**ABSTRACT**

Although the $B^0_s$ and $\Lambda^0_b$ hadrons differ only in the spectator quarks from the well-studied $B^0_d$ and $B^+_u$ mesons, they provide a unique window on the physics of the $b$-quark. With no experiments presently running at the $Z$ pole, hadron colliders now provide the best opportunity to study the $B^0_s$ and the $\Lambda^0_b$. The collider experiments at the Tevatron, CDF and DØ, have collected large numbers of $B^0_s$ and $\Lambda^0_b$. Some of their latest preliminary measurements are presented here, including masses, lifetimes, and charmless decays. Progress is made toward measuring the lifetime difference $\Delta \Gamma_s$ between the $B^0_s$ mass eigenstates and the oscillation frequency $\Delta m_s$. 

**BEAUTY PHYSICS WITH $B^0_s$ AND $\Lambda^0_b$**

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1 Introduction

Apart from the familiar $B_u^+$ and $B_0^0$ mesons, the existence of three more weakly decaying $B$ hadrons has been firmly established: the $B_s^0$ and $B_c^+$ mesons and one baryon, the $\Lambda_b^0$. Other weakly decaying hadrons have been predicted but have not yet been unambiguously observed: the $\Xi_b^0$, the $\Xi_b^-$ and the $\Omega_b^-$. While our primary physics interest is focused on the $b$-quark, there are three good reasons why the spectator quark plays a major role in the study of the $b$-quark:

- **The spectator quark can make or break a CP eigenstate.** A $B_s^0$ has a large branching ratio to the CP-even $D_s^+D_s^-$ final state, through the Cabbibo-favored $b \to c\bar{c}s$ transition. Since this final state is accessible by both $B_s^0$ and $\bar{B}_s^0$, it contributes to the lifetime difference between the heavy and the light $B_s^0$ mass eigenstates. The equivalent decay of the $B_s^0$ results in a $D_s^+D_s^-$ final state, which is flavor-specific, and the lifetime difference in the $B_s^0$ system is negligible.

- **The spectator quark can exchange $W$’s with the $b$ quark.** The most dramatic consequence of this are oscillations: through the exchange of two $W^\pm$, the $B_d^0$ and the $B_s^0$ can transform into their own anti-particle. The $B_s^0$ oscillates more than 20 times faster than the $B_d^0$, whose oscillation frequency is suppressed due to the tiny CKM matrix element $V_{td}$.

- **The spectator quark can annihilate with the $b$-quark.** This process is dominated by loop-diagrams involving the top-quark. The decay of a $B_s^0$ into two muons is expected to occur with a branching ratio larger by $|V_{ts}|^2/|V_{td}|^2$ compared to $B_d^0 \to \mu^+\mu^-$.

Rare decays and CP violation are not discussed here, since they are covered elsewhere in these proceedings [1, 2].

2 Production of $B_s$ and $\Lambda_b$

The present $B$ factories operate at the $\Upsilon(4S)$ resonance which produces only $B_u^+$ and $B_0^0$. The next resonance, the $\Upsilon(5S)$, is heavy enough to produce $B_s^0$ mesons. However, the $B_s^0$ cross-section at the $\Upsilon(5S)$ is an order of magnitude smaller than the $B_d^0$ production at the $\Upsilon(4S)$ [3], thus making it challenging to collect a competitive number of $B_s^0$ decays.

There are two other practical means of producing the $B_s$ and the $\Lambda_b^0$: [4]
• **$e^+e^-$ at the Z pole.** Each of the 4 LEP experiments has recorded about $880 \times 10^3$ $Z \rightarrow b\bar{b}$ events, and have contributed significantly to our knowledge of the $B^0_s$ and $\Lambda^0_b$. The $Z \rightarrow b\bar{b}$ sample produced at the Stanford Linear Collider (SLC) is smaller by an order of magnitude, but profited from the superior vertex resolution and from the beam polarization. The latter gives a strong correlation between the production hemisphere and the charge sign of the $b$ quark and provides an efficient flavor-tag, a key advantage for oscillation studies.

• **High-energy hadron colliders.** The Tevatron, a $p\bar{p}$ collider at 1.96 TeV center of mass energy, is presently operational and has a $b\bar{b}$ cross-section that is about $10^{-3}$ of the total inelastic cross-section. In 2007 the Large Hadron Collider (LHC) in Genève will provide an abundant source of $B$ hadrons. Proton-proton collisions at a center-of-mass energy of 14 TeV produce a $b\bar{b}$ pair roughly every hundred interactions.

