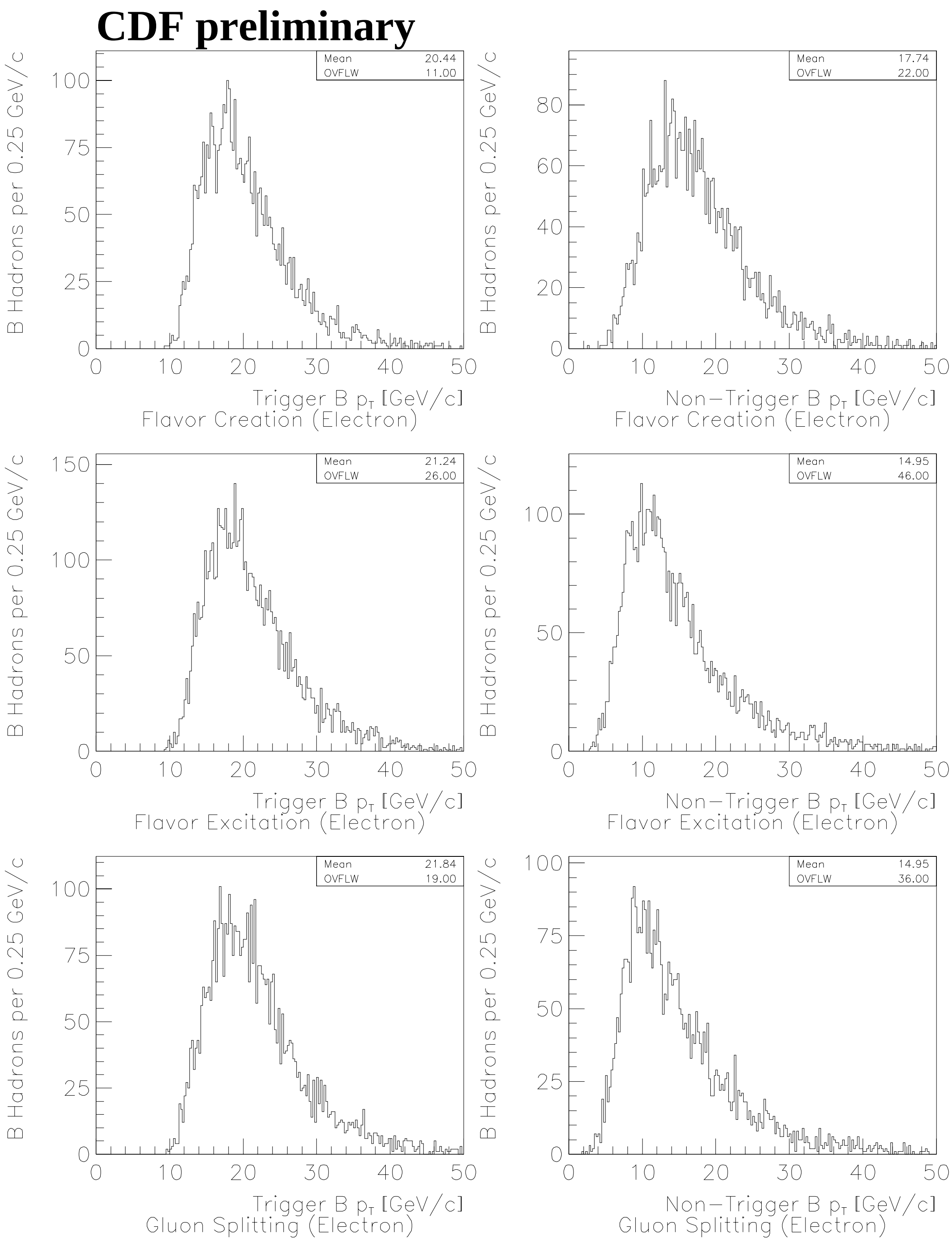

Figure 6 shows the *B* hadron p_T distributions for events from PYTHIA Monte Carlo with `PARP(67) = 4.0`, where both *B* hadrons were tagged and an electron provided the trigger lepton. The "Trigger *B*" is defined as the *B* whose semileptonic decay provided an electron for the trigger. The "Non-Trigger *B*" is the other *B* in the event.

