B Lifetimes and Mixing

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The Tevatron experiments, CDF and D0, have produced a wealth of new B-physics results since the start of Run II in 2001. We've observed new B-hadrons, seen new effects, and increased many-fold the precision with which we know the properties of b-quark systems. In these proceedings, we will discuss two of the most fruitful areas in the Tevatron B-physics program: lifetimes and mixing. We'll examine the experimental issues driving these analyses, present a summary of the latest results, and discuss prospects for the future.

1. Introduction

The Tevatron has been a hotbed of B-physics activity since the start of Run II in 2001. Although $p\bar{p}$ collisions at 1.96 TeV present a much more challenging environment than that seen at the B-factories, the fact that all types of B-hadrons are produced in CDF and D0 makes the Tevatron B-physics program complementary to those of BaBar, Belle, and CLEO. We will concentrate on two areas of this program: measurements of B-lifetimes and the determination of the oscillation frequencies between neutral B-mesons – B-mixing. Beside their intrinsic interest, these two topics are representative of the breadth of B-physics and highlight some of the key experimental issues facing physicists attempting to study the b-quark at hadron colliders. Other topics in B-physics at the Tevatron are covered in [1–3].

The measurement of B-hadron lifetimes and of the neutral B-meson oscillation frequencies probe different aspects of the Standard Model and its possible extensions. Lifetime measurements provide input to our understanding of how to use the theory of QCD. These measurements allow us to test extensions to the simple spectator model of weakly decaying B-hadrons [4]. In particular, ratios of B-hadron lifetimes are sensitive to different aspects of beyond-spectator-model effects and have now been calculated to $\mathcal{O}((\Lambda_{QCD}/m_b)^4))$ [4].

$$\frac{\tau_1}{\tau_2} = 1 + \left(\frac{\Lambda_{QCD}}{m_b}\right)^2 \Gamma_2$$
$$+ \left(\frac{\Lambda_{QCD}}{m_b}\right)^3 \left[\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(0)} + ...\right]$$
$$+ \left(\frac{\Lambda_{QCD}}{m_b}\right)^4 \left[\Gamma_4^{(0)} + ...\right] \quad (1)$$

In the above equation, the Γ_2 term is sensitive to meson/baryon differences and the Γ_3 terms reflect spectator-quark effects. Higher order terms have been found to be negligible for ratios of B^+, B_d, and B_s mesons, but might be sizable for ratios involving B-baryons. In the past, experimental results, particularly for $\tau(\Lambda_b)/\tau(B^0)$, have been in disagreement with these expectations. As we will see, recent Tevatron results have gone a long way towards clarifying the situation.

Lifetime results are also important inputs to the other topic covered in these proceedings – B-mixing measurements. Oscillations of neutral B-mesons (B_d and B_s) are very sensitive to the mechanism of electro-weak symmetry breaking because, within the Standard Model, the CKM matrix, which describes quark mixing, is a consequence of the Higgs mechanism. Since the Standard Model uses the simplest possible method of electro-weak symmetry breaking – a single Higgs doublet – the CKM matrix is described, within this model, by only four parameters – three angles and a single CP-violating phase. Other models of particle physics are, in general, much less constraining. Thus, measurements of the correlations between CKM matrix elements provide powerful insight into physics beyond the Standard Model.

Measurements of the frequency of B_d and B_s oscillations give us a handle on the CKM matrix element, V_{td}. The key to this relationship lies in the different eigenstates of neutral B-meson systems denoted *weak*, CP, and *mass*. The time evolution of the eigenstates of the weak interaction for B-mesons containing $q = d, s$ quarks, $|B_q^0(t)\rangle$ and $|\bar{B}_q^0(t)\rangle$, are governed by a Schrödinger equation with off-diagonal elements:

$$i\frac{d}{dt}\begin{pmatrix} |B_q^0(t)\rangle \\ |\bar{B}_q^0(t)\rangle \end{pmatrix}$$
$$= \begin{pmatrix} M^{(q)} - i\Gamma^{(q)}/2 & M_{12}^{(q)} - i\Gamma_{12}^{(q)}/2 \\ M_{12}^{(q)*} - i\Gamma_{12}^{(q)*}/2 & M^{(q)} - i\Gamma^{(q)}/2 \end{pmatrix} \begin{pmatrix} |B_q^0(t)\rangle \\ |\bar{B}_q^0(t)\rangle \end{pmatrix}$$
$$(2)$$

Eigenstates of the system with definite mass, $|B^H\rangle$ and $|B^L\rangle$, are thus linear combinations of the weak eigenstates. Oscillations between weak eigenstates then occur with a frequency proportional to the mass difference:

$$\Delta m_q = B_q^H - B_q^L \sim 2|M_{12}^{(q)}| \quad (3)$$

Further discussion of this, and of the CP-eigenstates can be found in [3].