In both of the above mentioned cases, the production fractions of $B^0_s$ and $\Lambda^0_b$ are approximately 10% each, while $B^+_c$ production is suppressed at the $10^{-3}$ level.

3 Reconstruction of $B$-decays

The types of $B$ decays that can be reconstructed at a hadron collider can be distinguished into three classes:

• **Semileptonic decays**, for example $B^0_s \rightarrow D^-_s \mu^+\nu_\mu$. These have large branching fractions, and large yields can be obtained simply by triggering on a lepton, but the missing neutrino prohibits complete reconstruction. Moreover, semileptonic decays cannot result in a CP eigenstates, and do not give access to many of the most interesting $B$ physics channels.

• **$B$ decays with a $J/\psi$ in the final state**, for example $B^0_s \rightarrow J/\psi \phi$. These have the advantage of providing a clear signature for the trigger, through the dimuon decay of the $J/\psi$. However, the sum of all branching ratios with a $J/\psi$ in the final state is only slightly more than one percent.

• **Hadronic decays**, such as $B^0_s \rightarrow D^-_s \pi^+$, $B^0_s \rightarrow K^+K^-$. These constitute about three quarters of all $B$ decays and offer a rich variety of $B$ physics. However, they are difficult to distinguish from the overwhelming background of hadronic interactions without heavy flavor. Its main signature are displaced
tracks, and to collect large samples of fully reconstructed hadronic $B$ decays requires specialized triggers that are capable of reading out and processing data from a silicon vertex detector at high speed.

4  Present and future experiments

Both the CDF and the DØ detectors are well equipped for a rich $B$ physics program: both have silicon detectors, high resolution trackers in a magnetic field, and lepton identification. DØ profits from its hermetic muon coverage and its efficient tracking in the forward regions, giving a high sensitivity for semileptonic and $J/\psi$ modes. CDF has better track momentum resolution, a high-bandwidth silicon track trigger, and particle identification capabilities through Time-of-Flight counters and $dE/dx$ measurements in its main drift chamber.

Two new specialized $B$ experiments may dramatically improve our knowledge of the $B^0_s$ and the $\Lambda^0_b$: the LHCb experiment, starting in 2007 at the LHC, and the BTeV experiment, starting in 2009 at the Tevatron. Both experiments use a dipole spectrometer and are instrumented at small angles with respect to the beam. Using the forward region has many advantages:

- The useful cross-section is higher, because of the large acceptance at small transverse momentum.

- Often both $B$‘s are in the detector acceptance, giving a high efficiency for flavor-tagging.

- The boost in the direction of the beam allows to accurately measure the decay time in the beam direction.

- The forward detector geometry allows to install Rich Imaging Cerenkov detectors for superb particle identification.

5  Mass measurements

A typical 'mass peak' of 200 fully reconstructed events with an experimental resolution of 15 MeV gives a mass measurement with a statistical uncertainty of $\approx$1 MeV. Both $B^0_s$ and $\Lambda_b^0$ have now been observed in fully reconstructed decay modes, but the $B_c^+$ has only been observed in the semileptonic decay $B_c^+ \rightarrow J/\psi \ell^+ \nu_\ell$, and the mass has an uncertainty of more than 400 MeV. This can be dramatically improved by observing the $B_c^+$ in fully reconstructed decay modes such as $B_c^+ \rightarrow J/\psi \pi^+$. Preliminary $B^0_s$ and $\Lambda_b^0$ mass measurements from CDF, shown in Figure 1, significantly
improve the previous best measurements. To achieve mass measurements at the 1 MeV level, the mass scale needs to be understood to $10^{-4}$. This has been achieved by calibrating on $J/\psi \rightarrow \mu^+\mu^-$ decays, which are copiously produced in hadron colliders.

$$M(B_s^0) [\text{MeV}]$$

- Delphi: $5374.0 \pm 16.0 \pm 2.0$
- Aleph: $5368.6 \pm 5.6 \pm 1.5$
- Opal: $5359.0 \pm 19.0 \pm 7.0$
- CDF: $5369.9 \pm 2.3 \pm 1.3$
- CDF II (this): $5366.01 \pm 0.73 \pm 0.33$

- World average: $5369.6 \pm 2.4$

$$M(\Lambda_b^0) [\text{MeV}]$$

- Delphi: $5668.0 \pm 16.0 \pm 8.0$
- Aleph: $5614.0 \pm 21.0 \pm 4.0$
- CDF: $5621.0 \pm 4.0 \pm 3.0$
- CDF II (this): $5619.7 \pm 1.2 \pm 1.2$

- World average: $5624.0 \pm 9.0$

Figure 1: Preliminary CDF measurements of $B$ hadron masses in the $B_s^0 \rightarrow J/\psi\phi$ and $\Lambda_b^0 \rightarrow J/\psi\Lambda$ channels.