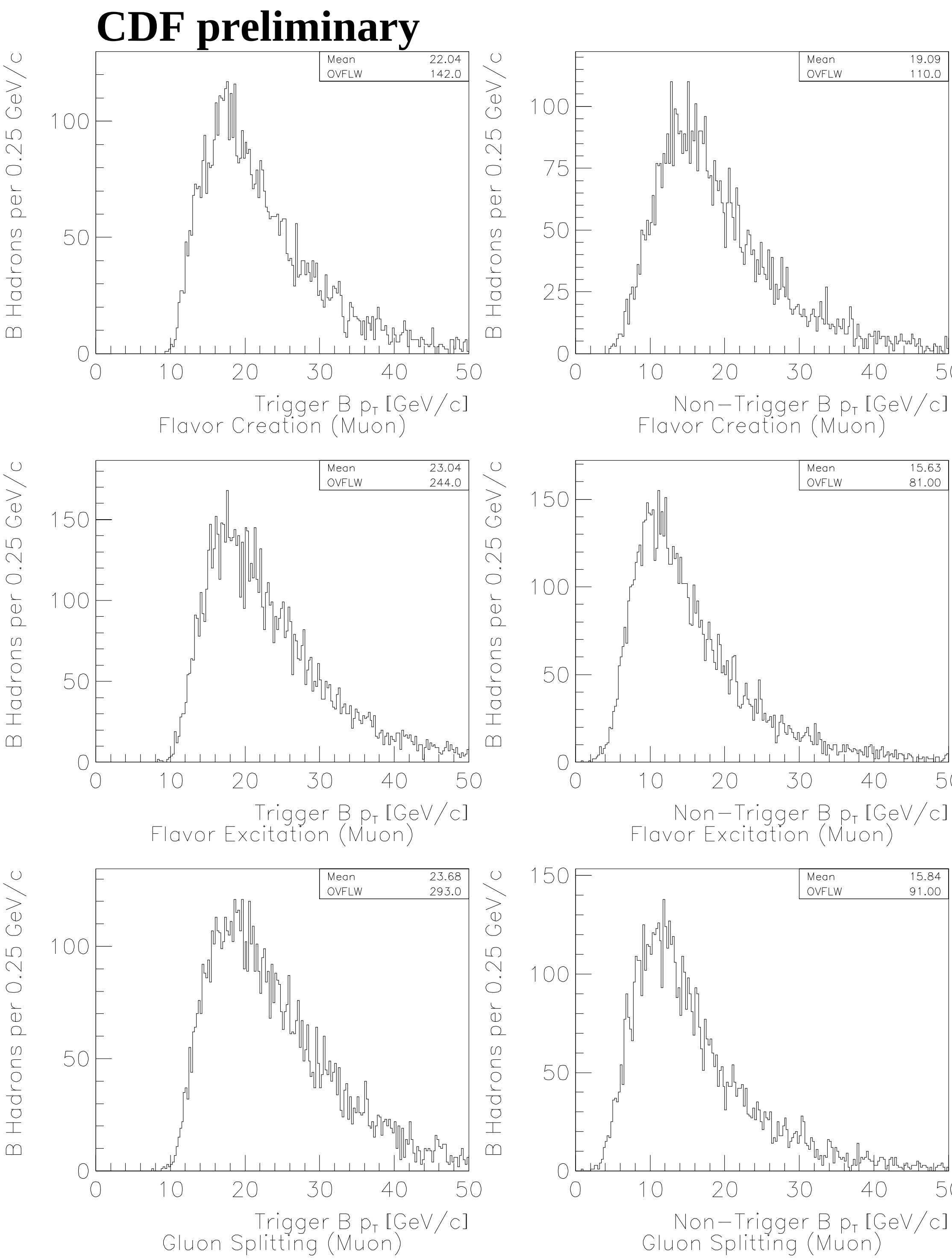

Figure 7 shows the *B* hadron p_T distributions for events from PYTHIA Monte Carlo with `PARP(67) = 4.0`, where both *B* hadrons were tagged and a muon provided the trigger lepton. The "Trigger *B*" is defined as the *B* whose semileptonic decay provided a muon for the trigger. The "Non-Trigger *B*" is the other *B* in the event.

