The Sources of b-Quarks at the Tevatron

- Important to have good leading (or leading-log) order QCD Monte-Carlo model predictions of collider observables.
- The leading-log QCD Monte-Carlo model estimates are the “base line” from which all other calculations can be compared.
- If the leading-log order estimates are within a factor of two of the data, higher order calculations might be expected to improve the agreement.
- If a leading-log order estimate is off by more than a factor of two, it usually means that one has overlooked something.
- I see no reason why the QCD Monte-Carlo models should not qualitatively describe heavy quark production (in the same way they qualitatively describe light quark and gluon production).
- “Something is goofy” (Rick Field, CDF B Group Talk, December 3, 1999).
Data from CDF and D0 for 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, PYTHIA, and ISAJET for the “flavor creation” subprocesses. The parton distribution functions CTEQ3L have been used for all three Monte-Carlo models.
“Flavor excitation” is, of course, very sensitive to the number of b-quarks within the proton (i.e. the structure functions).

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.
Data on the integrated b-quark total cross section (P_T > PTmin, |y| < 1) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of PYTHIA 6.158 (CTEQ3L, PARP(67)=4). The four curves correspond to the contribution from “flavor creation”, “flavor excitation”, “shower/fragmentation”, and the resulting total.
Data on the integrated 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 6.206 (CTEQ5L) with PARP(67)=1 (new default) and PARP(67)=4 (old default). The four curves correspond to the contribution from flavor creation, flavor excitation, shower/fragmentation, and the resulting total. PARP(67) is a scale factor that governs the amount of large angle initial-state radiation. Larger values of PARP(67) results in more large angle initial-state radiation!
Data on the integrated b-quark total and B+ meson cross section \((P_T > PT_{\text{min}}, \ |y| < 1)\) for proton-antiproton collisions at 1.8 TeV compared with the QCD Monte-Carlo model predictions of PYTHIA 6.158 (CTEQ3L, PARP(67)=4). The four curves correspond to the contribution from flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
Data on the integrated b-quark and B+ meson 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 6.4 (CTEQ5L). The four curves correspond to the contribution from flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
One should not take the QCD Monte-Carlo model estimates of “flavor excitation” and “shower/fragmentation” too seriously. The contributions from these subprocesses are qualitative estimates and more work needs to be done. There are many subtleties!

Clearly all three sources are important at the Tevatron.

“Nothing is goofy” (Rick Field, CDF B Group Talk, March 9, 2001).

Next step is to study in detail b-bbar correlations and the compare the predictions of HERWIG, ISAJET, and PYTHIA in order to understand how reliable the estimates are.

Want to know what the leading-log QCD Monte-Carlo Models predict, how stable the estimates are, and how they compare with data. Also, if it is possible we would like to tune the Monte-Carlo models to fit the data.
Predictions of PYTHIA 6.158 (CTEQ4L, PARP(67)=1) for the asymmetry $A = (PT_1 - PT_2)/(PT_1 + PT_2)$ for events with a b-quark with $PT_1 > 0$ GeV/c and $|y_1| < 1.0$ and a bbar quark with $PT_2 > 5$ GeV/c and $|y_2| < 1.0$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/dA$ (µb) for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
Predictions of PYTHIA 6.158 (CTEQ4L, PARP(67)=1) for the distance, R, in $\eta$-$\phi$ space between the b and bbar-quark with $PT_1 > 5$ GeV/c, $PT_2 > 5$ GeV/c, and $|y_1| < 1$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/dR$ ($\mu$b) for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
Distance R in $\eta$-$\phi$ Space