Although, in principle, only Δm_d is necessary to extract the CKM matrix element, V_{td}, in practice the theoretical uncertainty on this extraction is reduced by more than a factor of three when the ratio

$\Delta m_d / \Delta m_s$ is used [5]:

$$\frac{\Delta m_d}{\Delta m_s} = \left(\frac{M(B_d)}{M(B_s)}\right)\left(\frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}}\right)\left|\frac{V_{td}}{V_{ts}}\right|^2 \qquad (4)$$

Measurement of Δm_s has thus been a priority of the experimental high energy physics community since the first measurements of B-mixing [6].

2. Common Experimental Issues

The busy environment surrounding a B-hadron produced in a $p\bar{p}$ collision at the Tevatron leads to challenges for many aspects of the CDF and D0 detectors, particularly in the areas of triggering and tracking. These challenges are apparent when considering the generic steps taken in a lifetime or mixing analysis. First, candidate events must be recorded from the 2.5 MHz beam collision rate. Then B-hadrons must be reconstructed within the recorded events. Since both lifetime and mixing analyses involve understanding the proper time evolution of B-decays, this quantity must be reconstructed by measuring the candidate B-hadron's momentum and its decay length (the distance between the production and decay points of the hadron). Background levels must then be estimated. And finally, the relevant parameter (τ or Δm) must be extracted from a fit to the data of predictions including all detector effects (efficiencies, resolutions, etc) and background corrections.

Triggers are critical in the first step of this process. Both CDF and D0 employ three-level trigger systems to reduce the intrinsic interaction rate of $\sim$2.5 MHz (set by the bunch-crossing frequency) to the 100-150 Hz of events that can be written to permanent storage. The focus of the two experiments' B-physics triggers is quite different though. CDF relies heavily on triggers sensitive to tracks that are displaced from the primary vertex, while D0 uses mainly single- and di-muon triggers to collect its B-physics sample. The difference in approach stems from the different accept-rates allowed at the first level of triggering – 30 kHz for CDF compared to 2 kHz for D0. Higher level-1 bandwidth allows the CDF collaboration to collect a large sample of events containing fully-hadronic B-hadron decays. D0's large acceptance for muons, on the other hand, has allowed it to accumulate a large sample of semi-muonic B-decays with little intrinsic lifetime bias. As we will see, these types of triggers dictate the type of analyses done by the two collaborations.

Once an event has been recorded, it is scrutinized for the presence of B-hadrons. Because of its muon-based triggers, D0 tends to start this process by identifying candidate semi-muonic B-decays while CDF uses a more inclusive approach. In the next steps, tracking is used to identify charged particles potentially coming from a B-hadron decay chain. Helpful

in this process is the reconstruction of intermediate states in the chain, such as $D_s^- \to \phi\pi^-$ and $\phi \to K^+K^-$. Unlike at the B-factories, pion/kaon separation is not generally important here (although CDF makes use of its dE/dx and time-of-flight capabilities in some analyses). Good invariant mass resolution is critical, however, as reconstructed mass is generally used to identify specific hadrons. CDF has the edge here (by nearly a factor of four) because of their large-volume tracking system. Nevertheless, both experiments are able to accumulate large samples of B-hadron decays with high purities.

The final common feature in B-hadron reconstruction for lifetime and mixing analyses is the estimation of the proper time of the B-hadron's decay. This involves reconstructing the B's production and decay points using vertices found from combinations of charged tracks. Spatial resolution of the tracking systems is thus a crucial element of lifetime and mixing analyses. Both CDF and D0 have similar (and excellent) capabilities here, with average uncertainties on proper time reconstructed using only the charged particles from a B-decay of around 50 μm for semileptonic B-decays and 25 μm for fully hadronic decays. These resolutions are well below typical B-hadron lifetimes of $\sim$500 μm and are also smaller than the B_s oscillation period of $\sim$100 μm.