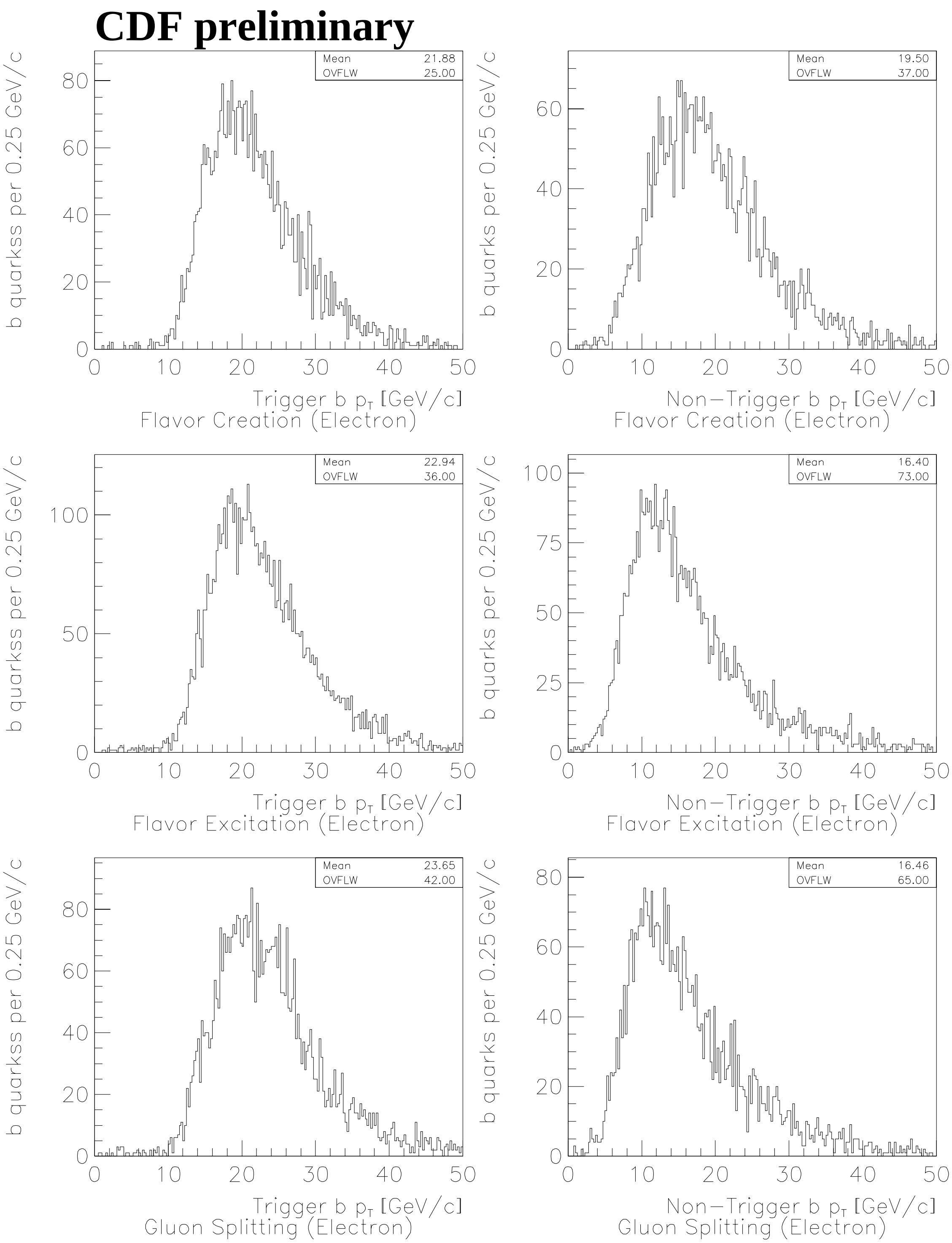

Figure 8 shows the *b* quark p_T distributions for events from PYTHIA Monte Carlo with `PARP(67) = 4.0`, where both *B* hadrons were tagged and an electron provided the trigger lepton. The "Trigger *b*" is defined as the *b* quark that hadronized to a *B* hadron whose semileptonic decay provided an electron for the trigger. The "Non-Trigger *b*" is the other *b* in the event.