Pictures of PYTHIA 6.158 (CTEQ4L, PARP(67)=1) for the distance, R, in $\eta$-$\phi$ space between the b and $\bar{b}$-quark with $|y_1|<1$ and $|y_2|<1$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/dR (\mu b)$ for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
Predictions of PYTHIA 6.158 (CTEQ4L, PARP(67)=1) for the azimuthal angle, $\Delta\phi$, between a b-quark with $P_{T1} > 5$ GeV/c and $|y_1| < 1$ and a bbar-quark with $P_{T2} > 0$ GeV/c and $|y_2| < 1$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/d\Delta\phi$ ($\mu b/\circ$) for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
Predictions of PYTHIA 6.206 (CTEQ5L) with PARP(67)=1 (new default) and PARP(67)=4 (old default) for the azimuthal angle, $\Delta \phi$, between a $b$-quark with $P_{T1} > 15$ GeV/c, $|y_1| < 1$ and $b\bar{b}$-quark with $P_{T2} > 10$ GeV/c, $|y_2| < 1$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/d\Delta \phi$ ($\mu$b/$\circ$) for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
Predictions of HERWIG 6.4 (CTEQ5L) for the azimuthal angle, $\Delta \phi$, between a b-quark with $PT_1 > 15$ GeV/c, $|y_1| < 1$ and bbar-quark with $PT_2 > 10$ GeV/c, $|y_2| < 1$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/d\Delta \phi$ ($\mu b/\pi$) for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
Azimuthal Correlations

Predictions of PYTHIA 6.206 (CTEQ5L) with PARP(67)=1 (new default) and PARP(67)=4 (old default) and HERWIG 6.4 (CTEQ5L) for the azimuthal angle, $\Delta \phi$, between a $b$-quark with $P_{T1} > 15$ GeV/c, $|y_1| < 1$ and $b\bar{b}$-quark with $P_{T2} > 10$ GeV/c, $|y_2| < 1$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/d\Delta \phi$ (µb/°) for flavor excitation, and shower/fragmentation.

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Rick Field - Florida/CDF
New Run I preliminary uncorrected CDF data for the azimuthal angle, $\Delta \phi$, between a b-quark $|y_1| < 1$ and bbar-quark $|y_2|<1$ in proton-antiproton collisions at 1.8 TeV.

Warning! Can compare theory with data only after detector simulation (this is being done).

Only a naïve theorist (like me!) would compare at this stage.

See talk by Kevin Lannon at DPF2002
Predictions of PYTHIA 6.158 (CTEQ5L) with PARP(67)=1 (new default) and PARP(67)=4 (old default) for diphoton system PT and the azimuthal angle, $\Delta\phi$, between a photon with $P_T^1 > 12$ GeV/c, $|y_1| < 0.9$ and photon with $P_T^2 > 12$ GeV/c, $|y_2| < 0.9$ in proton-antiproton collisions at 1.8 TeV compared with CDF data.
DiPhoton vs “Flavor Creation”
Azimuthal Correlations

Predictions of PYTHIA 6.158 (CTEQ5L) with PARP(67)=1 (new default) and PARP(67)=4 (old default) for diphoton production and b-bbar “flavor creation”.

Correlations: Azimuthal $\Delta\phi$ Distribution

```
| $|\Delta\phi|$ (degrees) |
|-----------------|----------------|
| 0               | 0.0001 |
| 30              | 0.0010 |
| 60              | 0.0100 |
| 90              | 0.1000 |
| 120             | 1.0000 |
```

$1/\sigma \cdot d\sigma/d\phi$ ($\mu b/\text{deg}$)

Pythia b-bbar Creation (67=1)
PYC5 DiPhoton PARP(67)=1
CDF DiPhoton Data

Correlations: Azimuthal $\Delta\phi$ Distribution

```
| $|\Delta\phi|$ (degrees) |
|-----------------|----------------|
| 0               | 0.0001 |
| 30              | 0.0010 |
| 60              | 0.0100 |
| 90              | 0.1000 |
| 120             | 1.0000 |
```

$1/\sigma \cdot d\sigma/d\phi$ ($\mu b/\text{deg}$)

Pythia b-bbar Creation (67=4)
PYC5 DiPhoton PARP(67)=4
CDF DiPhoton Data

Compare

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Predictions of PYTHIA 6.158 (CTEQ4L, PARP(67)=1) for the transverse momentum, \(PT_2\), of a \(b\bar{b}\)-quark with \(|y_2| < 1.0\) for events with a \(b\)-quark with \(PT_1 > 12 \text{ GeV/c}\) and \(|y_1| < 1\) in proton-antiproton collisions at 1.8 TeV. The curves correspond to \(d\sigma/dPT_2\) (\(\mu\text{b}/\text{GeV/c}\)) for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
“Toward” and “Away”
Pair Differential Cross Section