Reconstruction of the momenta of B-hadrons is, of course, also an important element in estimating proper time. For the case of fully reconstructed, hadronic B-decays the uncertainty that this introduces in the estimate of proper time is negligible compared to that associated with vertexing. For semileptonic decays, however, the true B-hadron momentum cannot be measured directly because of the presence of neutrinos in the decay. To deal with this, correction factors, derived from simulation, are applied to the reconstructed (from charged tracks) proper time of each B-candidate based on its assumed flavor and mode.

3. Lifetimes

CDF and D0 play an important role in our understanding of the lifetimes of weakly decaying B-hadrons. Not only are these experiments the only place where higher mass B-mesons and all B-baryons can be studied, they also provide competitive lifetime results for B^0 and B^+ mesons. In that area, CDF has produced recent preliminary measurements using fully reconstructed B^0 and B^+ decays to $D^{0/+}$ mesons and charged pions; semi-leptonic decays involving D and D^* mesons; and decays to $J/\psi K^{(*)}$. D0 has a published result on the B^+/B^0 lifetime ratio using $\mu D^{(*)}X$ final states. Taken together, these Tevatron results have a weight of $\sim$38% in the $\tau(B^+)/\tau(B^0)$ world average [7].

The Tevatron has also been active in studies of the B_s-meson, as we have seen in several contributions to this conference [1, 3]. The B_s lifetime plays a foundational role in these studies and both CDF and D0 have measured this quantity in a variety of ways. Care must be taken when interpreting B_s lifetime results as these mesons have a non-negligible width difference between their mass eigenstates [3], which, for these purposes, are approximately equivalent to the CP eigenstates. B_s lifetime results are thus only given for those decays in which the CP content is well-known and are quoted as the average lifetime of the heavy and light mass eigenstates. CDF and D0 have several new results in this area, summarized in Table I.

Measurements of B-baryon properties are also an important component of the Tevatron B-physics program [2]. Although several new baryon states have recently been observed by CDF and D0 [2], sufficient statistics to make a lifetime determination have only been accumulated for the Λ_b-baryon. Both $J/\psi\Lambda$ and $\mu\Lambda_c$ final states have been studied. Results are summarized in Table I. They indicate generally good agreement with theoretical expectations (see Fig. 1). However, there is some discrepancy between the CDF and D0 results that will need to be understood with more data.

The last lifetime measurement we will mention, that of the B_c-meson, probes different theoretical issues than those states discussed previously. Because the B_c is composed of two heavy quarks, it has more spectator-level decay possibilities than other weakly decaying B-hadrons. In fact, theory predicts that the B_c lifetime should be approximately one third of that of the other B-mesons.

On the experimental side, both CDF and D0 have now collected large samples of B_c candidates in semileptonic decay modes, as well as smaller sets of fully hadronic decays. Only semi-leptonic decays are currently used for the determination of the B_c lifetime, results of which are summarized in Table I.

As can be seen in Fig. 1, Run II Tevatron measurements of B-hadron lifetimes have dramatically increased the precision with which we can probe QCD. In this figure we see a comparison of world average results from 2000 [14] and 2002 [15] (before Run II results) and the current world averages from HFAG [7]. Also included are theoretical predictions of lifetime ratios [16] and B_c lifetimes [17]. The latest experimental measurements represent improvements of factors of three over pre-Run II results. They tend to be in good agreement with theoretical expectations. In some cases, experimental precision is smaller than uncertainties in the calculations allowing constraints to be put on models of B-decays.
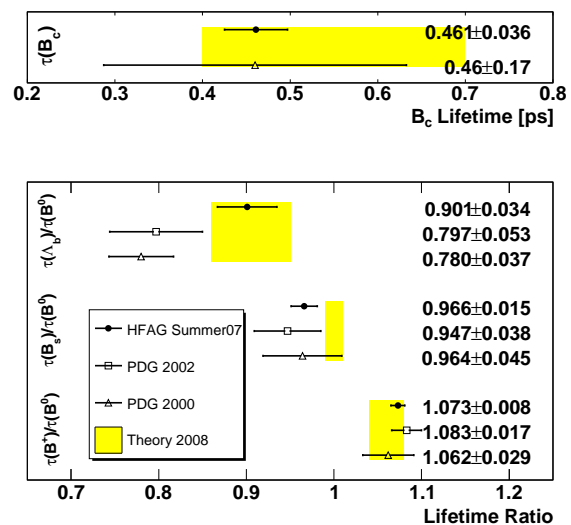

Figure 1: A comparison of world average lifetime ratios, and B_c lifetimes in 2000, 2002, and 2008 with current theoretical predictions.