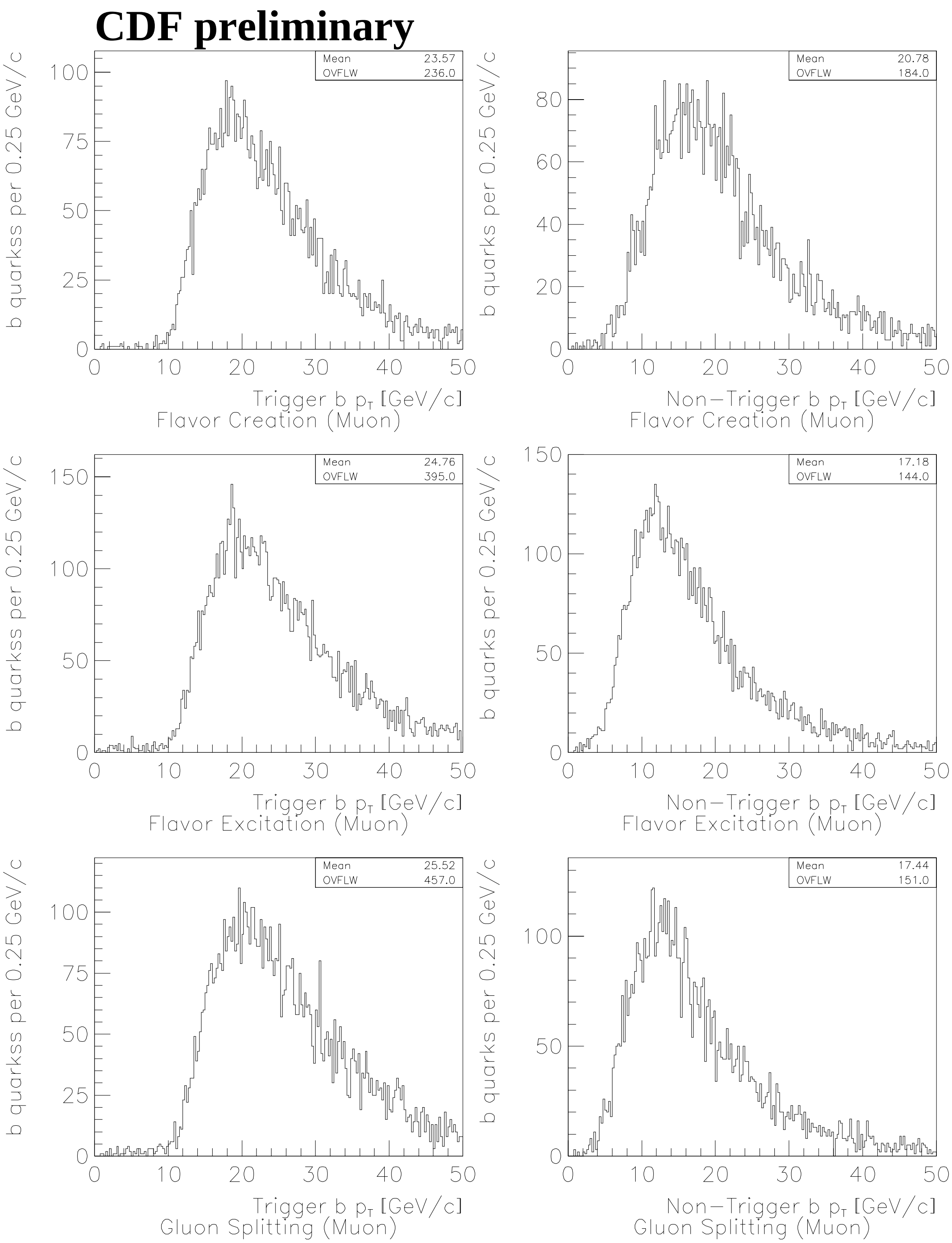

Figure 9 shows the *b* quark p_T distributions for events from PYTHIA Monte Carlo with `PARP(67) = 4.0`, where both *B* hadrons were tagged and a muon provided the trigger lepton. The "Trigger *b*" is defined as the *b* quark that hadronized to a *B* hadron whose semileptonic decay provided a muon for the trigger. The "Non-Trigger *b*" is the other *b* in the event.

Electron Monte Carlo (All numbers in GeV/c):

	***B* (leptonic)**		***B* (non-leptonic)**		***b* quark (leptonic)**		***b* quark (non-leptonic)**	
	Ave.	**90%**	**Ave**	**90%**	**Ave**	**90%**	**Ave**	**90%**
fc	20.4	14.1	18.4	10.9	21.9	14.5	20.3	11.5
fe	22.2	14.7	12.9	5.9	23.6	15.0	13.8	6.1
gs	21.9	14.8	15.4	7.5	23.7	15.6	17.0	8.3

Muon Monte Carlo (All numbers in GeV/c):

	***B* (leptonic)**		***B* (non-leptonic)**		***b* quark (leptonic)**		***b* quark (non-leptonic)**	
	Ave.	**90%**	**Ave**	**90%**	**Ave**	**90%**	**Ave**	**90%**
fc	21.8	13.9	19.6	11.2	23.4	14.5	21.3	12.0
fe	24.6	15.2	13.1	6.0	26.0	15.7	14.1	6.3
gs	23.7	14.9	16.0	7.8	25.7	15.9	17.6	8.5

Table 5 shows the average and the 90% threshold for the *B* hadron and *b* quark p_T distributions from PYTHIA Monte Carlo with `PARP(67) = 1.0.` "Leptonic" *B* hadrons are *B* hadrons that decay semileptocnically. "Leptonic" *b* quarks hadronize into *B* hadrons which decay semileptonically. "Non-leptonic" *B* hadrons and *b* quarks are associated with *B* hadrons that don't decay semileptonically.

