BEAUTY PHYSICS WITH B_s^0 AND Λ_b^0

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ABSTRACT

Although the B_s^0 and Λ_b^0 hadrons differ only in the spectator quarks from the well-studied B_d^0 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_s^0 and the Λ_b^0. The collider experiments at the Tevatron, CDF and DØ, have collected large numbers of B_s^0 and Λ_b^0. 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_s^0 mass eigenstates and the oscillation frequency Δm_s.

1 Introduction

Apart from the familiar B_u^+ and B_d^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 Λ_b^0. Other weakly decaying hadrons have been predicted but have not yet been unambiguously observed: the Ξ_b^0, the Ξ_b^- and the Ω_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_d^0 results in a $D_s^+ D^-$ final state, which is flavor-specific, and the lifetime difference in the B_d^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 Λ_b

The present B factories operate at the $\Upsilon(4S)$ resonance which produces only B_u^+ and B_d^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 Λ_b^0:

- **e^+e^- at the Z pole**. Each of the 4 LEP experiments has recorded about 880×10^3 $Z \to b\bar{b}$ events, and have contributed significantly to our knowledge of the B_s^0 and Λ_b^0. The $Z \to b\bar{b}$ 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_s^0 and Λ_b^0 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 $B_s^0 \to D_s^- \mu^+ \nu_\mu$. 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/ψ in the final state**, for example $B_s^0 \to J/\psi\phi$. These have the advantage of providing a clear signature for the trigger, through the dimuon decay of the J/ψ. However, the sum of all branching ratios with a J/ψ in the final state is only slightly more than one percent.

- **Hadronic decays**, such as $B_s^0 \to D_s^- \pi^+$, $B_s^0 \to K^+K^-$. 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/ψ 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_s^0 and the Λ_b^0: 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 ≈1 MeV. Both B_s^0 and Λ_b^0 have now been observed in fully reconstructed decay modes, but the B_c^+ has only been observed in the semileptonic decay $B_c^+ \to J/\psi \ell^+ \nu_\ell$, 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 $B_c^+ \to J/\psi \pi^+$. Preliminary B_s^0 and Λ_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 $J/\psi \to \mu^+\mu^-$ decays, which are copiously produced in hadron colliders.

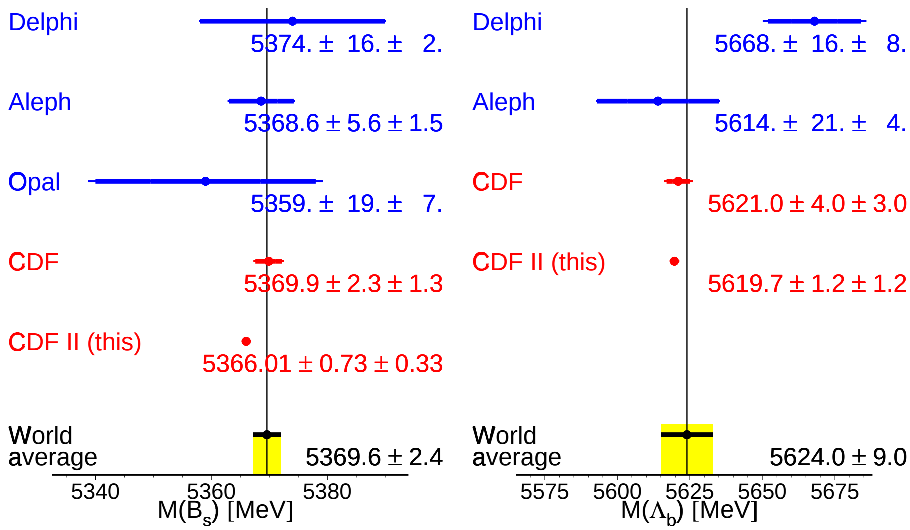

Figure 1: *Preliminary CDF measurements of B hadron masses in the* $B_s^0 \to J/\psi\phi$ *and* $\Lambda_b^0 \to J/\psi\Lambda$ *channels.*