4. Mixing

Measurement of the oscillation frequency between B_s^0 and $\bar{B}_s^0$ mesons (or equivalently, the mass difference, Δm_s, between the heavy and light mass eigenstates) was one of the goals of Run II at the Tevatron. This goal was achieved in the spring of 2006 when D0 saw first hints of a mixing signal [18], followed quickly by a $>3\sigma$ significance measurement by CDF [19]. These early results have now been updated with a new published measurement from CDF [20] and a set of preliminary results from D0. Basic features of the analyses are given in Table II, and are described in more detail in the following.

The analyses producing the results mentioned above are similar to lifetime analyses in that they examine the proper time evolution of candidate B_s decays. An

Table I Recent B-lifetime measurements from CDF and D0. Integrated luminosity is given in fb^{-1}.

Mode	Exp	Lumi	Signal	τ (ps)
$B_s \to J/\psi\phi$	CDF	1.7	2500	$1.52\pm0.04\pm0.02$ [8]
	D0	2.8	1976	$1.52\pm0.05\pm0.01$ [9]
$B_s \to \pi D_s$	CDF	1.3	3340	$1.517\pm0.041\pm0.025$ (prel)
$B_s \to \ell D_s X$	CDF	0.4	1155	$1.381\pm0.055^{+0.052}_{-0.048}$ (prel)
	D0	0.4	5176	$1.398\pm0.044^{+0.028}_{-0.025}$ [10]
$\Lambda_b \to J/\psi\Lambda$	CDF	1.0	557	$1.58\pm0.08\pm0.01$ (prel)
	D0	1.2	171	$1.22^{+0.13}_{-0.11}\pm0.04$ [11]
$\Lambda_b \to \mu\Lambda_c X$	D0	1.3	3727	$1.29^{+0.12}_{-0.11}\pm0.09$ [12]
$B_c \to J/\psi\ell$	CDF	1.0	916	$0.475^{+0.053}_{-0.049}\pm0.018$ (prel)
$B_c \to J/\psi\mu$	D0	1.3	881	$0.448^{+0.038}_{-0.036}\pm0.032$ [13]

Table II A comparison of B_s-candidate sample sizes, tagging power (εD^2, for opposite and same side tagging), and sensitivity between various decay modes used in the CDF [20] and D0 preliminary analyses and in the previously most sensitive result from ALEPH [21].

Exp	Mode	Sample	$\varepsilon \mathbf{D^2}$ OST	SST	Sensitivity (ps^{-1})
ALEPH	Hadronic	28.5	27%		13.6
D0	ℓD_s	64,500	4.5%		25.4
	πD_s	249	2.5%		14.0
CDF	ℓD_s	61,500	1.8%	4.8%	19.3
	$(3)\pi D_s$	8,700	1.8%	3.7%	30.7

added feature is the use of *tagging* to determine the flavor (B_s^0 or $\bar{B}_s^0$) of the meson at production and decay. Tagging the decay flavor is straightforward using charges of the decay products. Production flavor tagging, however, is harder. Two classes of techniques are used here: opposite side tagging (OST) and same side tagging (SST).

Because b-quarks are produced in quark-antiquark pairs at the Tevatron, the OST technique uses information about the "other" (non-B_s) B-hadron in the event to determine its production flavor. The B_s candidate is then assumed to have been produced with the opposite flavor. SST, on the other hand, uses information gleaned from fragmentation and other particles associated with the B_s-meson itself to determine its flavor at production. The figure of merit associated with these techniques is called the *tagging power*, εD^2. It is composed of the efficiency, ε, for an event to be tagged as either oscillated or non-oscillated and the dilution, D, a quantity related to the purity of the tagging method: $D = 2\eta - 1$, where η is the fraction of tags where the oscillated or non-oscillated state is correctly identified. Tagging powers for the various modes used in CDF and D0 B_s mixing analyses are give in Table II.

Understanding tagging is obviously a critical component of mixing analyses into which the experiments have put a lot of effort. Briefly speaking, OST is calibrated by measuring the well-known B_d oscillation frequency. The B_d mass difference, Δm_d, has been measured extremely accurately by BaBar and Belle (see [7] for a compilation of these results). CDF and D0 [22] cannot compete with these measurements, but do use Δm_d analyses to simultaneously determine OST calibration parameters. The results obtained for Δm_d are fully consistent with the world average, giving us confidence in the OST technique.