Electron Monte Carlo (All numbers in GeV/c):

	***B* (leptonic)**		***B* (non-leptonic)**		***b* quark (leptonic)**		***b* quark (non-leptonic)**	
	Ave.	**90%**	**Ave**	**90%**	**Ave**	**90%**	**Ave**	**90%**
fc	21.4	14.5	18.0	9.4	23.4	15.5	20.5	11.0
fe	22.0	15.0	15.3	7.6	23.7	15.7	17.4	8.5
gs	21.1	14.4	14.8	7.5	22.8	15.3	16.4	8.3

Muon Monte Carlo (All numbers in GeV/c):

	***B* (leptonic)**		***B* (non-leptonic)**		***b* quark (leptonic)**		***b* quark (non-leptonic)**	
	Ave.	**90%**	**Ave**	**90%**	**Ave**	**90%**	**Ave**	**90%**
fc	22.8	14.5	19.2	9.9	24.9	15.5	21.9	11.4
fe	24.1	14.7	16.4	7.8	26.1	15.5	18.5	8.7
gs	23.0	14.7	15.5	7.5	24.8	15.7	17.3	8.5

Table 6 shows the average and the 90% threshold for the *B* hadron and *b* quark p_T distributions from HERWIG Monte Carlo. "Leptonic" *B* hadrons are *B* hadrons that decay semileptocnically. "Leptonic" *b* quarks hadronize into *B* hadrons which decay semileptonically. "Non-leptonic" *B* hadrons and *b* quarks are associated with *B* hadrons that don't decay semileptonically.

10 Appendix

The following sections give samples from the TCL files used to generate and decay the Monte Carlo data, as well as an example UIC file for processing the Monte Carlo events through the detector simulation, reconstruction, and analysis code.

10.1 PYTHIA Generation TCL File

The example TCL files shown below are for generating PYTHIA Monte Carlo with the higher amount of initial state radiation—`PARP(67) = 4.0`. To generate events with less initial state radiation, some parameters need to be changed. See section 3.4 for details.

10.1.1 Flavor Creation

```
useRCP set false

module input GenInputManager
mod enable HepRootManager
mod enable Pythia
mod enable PythiaFilter
mod disable FillRun1Banks

creator set GEN

filter PythiaFilter on

talk PythiaFilter
   idHrd1 set t
   idHrd2 set t
exit

talk HepRootManager
   histfile set pytfc0_1_oldisr_hist.root
exit

module output DHOutput
talk DHOutput
   output create main_stream pytfc0_1_oldisr_raw.root
   output path main_stream AllPath
   output keepList main_stream LRID_StorableBank LRIH_StorableBank \
      EVCL_StorableBank HEPG_StorableBank
exit

path enable AllPath

path list

talk RandomGenManager
   SaveRandomStreams set true
   RandomNumberMenu
      RandomSeedPYTHIA1 set 112570
      RandomSeedPYTHIA2 set 165980
   exit
exit

module talk Pythia
   PythiaMenu
      listFirst set 1
      listLast set 2
      msel set 5
      cmEnergy set 1800.
      commonMenu
# PDFs - CTEQ Set 5L (LO)
         set_mstp -index=51 -value=4046
         set_mstp -index=52 -value=2
# Set pt_hat
```

```
          set_ckin -index=3 -value=8.0
          set_ckin -index=4 -value=900.0
# Set ISR max scale factor parameter
          set_parp -index=67 -value=4.0
# Multiple Interaction parameters
          set_mstp -index=81 -value=1
          set_mstp -index=82 -value=3
          set_parp -index=82 -value=1.7
          set_parp -index=85 -value=1.0
          set_parp -index=86 -value=1.0
          set_parp -index=89 -value=1800.
# Top Mass
          set_pmas -masscode=6 -mass=175.
          show_ckin
          show_mstp
          show_parp
          show_mstu
          show_paru
          show_mstj
          show_parj
       exit
   exit
quit

begin -nev 50000

show timer

exit
```

