Chapter 10

Summary and Highlights

During the coming decade a wide range of measurements in the production and decay of b flavored hadrons will be made at the Tevatron. In this chapter, we summarize the most important ones. Particularly in the decays, some observables are key to pinning down the flavor structure of the Standard Model and, possibly, uncovering new physics. Some are unique to the Tevatron, and some are expected to be competitive with measurements at the e^+e^- B factories. The Tevatron enjoys a few advantages that compensate for the clean environment in e^+e^- collisions. First, the $b\bar{b}$ production cross section is much higher at the Tevatron than at e^+e^- machines. Thus, despite the higher background rates at the Tevatron, it is possible to use selective triggers to obtain high statistics samples with good signal-to-noise ratio. Second, all b flavored hadrons are created (B_s, Λ_b, etc.), whereas an e^+e^- machine operating at the $\Upsilon(4S)$ resonance produces only $B^\pm$, $\overline{B}{}^0_d$ and B^0_d. Consequently, the B decay program at hadron colliders complements that at the e^+e^- B factories.

The CDF, DØ, and BTeV detectors and simulation tools used for this report are described in Chapters 2–5. Since Run I, both CDF and DØ have gone through major upgrades, and both will be much more powerful for doing B physics in Run II. Both detectors feature excellent charged particle tracking using solenoidal magnetic fields, and both have silicon (Si) vertex detectors capable of tracking in three dimensions. The magnetic field is 2 T at DØ and 1.4 T at CDF. DØ has a smaller radius tracking volume (50 cm), which allows for Si and scintillating fiber tracking out to $\eta = 1.6$, and Si disk tracking to $\eta = 3$. CDF has a larger tracking radius (140 cm), with full Si and drift chamber tracking out to $\eta = 1$, and Si-only tracking (to 30 cm radius) out to $\eta = 2$. DØ muon coverage extends to $\eta = 2$; CDF to $\eta = 1.5$. Both detectors have track based triggers at level-1 and Si vertex impact triggers at level-2. Because of the larger level-1 bandwidth (40 kHz) and the use of deadtimeless SVX3 chip readout, CDF can deploy a Si vertex hadronic decay trigger at level-2, which is directly sensitive to decays like $B \to \pi^+\pi^-$ and $B_s \to D_s^-\pi^+$. With a smaller level-1 bandwidth (10 kHz), DØ does not plan to implement such a strategy. CDF has two methods for particle ID — time-of-flight at low momentum ($p < 2\,\mathrm{GeV}/c$) and relativistic rise dE/dx for high momentum ($p > 2\,\mathrm{GeV}/c$); the latter is crucial for channels like $B \to \pi^+\pi^-$, where a statistical separation of $\pi\pi$ and $K\pi$ signals can be used. In summary, both CDF and DØ have comparable B physics reach; CDF has an advantage in particle ID and in Si vertex triggering.

BTeV is slated to run in earnest after Run II, following construction and some running during Run IIb. It will have competition from LHC-b at CERN, and from experiments at the e^+e^- B factories, which by then are expected deliver an order of magnitude higher luminosity than at present. BTeV is not a central detector (as are CDF and DØ), but a two-arm forward spectrometer. The key features of its design are a silicon pixel detector, a flexible trigger based on detached vertices, particle ID with excellent K/π separation, and an electromagnetic calorimeter capable of identifying π^0's and photons.

In this workshop, simulations of the CDF, DØ and BTeV detectors have made common assumptions about production rates, branching ratios, and flavor tagging efficiencies. The common starting point is needed for comparing the reaches of the three detectors, but it is nevertheless difficult to make meaningful comparisons without Run II data. At hadron colliders all signal channels, as well as issues like flavor tagging, have backgrounds that will be detector dependent and that, in many cases, cannot be reliably predicted from a heavy flavor production Monte Carlo. These backgrounds affect both signal-to-background statistics and also the strategies used to reject background, which in turn affect signal yields. For example, for $B \to \pi^+\pi^-$, to reject the combinatorics from all sources of backgrounds, making harder cuts on the detachment of the secondary vertex and other quantities will affect both the statistical accuracy and the ability to separate the direct and mixing induced CP asymmetries. While CDF has Run I data on many channels and flavor tags, DØ and BTeV will need real data to understand fully the effects of backgrounds.

Most simulations carried out during this workshop considered an integrated luminosity of $2\,\mathrm{fb}^{-1}$, corresponding to Run IIa for DØ and CDF and to the first year of running for BTeV. Other workshops in this series, which focused on high p_T physics, considered also the potential for $10\,\mathrm{fb}^{-1}$ and $30\,\mathrm{fb}^{-1}$. In the case of B physics, the role of real data in optimizing event selection makes it difficult to make sensible estimates for such high luminosity until more experience is at hand.