Same side tagging performance, unlike that of the OST, is dependent upon the particular B-meson flavor being considered. The method to verify its calibration therefore consists of ensuring that the SST gives similar results in data and MC control samples,

such as $B^+ \to J/\psi K^+$. The MC is then assumed to give a correct description of the SST in B_s-events.

With tagging well in hand, fits are performed to determine the value of Δm_s. Scans of $\ln \mathcal{L}$ vs. assumed Δm_s are shown in Fig. 2 for all analysis modes in CDF [20] and for the preliminary, combined D0 result. Both experiments see minima in $-\ln \mathcal{L}$ around 18 ps^{-1}, measuring the following values for Δm_s:

$$17.77 \ \pm \ 0.10 \ \pm \ 0.07 \mathrm{ps}^{-1} \ \text{CDF} \ [20]$$
$$18.53 \ \pm \ 0.93 \ \pm \ 0.30 \mathrm{ps}^{-1} \ \text{D0} \quad \text{(prelim)} \quad (5)$$

Scans of $-\ln \mathcal{L}$ vs Δm_s for the two experiments are shown in Fig. 2. The significance of the CDF result is 5.4σ (background fluctuation probability of 8×10^{-8}), while that of the D0 measurement is 2.9σ (with systematic effects included).

Using the two measurements above and Eq. 4, we find an average value of $|V_{td}/V_{ts}|$ of:

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.2060 \ \pm 0.0012 (\text{exp}) \ ^{+0.0081}_{-0.0060} (\text{theor}) \quad (6)$$

where the "exp" error includes all statistical and systematic errors on the measurements of Δm_s, while the "theor" error comes from the uncertainty on the ratio of decay constants and bag parameters from lattice calculations [5]:

$$\xi \equiv \frac{f_{Bs}\sqrt{B_{Bs}}}{f_{Bd}\sqrt{B_{Bd}}} = 1.210^{+0.047}_{-0.035} \quad (7)$$

It is interesting to note that the theoretical error on ξ completely dominates the uncertainty of the CKM element ratio (by a factor of nearly 7) and also that the relative error on the world average value of Δm_s (0.3%) is now smaller than that on Δm_d (0.5%) [7].

These new measurements of Δm_s have a large impact on tests of the consistency of the CKM picture of quark mixing. This is particularly evident when comparing experimental reconstruction of the "unitarity triangle" (formed from one element of the CKM unitarity condition: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$). Figure 3 shows a comparison of the state of our knowledge of this triangle in 2003 and 2007 [23] (see also [24]). The new measurement of Δm_s significantly increases the accuracy with which we know the apex of the unitarity triangle and favors those models of new physics that have a Standard Model, CKM-like flavor structure.