10.1.2 Flavor Excitation

Generating the flavor excitation contribution to $b\bar{b}$ production can be somewhat tricky in PYTHIA. It is necessary to break the generation up into two phases, as described in section 3.2. For each phase, one needs a TCL file and a `PYGIVE` file to specify the flavor available for the incoming partons. The example TCL and `PIGIVE` files shown below are for the case in which all flavors except bottom are turned off for the beam (proton) particles. To turn off all flavors except bottom in the target (antiproton) particles, the first index in the `KFIN` arrays from the `PYGIVE` file simply needs to be changed from "1" to "2."

```
useRCP set false

module input GenInputManager
mod enable HepRootManager
mod enable Pythia
mod enable PythiaFilter
mod disable FillRun1Banks

creator set GEN

filter PythiaFilter on

talk PythiaFilter
   idHrd3 set t
   idHrd4 set t
   idHrd5 set t
exit

talk HepRootManager
```

```
   histfile set pytfep0_1_oldisr_hist.root
exit

module output DHOutput
talk DHOutput
   output create main_stream pytfep0_1_oldisr_raw.root
   output path main_stream AllPath
   output keepList main_stream LRID_StorableBank LRIH_StorableBank \
      EVCL_StorableBank HEPG_StorableBank
exit

path enable AllPath

path list

talk RandomGenManager
   SaveRandomStreams set true
   RandomNumberMenu
      RandomSeedPYTHIA1 set 143590
      RandomSeedPYTHIA2 set 115890
   exit
exit

module talk Pythia
   PythiaMenu
      listFirst set 1
      listLast set 2
      pygiveFile set "proton_file.txt"
      pygiveFile list
      msel set 1
      cmEnergy set 1800.
      commonMenu
# PDFs - CTEQ Set 5L (LO)
         set_mstp -index=51 -value=4046
         set_mstp -index=52 -value=2
# Set pt_hat
         set_ckin -index=3 -value=8.0
         set_ckin -index=4 -value=900.0
# Set ISR max scale factor parameter
         set_parp -index=67 -value=4.0
# Multiple Interaction parameters
         set_mstp -index=81 -value=1
         set_mstp -index=82 -value=3
         set_parp -index=82 -value=1.7
         set_parp -index=85 -value=1.0
         set_parp -index=86 -value=1.0
         set_parp -index=89 -value=1800.
# Top Mass
         set_pmas -masscode=6 -mass=175.
         show_ckin
         show_mstp
         show_parp
         show_mstu
         show_paru
         show_mstj
         show_parj
      exit
   exit
quit
```

```
begin -nev 50000

show timer

exit
```

The PYGIVE file given below is for turning off all flavors in the beam (proton) particle except bottom. To change this to turning off all flavors except bottom in the target (antiproton) particle, simply replace the "1" in the first index of the KFIN variable with "2."

```
KFIN(1,1)=0
KFIN(1,-1)=0
KFIN(1,2)=0
KFIN(1,-2)=0
KFIN(1,3)=0
KFIN(1,-3)=0
KFIN(1,4)=0
KFIN(1,-4)=0
KFIN(1,21)=0
```

10.1.3 Gluon Splitting

```
useRCP set false

module input GenInputManager
mod enable HepRootManager
mod enable Pythia
mod enable PythiaFilter
mod disable FillRun1Banks

creator set GEN

filter PythiaFilter on

talk PythiaFilter
   idHrd6 set t
   idHrd7 set t
   idHrd8 set t
exit

talk HepRootManager
   histfile set pytgs0_1_oldisr_hist.root
exit

module output DHOutput
talk DHOutput
   output create main_stream pytgs0_1_oldisr_raw.root
   output path main_stream AllPath
   output keepList main_stream LRID_StorableBank LRIH_StorableBank \
      EVCL_StorableBank HEPG_StorableBank
exit

path enable AllPath

path list

talk RandomGenManager
   SaveRandomStreams set true
   RandomNumberMenu
      RandomSeedPYTHIA1 set 109870
      RandomSeedPYTHIA2 set 145670
```

```
   exit
exit

module talk Pythia
   PythiaMenu
      listFirst set 1
      listLast set 2
      msel set 1
      cmEnergy set 1800.
      commonMenu
# PDFs - CTEQ Set 5L (LO)
         set_mstp -index=51 -value=4046
         set_mstp -index=52 -value=2
# Set pt_hat
         set_ckin -index=3 -value=12.0
         set_ckin -index=4 -value=900.0
# Set ISR max scale factor parameter
         set_parp -index=67 -value=4.0
# Multiple Interaction parameters
         set_mstp -index=81 -value=1
         set_mstp -index=82 -value=3
         set_parp -index=82 -value=1.7
         set_parp -index=85 -value=1.0
         set_parp -index=86 -value=1.0
         set_parp -index=89 -value=1800.
# Top Mass
         set_pmas -masscode=6 -mass=175.
         show_ckin
         show_mstp
         show_parp
         show_mstu
         show_paru
         show_mstj
         show_parj
      exit
   exit
quit

begin -nev 1000000

show timer

exit
```

10.2 HERWIG Generation TCL File

The following sections show example TCL files for HERWIG event generation. In HERWIG, flavor creation and flavor excitation are generated as a single job and the output must be filtered and split into separate files.