The most important measurements at the Tevatron can be divided roughly into two categories. Some modes have a relatively simple theoretical interpretation, in the context of the Standard Model, either because hadronic uncertainties are under good control, or because loops, small CKM angles, or GIM effects suppress the Standard Model rate. These modes test the CKM mechanism and probe for non-CKM sources of CP and flavor violation. Other measurements are more sensitive to QCD in ways that are theoretically challenging. They do not (yet) probe flavor dynamics, but, clearly, better understanding of QCD in B physics can be reinvested in understanding the flavor sector. We therefore present two semi-prioritized lists labeled “tests of flavor and CP violation” and “test of QCD”, but both labels should be construed loosely. Moreover, the composition of these lists is colored by our understanding during the course of the workshop. In the coming decade theoretical and experimental developments are likely to spur changes in the lists. Many other interesting observables, not discussed in this summary, are covered throughout Chapters 6–9.

Tests of flavor and CP violation

- $B_s^0 - \overline{B}_s^0$ mixing: Both CDF and DØ can measure $x_s \lesssim 30$ from events with a semileptonic B_s decay. This covers some of the expected range $x_s \lesssim 45$. With nonleptonic modes, CDF can measure $x_s \lesssim$ 59–74, depending on assumptions, and BTeV $x_s \lesssim 75$. As soon as a 5σ observation of mixing is made, the statistical error of x_s is very small, about ± 0.14. In the Standard Model, x_s/x_d can be used to determine $|V_{ts}/V_{td}|$, relying on input from lattice QCD for the size of $SU(3)$ breaking.

- CP asymmetries in $B_s \to \psi\phi$, $\psi\eta^{(\prime)}$: These measure the relative phase between the amplitudes for $B_s^0 - \overline{B}_s^0$ mixing and $b \to c\bar{c}s$ decay, β_s. In the Standard Model $\sin 2\beta_s$ is a few percent, so observation of a large CP asymmetry would be a clear sign of new physics. The expected error at CDF is about 1.6 times that of $\sin 2\beta$, further diluted by the CP-odd contribution to the $\psi\phi$ final state. Although this CP-odd contribution is expected to be small, it can be avoided by using the decay modes $B_s \to \psi\eta^{(\prime)}$, which are pure CP-even. With its excellent photon detection, BTeV is well optimized to measure the asymmetries in these neutral modes.

- CP asymmetries in $B_s \to D_s^{\pm} K^{\mp}$: Combining the time dependent asymmetries in these four modes allows the cleanest determination of $\gamma - 2\beta_s$. These measurements must be carried out in the presence of the large Cabibbo allowed $B_s \to D_s\pi$ background. Combined with the measurement (or bound) on β_s, one obtains γ, one of the angles of the unitarity triangle. At the Tevatron, this measurement will probably be possible only at BTeV, with an expected precision of $\sigma(\gamma) \simeq 10^\circ$.

- CP asymmetries in $B_d \to \rho\pi$: These asymmetries seem to be the cleanest way to measure α, the angle at the apex of the unitarity triangle. Once enough events are available to isolate the $\Delta I = 3/2$ channel, it is possible to measure α without uncertainties from penguin amplitudes, which contribute only to $\Delta I = 1/2$. With its excellent electromagnetic calorimetry, BTeV should compete well with BaBar and Belle, on a similar time scale.

- CP asymmetry in $B_d \to \psi K_S$: These asymmetries measure the relative phase between the amplitudes for $B_d^0 - \overline{B}_d^0$ mixing and $b \to c\bar{c}s$ decay. In the Standard Model, this is the angle β of the unitarity triangle, and it is obtained with very small theoretical uncertainty. By the end of Run IIa, the CDF and DØ measurements may become competitive with BaBar and Belle. Based on $B \to J/\psi K_S$ only, DØ and CDF anticipate a precision on $\sin 2\beta$ in the range 0.04–0.05, with $2\,\mathrm{fb}^{-1}$.

- CP asymmetries in $B_{d,s} \to h_1^+ h_2^-$, $h_i = K, \pi$: The utility of these modes depends on how well the uncertainty from flavor $SU(3)$ breaking can be controlled. Data for these and other processes will tell us the range of such effects; the resulting Standard Model constraints could be quite stringent. A study by CDF shows that 20% effects from $SU(3)$ breaking lead to an uncertainty of only $\sim 3^\circ$ on γ, which is much smaller than CDF's expected statistical error with $2\,\mathrm{fb}^{-1}$ of $\sim 10^\circ$.