Predictions of PYTHIA 6.206 (CTEQ5L, PARP(67)=1) for the transverse momentum, $P_{T2}$, of a $b\bar{b}$-quark with $|y_2| < 1.0$ for events with a $b$-quark with $P_{T1} > 12$ GeV/c and $|y_1| < 1$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/dP_{T2} (\mu b/GeV/c)$ for the “toward” and “away” region of $\Delta \phi$ for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
“Toward” and “Away”
Pair Differential Cross Section

Predictions of PYTHIA 6.206 (CTEQ5L, PARP(67)=4) for the transverse momentum, $\text{PT}_2$, of a $b\bar{b}$-quark with $|y_2| < 1.0$ for events with a $b$-quark with $\text{PT}_1 > 12$ GeV/c and $|y_1| < 1$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/d\text{PT}_2$ ($\mu$b/GeV/c) for the “toward” and “away” region of $\Delta\phi$ for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
“Toward” and “Away”
Pair Differential Cross Section

Predictions of HERWIG 6.4 (CTEQ5L) for the transverse momentum, $P_{T2}$, of a $b\bar{b}$-quark with $|y_2| < 1.0$ for events with a $b$-quark with $P_{T1} > 12$ GeV/c and $|y_1| < 1$ in proton-antiproton collisions at 1.8 TeV. The curves correspond to $d\sigma/dP_{T2}$ ($\mu$b/GeV/c) for the “toward” and “away” region of $\Delta\phi$ for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
“Toward” and “Away”
Pair Differential Cross Section

Predictions of PYTHIA 6.206 (CTEQ5L) PARP(67)=1 and PARP(67)=4 and HERWIG 6.4 (CTEQ5L) for the transverse momentum, PT, of a bbar-quark with |y| < 1.0 for events with a b-quark with PT > 12 GeV/c and |y| < 1 in proton-antiproton collisions at 1.8 TeV. The curves correspond to dσ/dPT (µb/GeV/c) for the “toward” and “away” region of Δφ for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.
Predictions of PYTHIA 6.206 (CTEQ5L, PARP(67)=4) and HERWIG 6.4 (CTEQ5L) for the integrated pair cross section for a bbar-quark with \( \text{PT}_2 > \text{PT}_{2\text{min}} \), \( |y_2| < 1 \) for events with a b-quark with \( \text{PT}_1 > 6.5 \text{ GeV/c} \), \( |y_1| < 1 \) in proton-antiproton collisions at 1.8 TeV. The curves correspond to \( \sigma(\mu b) \) for flavor creation, flavor excitation, shower/fragmentation, and the resulting total.

Important to see the data at the meson level as well as the quark level and both separated into the “toward” and “away” region!
The QCD leading-log Monte-Carlo models do a fairly good job in describing the majority of the b-quark data at the Tevatron. The QCD Monte-Carlo models do a much better job fitting the b data than most people realize!

Much more Run II (and Run I) CDF data is on the way. In particular, we should be able experimentally to isolate the individual contributions to b-quark production by studying b-bbar correlations and we will find out in much greater detail how well the QCD Monte-Carlo models actually describe the data.

Personal remark: I do not like it when the experimenters extrapolate to the parton level and publish parton level results. The parton level is not an observable! Experiments measure hadrons! To extrapolate to the parton level requires making additional assumptions that may or may not be correct (and often the assumptions are not clearly stated or are very complicated). However, I understand why this happens (and I cannot stop it) so I suggest that the experimenters always publish the corresponding hadron level result along with their parton level extrapolation.

Personal remark: I do not like it when theorists attempt to compare parton level calculations with experimental data. Hadronization and initial/final-state radiation effects are almost always important and theorists should embed their parton level results within a parton-shower/hadronization framework (e.g. HERWIG or PYTHIA).
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