6 Lifetime measurements

To first order, $B$-hadron lifetimes are determined by the fastest decaying quark:

$$\tau(B_u^+) \approx \tau(B_d^0) \approx \tau(B_s^0) \approx \tau(\Lambda_b^0) \gg \tau(B_c^+)$$

(1)

Spectator effects can be calculated in the Heavy Quark Expansion, but have been determined to be small: the dominant contributions scale with $(\Lambda_{QCD}/m_b)^3$. A recent calculation includes $m_b^{-4}$ contributions \cite{4} and finds:

$$\frac{\tau(B_u^+)}{\tau(B_d^0)} = 1.09 \pm 0.03, \quad \frac{\tau(B_s^0)}{\tau(B_d^0)} = 1.00 \pm 0.01, \quad \frac{\tau(\Lambda_b^0)}{\tau(B_s^0)} = 0.87 \pm 0.05.$$

(2)

The best lifetime measurements of the $B_s^0$ and the $\Lambda_b^0$ come from semileptonic decays at CDF-I and LEP. The current World Average \cite{5} is:

$$\tau(B_s^0) = 1.46 \pm 0.06 \text{ ps} \quad \text{and} \quad \tau(\Lambda_b^0) = 1.23 \pm 0.08 \text{ ps}.$$

(3)
Semileptonic measurements, however, suffer from incomplete reconstruction due to the missing neutrino. This introduces irreducible systematic uncertainties both from the production model and from the decay model. Fully reconstructed $B$ decays are not affected by model-dependencies, since the lifetime is measured on an event-by-event basis, but they provide smaller statistics. Both DØ and CDF have recently measured the lifetimes of the $B^0_s$ and $\Lambda^0_b$ in fully reconstructed modes with a precision similar to the semileptonic measurements:

CDF 220 pb$^{-1}$: $\tau(B^0_s \rightarrow J/\psi\phi) = 1.37 \pm 0.10 \pm 0.01$ ps, \hfill (4)

DØ 115 pb$^{-1}$: $\tau(B^0_s \rightarrow J/\psi\phi) = 1.19 \pm 0.19 \pm 0.14$ ps, \hfill (5)

CDF 65 pb$^{-1}$: $\tau(\Lambda^0_b \rightarrow J/\psi\Lambda) = 1.25 \pm 0.26 \pm 0.10$ ps. \hfill (6)

The last one represents the first measurement of the $\Lambda^0_b$ lifetime from fully reconstructed decays. In the near future these measurements will be updated with more data, and we can expect lifetime measurements from semileptonic and hadronic modes.

7 The $B^0_s$ lifetime difference

Because of mixing, the time evolution of neutral $B$ mesons is not governed by the flavor eigenstates $B^0$, $\bar{B}^0$, but by the mass eigenstates $B_L$, $B_H$, which may differ not only in mass, but also in decay width by $\Delta \Gamma = \Gamma_L - \Gamma_H$. For non-zero $\Delta \Gamma$, the decay time distribution follows a double instead of a single exponential. If the $B_s$ mixing phase is as small as predicted, $\phi_s \approx 0.03$, the $B^0_s$ mass eigenstates coincide almost exactly with the CP eigenstates. A significant lifetime difference is then expected from the Cabibbo-favored $b \rightarrow c\bar{c}s$ transition that results in a large fraction of final states that are CP even and common to $B^0_s$ and $\bar{B}^0_s$.

A recent calculation [6] predicts $\Delta \Gamma_s/\Gamma_s = 0.074 \pm 0.024$, consistent with the experimental world-average value $\Delta \Gamma_s/\Gamma_s = 0.07^{+0.09}_{-0.07}$, obtained under the assumption that $\tau(B^0_s) = \tau(B^0_s)$, or $\Delta \Gamma_s/\Gamma_s = 0.16^{+0.15}_{-0.16}$ without this constraint [7].

Three methods are available to measure $\Delta \Gamma_s$:

1. Take a CP-mixed decay, and fit the lifetime distribution to a double exponential. A disadvantage is that this is sensitive to $(\Delta \Gamma_s)^2$, making it difficult to probe small values of $\Delta \Gamma_s$.