- Rare semileptonic and radiative decays, such as $B \to K^*\ell^+\ell^-$ or $B \to K^*\gamma$: Although the rate for $B \to K^*\gamma$ is higher, the Tevatron detectors will probably not compete with BaBar and Belle. In the case of $B \to K^*\ell^+\ell^-$, the high rate of a hadron machine is needed, and the lepton pair provides a good trigger. In $B \to K^*\ell^+\ell^-$ the forward-backward asymmetry is especially intriguing, because it is sensitive to short distance physics.

- Search for $B_{d,s} \to \ell^+\ell^-$: These flavor-changing neutral current processes are highly suppressed in the Standard Model. Limits on the rate constrain non-standard models, which often have other ways to mediate such decays. Late in Run II or at BTeV, it may be possible to observe a handful of events at the standard model rate.

- CP asymmetries in flavor specific final states: These can be used to measure the relative phase between the mass and width mixing amplitudes, analogous to $\mathrm{Re}\,(\epsilon_K)$ in the kaon sector. The most often cited example is semileptonic decays, but if this asymmetry is sufficiently large, it may be possible to detect it using fully reconstructed modes such as $B_s \to D_s^- \pi^+$. In the B system, the SM predicts the relative phase to be very small, but new physics could make these asymmetries measurable without pushing the measured value of $\sin 2\beta$ outside its expected range.

The most striking thing about this list is that the whole program, taken together, is much more interesting than any single measurement. Indeed, if one adds in measurements from the e^+e^- machines, the list becomes even more compelling. In the near future, BaBar, Belle, CDF, and DØ will measure $\sin 2\beta$ at the few percent level; the Tevatron measurement of x_s combined with the known value of x_d will determine $|V_{td}/V_{ts}|$; BaBar's and Belle's measurements of semileptonic decays will determine $|V_{ub}/V_{cb}|$. Apart from $\sin 2\beta$, some input from hadronic physics is needed, but the combination of these results will still test the unitarity of the CKM matrix below the 10% level.

Tests of QCD

- B_s width difference $\Delta\Gamma_s$: The theoretical prediction of $\Delta\Gamma_s$ requires hadronic matrix elements of two four-quark operators, so it relies on lattice QCD calculations to a greater extent than x_s. It is still an interesting measurement, especially if it is smaller than expected in the Standard Model.

- Λ_b lifetime: The measured value of the Λ_b lifetime does not agree with theoretical expectations. It is important to improve the measurements with fully reconstructed hadronic decays. If the discrepancy remains, it would presumably imply a failure of the operator product expansion employed in inclusive decays and lifetimes, and one would have to reconcile the failure here with success for other lifetimes and for inclusive semileptonic decay distributions.

- Semileptonic form factors: The q^2 dependence of the decay distribution for $\Lambda_b \to \Lambda_c \ell \bar{\nu}$, $B \to K^{(*)}\ell^+\ell^-$, etc., can be combined with theoretical information, potentially reducing the (theoretical) error on $|V_{cb}|$, $|V_{ub}|$, and $|V_{ts}|$.

- Quarkonium production and polarization: Run I data for charmonium production disagrees at large p_T with predictions from NRQCD. If the discrepancies persist, and are confirmed through bottomonium production, they would pose an important riddle. To make meaningful measurements, experiments must collect higher statistics, extend to higher p_T, cleanly separate states with different quantum numbers, and distinguish feed-down from direct production.

- $b\bar{b}$ production cross section: The cross section $\sigma(p_T > p_T^{\rm min})$ measured in Run I data is about twice the prediction from perturbative QCD. With all scales (m_b, $\sqrt{\hat{s}}$, p_T) much larger than $\Lambda_{\rm QCD}$, perturbative QCD should be reliable. A variety of QCD effects have been studied, but do not seem to account for the excess. If the excess is confirmed (with much higher statistics) in Run II, one must ask whether something in the theory has gone awry, or whether a non-standard mechanism produces $b\bar{b}$ events.

- Spectra of B_c and other doubly heavy hadrons: CDF's B_c mass and lifetime measurements from Run I will be improved. Fully reconstructed nonleptonic decays are needed to obtain a good measurement of the mass, which can be compared to calculations based on potential models or from lattice QCD. Because there are now two heavy quarks, the lifetimes and decay widths of B_c and other doubly heavy hadrons provide novel tests of the theory.

Each of these is interesting for its interaction with QCD theory, and, at least for the next several years, each can be studied only at the Tevatron.

In conclusion, one sees that B physics at the Tevatron will produce a program of many interesting and, in some cases, essential measurements. In the case of B decay measurements, the information gained is competitive with and complementary to that gained from experiments in e^+e^- accelerators at the $\Upsilon(4S)$. Indeed, the full suite of measurements from B_u, B_d, and B_s decays is much more interesting than any one or two measurements taken in isolation.