5. Conclusions and Future Prospects

We've made remarkable progress in the field of B-physics since the start of Run II at the Tevatron. To cite just a few examples discussed here: our knowledge of B-hadron lifetimes has improved by a factor of two or more depending on the hadron; the accuracy
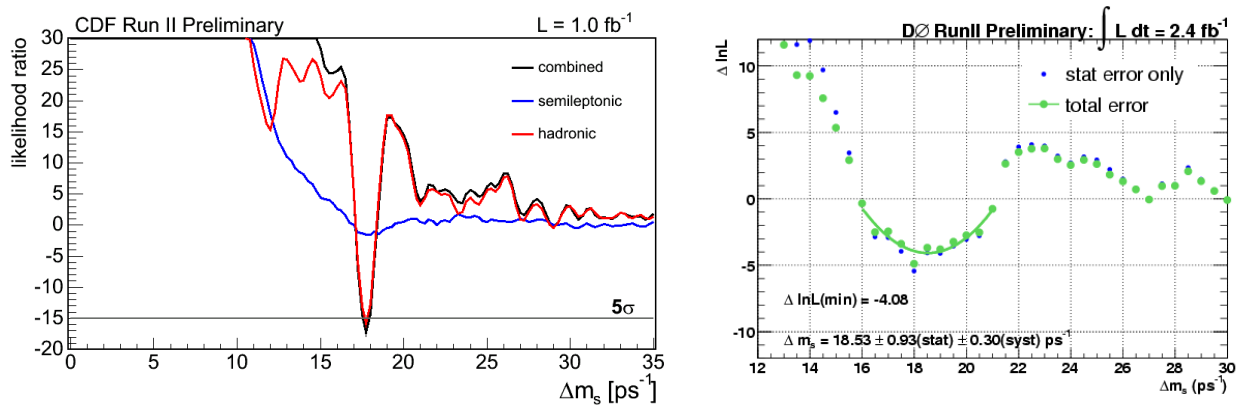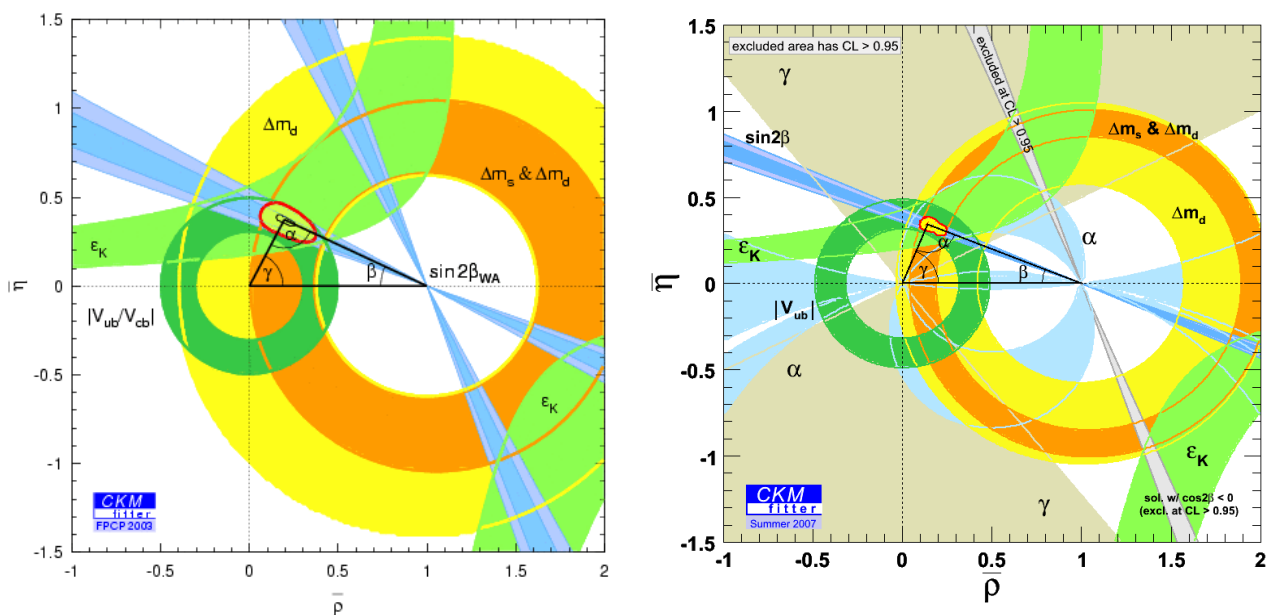
Figure 2: Scans of $-\ln \mathcal{L}$ vs Δm_s for the CDF and D0 B_s mixing analyses.

Figure 3: Experimental constraints on the unitarity triangle in 2003 (left plot) and 2007 (right plot) from the CKMfitter group.

to which we measure the B_d mixing frequency has increased by a factor of more than three, thanks to hard work at the B-factories; and we have finally observed B_s oscillations, which are now measured with an uncertainty of only 0.3%. All these measurements, and many others, point to a picture of flavor that is consistent with the Standard Model CKM description. However, some cracks may be appearing in the mirror due to recent measurements of CP violation in B_s-mesons [3].

Certainly then, the B_s is a system to watch – particularly in the CP-sector. Advances on the oscillation frequency side will need to come from improved calculations though, since that is where the main source

of uncertainty now lies. For lifetime measurements, the increasingly large data sets being collected at the Tevatron (more than 4 fb^{-1} have now been delivered to each experiment) hold out the prospect of comprehensive tests of QCD models using a wide range of B-hadrons. The experimental focus here will shift to baryons (and the B_c), including the newly observed Ξ_b and Σ_b states.

With many past successes and a bright future ahead, B-physics will remain a vital part of the Tevatron program while we await the next big step – LHCb.

Acknowledgments

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