10.2.1 Flavor Creation and Flavor Excitation

```
useRCP set false

module input GenInputManager
mod enable HepRootManager
mod enable herwig
mod enable HerwigFilter
```

```
mod disable FillRun1Banks

creator set GEN

#
#  Make a clone for flavor excitation
#
mod clone HerwigFilter 2

#
#  Flavor creation filter
#
filter HerwigFilter on

talk HerwigFilter
   idHrd1 set t
   idHrd2 set t
exit

#
#  Flavor excitation filter
#
filter HerwigFilter-2 on

talk HerwigFilter-2
   idHrd3 set t
   idHrd4 set t
   idHrd5 set t
exit

# Create two paths, one for flavor creation
path create FCPath ManagerSequence HepRootManager HardScatGenSequence
path append FCPath GenOutputManager HerwigFilter
filter -path FCPath HerwigFilter on

# and one for flavor excitation
path create FEPath ManagerSequence HepRootManager HardScatGenSequence
path append FEPath GenOutputManager HerwigFilter-2
filter -path FEPath HerwigFilter-2 on

talk HepRootManager
   histfile set herfcfe0_1_hist.root
exit

module output DHOutput
talk DHOutput
   output create FCStream herfc0_1_raw.root
   output path FCStream FCPath
   output keepList FCStream LRID_StorableBank LRIH_StorableBank \
      EVCL_StorableBank HEPG_StorableBank
   output create FEStream herfe0_1_raw.root
   output path FEStream FEPath
   output keepList FEStream LRID_StorableBank LRIH_StorableBank \
      EVCL_StorableBank HEPG_StorableBank
exit

path enable FCPath
path enable FEPath

path list

talk RandomGenManager
   SaveRandomStreams set true
```

```
   RandomNumberMenu
      RandomSeedHERWIG1 set 112570
      RandomSeedHERWIG2 set 165980
   exit
exit

module talk herwig
   Process set 1705
   Maxer set 50000
   Lambda_QCD set 0.192
   Beam
      Pbeam1 set 900.
      Pbeam2 set 900.
      show
   exit
   Struc_Function
      Autpdf set CTEQ
      Modpdf set 46
      show
   exit
   Hards
      Ptmin set 8.0
      show
   exit
   Hadronization
      Clpow set 1.26
   exit
   Masses
      top set 175.
   exit
   Prints
      maxpr set 2
      prvtx set 0
   exit
quit

begin -nev 50000

show timer

exit
```

10.2.2 Gluon Splitting

```
useRCP set false

module input GenInputManager
mod enable HepRootManager
mod enable herwig
mod enable HerwigFilter
mod disable FillRun1Banks

creator set GEN

filter HerwigFilter on

talk HerwigFilter
   idHrd6 set t
   idHrd7 set t
```

```
   idHrd8 set t
exit

talk HepRootManager
   histfile set hergs0_1_hist.root
exit

module output DHOutput
talk DHOutput
   output create main_stream hergs0_1_raw.root
   output path main_stream AllPath
   output keepList main_stream LRID_StorableBank LRIH_StorableBank \
      EVCL_StorableBank HEPG_StorableBank
exit

path enable AllPath
path list

talk RandomGenManager
   SaveRandomStreams set true
   RandomNumberMenu
      RandomSeedHERWIG1 set 140010
      RandomSeedHERWIG2 set 133330
   exit
exit

module talk herwig
   Process set 1500
   Maxer set 50000
   Lambda_QCD set 0.192
   Beam
      Pbeam1 set 900.
      Pbeam2 set 900.
      show
   exit
   Struc_Function
      Autpdf set CTEQ
      Modpdf set 46
      show
   exit
   Hards
      Ptmin set 10.0
      show
   exit
   Hadronization
      Clpow set 1.26
   exit
   Masses
      top set 175.
   exit
   Prints
      maxpr set 2
      prvtx set 0
   exit
quit

begin -nev 1000000

show timer
```

```
exit
```