6 Lifetime measurements

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

$$\tau(B_u^+) \approx \tau(B_d^0) \approx \tau(B_s^0) \approx \tau(\Lambda_b^0) \gg \tau(B_c^+) \tag{1}$$

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 [4] and finds:

$$\frac{\tau(B_u^+)}{\tau(B_d^0)} = 1.09 \pm 0.03, \quad \frac{\tau(B_s^0)}{\tau(B_d^0)} = 1.00 \pm 0.01, \quad \frac{\tau(\Lambda_b^0)}{\tau(B_d^0)} = 0.87 \pm 0.05. \tag{2}$$

The best lifetime measurements of the B_s^0 and the Λ_b^0 come from semileptonic decays at CDF-I and LEP. The current World Average [5] is:

$$\tau(B_s^0) = 1.46 \pm 0.06\,\text{ps} \quad \text{and} \quad \tau(\Lambda_b^0) = 1.23 \pm 0.08\,\text{ps}. \tag{3}$$

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_s^0 and Λ_b^0 in fully reconstructed modes with a precision similar to the semileptonic measurements:

$$\text{CDF } 220\,\text{pb}^{-1} : \tau(B_s^0 \to J/\psi\phi) = 1.37 \pm 0.10 \pm 0.01\,\text{ps}, \tag{4}$$

$$\text{DØ } 115\,\text{pb}^{-1} : \tau(B_s^0 \to J/\psi\phi) = 1.19 \pm 0.19 \pm 0.14\,\text{ps}, \tag{5}$$

$$\text{CDF } 65\,\text{pb}^{-1} : \tau(\Lambda_b^0 \to J/\psi\Lambda) = 1.25 \pm 0.26 \pm 0.10\,\text{ps}. \tag{6}$$

The last one represents the first measurement of the Λ_b^0 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_s^0 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_s^0 mass eigenstates coincide almost exactly with the CP eigenstates. A significant lifetime difference is then expected from the Cabibbo-favored $b \to c\bar{c}s$ transition that results in a large fraction of final states that are CP even and common to B_s^0 and $\bar{B}_s^0$.

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 $\tau(B_s^0) = \tau(B_d^0)$, 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_s^0 lifetime in a CP-even to a CP-odd or CP-mixed state. B decays to two spin-1 particles, such as $B_s^0 \to J/\psi\phi$, can be decomposed through an angular analysis into CP-odd and CP-even states.

3. Since the lifetime difference is dominated by the decay $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$, measurements of these branching fractions provide an indirect measurement of $\Delta\Gamma_s$.

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

$$A_0 = 0.767 \pm 0.045 \pm 0017, \quad (7)$$

$$A_{||} = (0.424 \pm 0.118 \pm 0.013) e^{(2.11 \pm 0.55 \pm 0.29)i}, \quad (8)$$

$$A_T = 0.482 \pm 0.104 \pm 0.014. \quad (9)$$

This shows that $B_s^0 \to J/\psi\phi$ 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 $b \to u$ transitions probe the CKM matrix element V_{ub} and its phase, often called γ. In practice, interfering contributions from penguin decays complicate precision measurements of γ from charmless B decays. Comparing various two-body decays of B_s^0 and B_d^0 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 $B_d^0 \to \pi^+\pi^-$ decay from a $B_s^0 \to K^+K^-$ decay without strong particle identification. Using specific ionization in their drift chamber, CDF achieves a π/K separation of $1.15\,\sigma$, enough to disentangle the four main contributions to the peak in their $m(\pi^+\pi^-)$ histogram, and measures $Br(B_s^0 \to K^+K^-)/Br(B_d^0 \to K^+\pi^-) = 2.71 \pm 0.73 \pm 0.88$. This measurement is related to the direct CP violation in $B_d^0 \to \pi^+\pi^-$ 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 $\Lambda_b^0 \to p\pi^-, pK^-$. The predicted branching ratios, $(1.4 - 1.9) \times 10^{-6}$ for $\Lambda_b^0 \to pK^-$ and $(0.8 - 1.2) \times 10^{-6}$ for $\Lambda_b^0 \to p\pi^-$ [10], are considerably lower than the best experimental upper limit: $Br(\Lambda_b^0 \to p\pi^-, pK^-) \leq 50 \times 10^{-6}$ at 90%CL [11]. CDF finds no evidence for a signal and improves the upper limit to $Br(\Lambda_b^0 \to p\pi^-, pK^-) \leq 22 \times 10^{-6}$ at 90%CL. Figure 2 shows the $B \to h^+h^-$ meson signal, the Λ_b search window and simulated $\Lambda_b^0 \to pK^-, p\pi^-$ signals. Particularly interesting charmless decays come from the pure penguin $b \to s\bar{s}s$ transition, since the Belle collaboration has observed a 3.5σ deviation from the expected value of the weak phase in the $B_d^0 \to \phi K_S^0$