2. Compare the $B^0_s$ lifetime in a CP-even to a CP-odd or CP-mixed state. $B$ decays to two spin-1 particles, such as $B^0_s \rightarrow J/\psi\phi$, can be decomposed through an angular analysis into CP-odd and CP-even states.
3. Since the lifetime difference is dominated by the decay $B^0_s \rightarrow D^{(*)+}D^{(*)-}$, measurements of these branching fractions provide an indirect measurement of $\Delta \Gamma_s$.

CDF has recently completed a preliminary angular analysis of $B^0_s \rightarrow J/\psi \phi$, extracting three complex amplitudes, the short-lived CP-even $A_0$ and $A_{||}$, and the long-lived CP-odd $A_T$, finding:

\[
A_0 = 0.767 \pm 0.045 \pm 0.017, \quad (7)
\]
\[
A_{||} = (0.424 \pm 0.118 \pm 0.013)e^{(2.11 \pm 0.55 \pm 0.29)i}, \quad (8)
\]
\[
A_T = 0.482 \pm 0.104 \pm 0.014. \quad (9)
\]

This shows that $B^0_s \rightarrow J/\psi \phi$ is mostly CP-even, but also has a significant CP-odd component, making it possible to measure $\Delta \Gamma_s$ from this channel alone.

8 Charmless decays

The strongly suppressed $b \rightarrow u$ transitions probe the CKM matrix element $V_{ub}$ and its phase, often called $\gamma$. In practice, interfering contributions from penguin decays complicate precision measurements of $\gamma$ from charmless $B$ decays. Comparing various two-body decays of $B^0_s$ and $B^0_d$ allows to disentangle the tree and penguin contributions \[8\]. The challenge of reconstructing 2-body $B$ decays at a hadron collider resides both in rejecting large backgrounds and in distinguishing for example a $B^0_d \rightarrow \pi^+\pi^-$ decay from a $B^0_s \rightarrow K^+K^-$ decay without strong particle identification. Using specific ionization in their drift chamber, CDF achieves a $\pi/K$ separation of $1.15\sigma$, enough to disentangle the four main contributions to the peak in their $m(\pi^+\pi^-)$ histogram, and measures $Br(B^0_s \rightarrow K^+K^-)/Br(B^0_d \rightarrow K^+\pi^-) = 2.71 \pm 0.73 \pm 0.88$. This measurement is related to the direct CP violation in $B^0_d \rightarrow \pi^+\pi^-$ decays and was found to agree with the Standard Model expectation \[9\]. The same data have also been used to search for the charmless decay $\Lambda^0_b \rightarrow p\pi^-, pK^-$. The predicted branching ratios, \((1.4 - 1.9) \times 10^{-6}\) for $\Lambda^0_b \rightarrow pK^-$ and \((0.8 - 1.2) \times 10^{-6}\) for $\Lambda^0_b \rightarrow p\pi^-$ \[10\], are considerably lower than the best experimental upper limit: $Br(\Lambda^0_b \rightarrow p\pi^-, pK^-) \leq 50 \times 10^{-6}$ at 90\%CL \[11\]. CDF finds no evidence for a signal and improves the upper limit to $Br(\Lambda^0_b \rightarrow p\pi^-, pK^-) \leq 22 \times 10^{-6}$ at 90\%CL. Figure 2 shows the $B \rightarrow h^+h^-$ meson signal, the $\Lambda_b$ search window and simulated $\Lambda^0_b \rightarrow pK^-, p\pi^-$ signals. Particularly interesting charmless decays come from the pure penguin $b \rightarrow s\bar{s}s$ transition, since the Belle collaboration has observed a $3.5\sigma$ deviation from the expected value of the weak phase in the $B^0_d \rightarrow \phi K^0_S$.
CDF Run II Preliminary

Figure 2: $B \rightarrow h^+h^-$ plot with the pion mass assumption for both tracks, indicating the search window for $\Lambda_b^0 \rightarrow pK^-$, $p\pi^-$. The peak at $m_{\pi\pi} \approx 5.27$ GeV is dominated by $B_d^0 \rightarrow K^+\pi^-$ decays used for normalization.

channel [12]. CDF observes 12 $B_s^0 \rightarrow \phi\phi$ candidates with an expected background of $1.95 \pm 0.62$ events, constituting the first $b \rightarrow s\bar{s} s$ in $B_s^0$ decays. They measure $Br(B_s^0 \rightarrow \phi\phi) = (14 \pm 6_{\text{stat}} \pm 2_{\text{syst}} \pm 5_{Br}) \times 10^{-6}$, where the last uncertainty comes from $Br(B_s^0 \rightarrow J/\psi\phi)$ that is used as a normalization mode. The measured branching fraction is consistent with the wide range of predictions, which cover the range $(0.4 - 37) \times 10^{-6}$ [13, 14]. The large branching ratio, combined with a distinct and low-background experimental signature, promises a bright future for this channel including angular analyses, measurements of $\Delta \Gamma_s$, and CP violation.