10.3 Redecay TCL File

The example redecay file shown below was used on a PYTHIA flavor creation file with `PARP(67) = 4.0`. The TCL file for other redecay jobs takes the same form. The forcing of particular decays is handled through QQ user decay files. Redecaying events multiple times is handled by looping over the event file multiple times in the same job. In this TCL file, each event is redecayed ten times.

```
module input DHInput
mod enable HepRootManager
mod enable QQModule
mod enable LepTrigFilt

creator set RDCY

filter LepTrigFilt on

talk HepRootManager
   createHistoFile set f
exit

module output DHOutput
talk DHOutput
   output create main_stream pytfc0_1_oldisr_decay.root
   output path main_stream AllPath
   output keepList main_stream LRID_StorableBank LRIH_StorableBank \
      EVCL_StorableBank HEPG_StorableBank:Redecayed
   output processDropList main_stream GEN
exit

path enable AllPath

path list

talk QQModule
   Decay_B_Baryons set 1
   Decay_Bc set 1
exit

talk LepTrigFilt
   useHepgDesc set t
   hepgDesc set Redecayed
   elePtCut set 5.0
   eleEtaCut set 1.0
   muoPtCut set 7.0
   muoEtaCut set 0.6
exit

talk DHInput
   reset file
   include file pytfc0_1_oldisr_raw.root*
exit
begin

talk DHInput
   reset file
   include file pytfc0_1_oldisr_raw.root*
exit
```

```
begin

talk DHInput
   reset file
   include file pytfc0_1_oldisr_raw.root*
exit
begin

talk DHInput
   reset file
   include file pytfc0_1_oldisr_raw.root*
exit
begin

talk DHInput
   reset file
   include file pytfc0_1_oldisr_raw.root*
exit
begin

talk DHInput
   reset file
   include file pytfc0_1_oldisr_raw.root*
exit
begin

talk DHInput
   reset file
   include file pytfc0_1_oldisr_raw.root*
exit
begin

talk DHInput
   reset file
   include file pytfc0_1_oldisr_raw.root*
exit
begin

talk DHInput
   reset file
   include file pytfc0_1_oldisr_raw.root*
exit
begin

talk DHInput
   reset file
   include file pytfc0_1_oldisr_raw.root*
exit
begin

show timer
exit
```

10.4 QFL′, Reconstruction, and Analysis UIC File

```
hist open/file="pytfc0_1_oldisr_b.uic"/reclength=4095/max_nrec=65000
hist/mod=mcgenb off
hist/mod=bvtxcorr off
hist/mod=ntcomb on
```

```
set exptyp run1b
sho exptyp

talk qfl
   year 1993
   bfield -14.116
   sigmaz 33.0
   z_offset 0.
   z_cut 35.
   beam_spot -0.01 5.0E-04 2.5E-03 -0.1 -5.0E-04 2.5E-03
   decays yes
   mult_scatt yes
   Cese yes
   brem yes
   gamma yes
   lisp no
   Cprd CPR_ON yes return
   move_genp_decays yes yes
   Muons Enable_muon ON return
   hepevt yes no
   track
      qtrk yes
      ewire "/home/xlv5/lannon/mc/ewire_1b.dbt"
   return
return

talk trkfix
   bpo auto
   field auto
   covariance 2.0
   show
return

talk trcontrol
   talk svx
      bank trks
      cluster
         one_str 4.0 4.0 4.0 4.0
         two_str 2.5 2.5 2.5 2.5
      exit
      rec_param
         12 1.3E-03
         13 1.1E-03
         14 1.9E-03
      ok
      dte true       ! do svx clustering
      d_to_e
         qcut true   ! charge<8 ADC cut
         pdtype pdq
         force true 57972
      exit
      status
   exit
   show
return

talk getlep
   get both
   svx no
```

```
   ele
      strip 10.0
      wire 10.0
      dz 3.0
      dx 1.5
      et 7.5
      pt 6.0
      hem 0.04
      lshr 0.2
   return
   muon
      type 1 no
      type 2 no
      type 3 yes
      type 4 no
      type 5 no
      type 6 no
      type 7 no
      pt 6.0
      mx 9.0
      mz 12.0
      px 9.0
      xx 9.0
      xz 12.0
      had 0.5
   return
   show
return

talk do_trkclu
   drseed 1.0
   show
return

talk bvtxmulti
   method 3
   inclep 0
   track_cone 1.0
   show
ret

talk cenmuo
   endte -1 -1 -1 -1 0
   enets -1 -1 -1 -1
   enreg 0
   enlnk -1
   tlklnk original 0 notrck -1 quit
quit

talk stpana
   ces reconstruction 1 quit
   pes reconstruction 0 quit
quit

talk dimutg
   use_prescale no
return

input module read_file
```

```
use qfl mcgenb -
   svxclu do_svx_pad  -
   jetclu emclst stpana elctrn cenmuo metser qtowcr -
   mufndr getlep leptrig -
   bprim do_trkclu bsetup bvtxmulti bvtxcorr -
   ntcomb

filter mcgenb off
filter leptrig on
filter bvtxcorr on
input file "pytfc0_1_oldisr_b.ybos"
b/report=100
hist write
show all
exit
```

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