9 $B_s^0$ oscillations

The well-measured $B_d^0$ oscillations provide a measurement of the CKM element $|V_{td}|$, but the extraction is plagued by theoretical uncertainties. A more accurate measurement can be obtained by measuring also the $B_s^0$ oscillation frequency and use [15]

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m(B_s^0)}{m(B_d^0)} \left(1.15 \pm 0.06_{0.00}^{0.12}\right)^2 \left|\frac{V_{ts}}{V_{td}}\right|^2,$$

where the last (asymmetric) uncertainty comes from the chiral extrapolation. Seen the other way around, the Standard Model gives an accurate prediction of $\Delta m_s$, and many new physics models allow significantly larger values [16, 17]. In addition, a precise measurement of $\Delta m_s$ is a prerequisite for many time-dependent
CP violation studies in the $B_s^0$ system. The present experimental lower limit is $\Delta m_s \geq 14.4\,\text{ps}^{-1}$, implying more than three full $B_s^0$ oscillation cycles within one lifetime. Because of these very fast oscillations, the precise measurement of the proper decay time is of crucial importance: since the uncertainty on the oscillation amplitude scales like $\sigma(A) \propto e^{(\sigma t \Delta m_s)^2/2}$, a proper time resolution larger than $67\,\text{fs}^{-1}$ seriously affects the sensitivity above $15\,\text{ps}^{-1}$. The first ingredient for mixing is a large $B_s^0$ yield. Figure 3 shows the large yields from DØ in $B_s^0 \to D^- \mu^+\nu_{\mu}$ decays and the first $B_s^0 \to D^- \pi^+$ signal from CDF, which is much smaller in statistics, but provides a more accurate measurement of the proper decay time.

Another crucial ingredient for any mixing measurement is flavor tagging, to determine whether a $B_s^0$ or a $\bar{B}_s^0$ was produced. This information can be obtained either from the fragmentation tracks of the $B_s^0$ under study (“same side tag”), or from the decay products of the $b$ quark that is produced in association with the $B_s^0$ (“opposite side tag”). The effectiveness of a flavor tagger is usually expressed in its efficiency $\varepsilon$ and its “Dilution factor” $D = 1 - 2W$, where $W$ is the fraction of wrong charge assignments. The statistical power of a flavor tagger scales as $\varepsilon D^2$. Contrary to $B$ physics at the $Y(4S)$, where values of $\varepsilon D^2 \approx 30\%$ are readily achieved, the flavor taggers at hadron colliders rarely exceed an $\varepsilon D^2$ of one percent.

Both DØ and CDF have shown non-zero dilutions for opposite side muon and jet-charge taggers. Both have also shown powerful tagging using fragmentation.

Figure 3: semileptonic $B_s^0$ yields from DØ (left) and fully hadronic yields from CDF (right).
particles associated with the $B^+_d$. However, for the $B^0_s$, the flavor information is typically carried by a kaon, and it requires good $\pi/K$ separation to use same-side taggers for the $B^0_s$.

CDF and DØ have produced preliminary $B^0_d$ mixing measurements. DØ measures $\Delta m_d = 0.506 \pm 0.055 \pm 0.049 \text{ps}^{-1}$ using semileptonic $B^0_d$ decays and an opposite side muon tag. CDF measures $\Delta m_d = 0.55 \pm 0.10 \pm 0.01 \text{ps}^{-1}$ using fully reconstructed hadronic decays and a same-side tag.

10 Conclusions

The physics of the $B_s$ and $\Lambda_b$ provide a unique window on $B$ physics that is not accessible at the $\Upsilon(4S)$. New measurements of masses, lifetimes and observations in new decay modes have recently come available from the collider experiments at the Tevatron. These, and future measurements of the $B^0_s$ mixing parameters $\Delta m_s$ and $\Gamma_s$ will determine the physics opportunities at the next generation hadron $B$ physics experiments at hadron colliders.

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