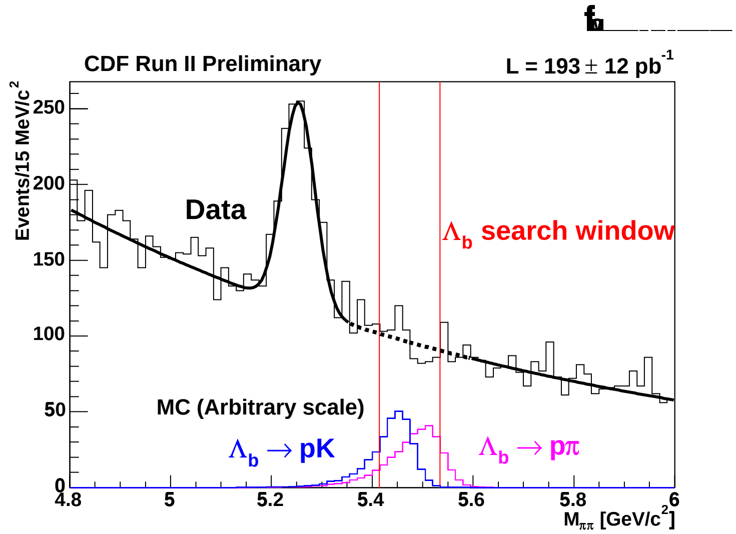

Figure 2: *$B \to h^+h^-$ plot with the pion mass assumption for both tracks, indicating the search window for $\Lambda_b^0 \to pK^-, p\pi^-$. The peak at $m_{\pi\pi} \approx 5.27\,GeV$ is dominated by $B_d^0 \to K^+\pi^-$ decays used for normalization.*

channel [12]. CDF observes 12 $B_s^0 \to \phi\phi$ candidates with an expected background of 1.95 ± 0.62 events, constituting the first $b \to s\bar{s}s$ in B_s^0 decays. They measure $Br(B_s^0 \to \phi\phi) = (14 \pm 6_{stat} \pm 2_{syst} \pm 5_{Br}) \times 10^{-6}$, where the last uncertainty comes from $Br(B_s^0 \to J/\psi\phi)$ 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]

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m(B_s^0)}{m(B_d^0)} \left(1.15 \pm 0.06^{+0.12}_{-0.00}\right)^2 \left|\frac{V_{ts}}{V_{td}}\right|^2, \tag{10}$$

where the last (asymmetric) uncertainty comes from the chiral extrapolation. Seen the other way around, the Standard Model gives an accurate prediction of Δm_s, and many new physics models allow significantly larger values [16, 17]. In addition, a precise measurement of Δm_s is a prerequisite for many time-dependent

CP violation studies in the B_s^0 system. The present experimental lower limit is $\Delta m_s \geq 14.4\,\mathrm{ps}^{-1}$ [5], 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 $67\,\mathrm{fs}^{-1}$ seriously affects the sensitivity above $15\,\mathrm{ps}^{-1}$. The first ingredient for mixing is a large B_s^0 yield. Figure 3 shows the large yields from DØ in $B_s^0 \to D_s^- \mu^+ \nu_\mu$ decays and the first $B_s^0 \to D_s^- \pi^+$ signal from CDF, which is much smaller in statistics, but provides a more accurate measurement of the proper decay time.

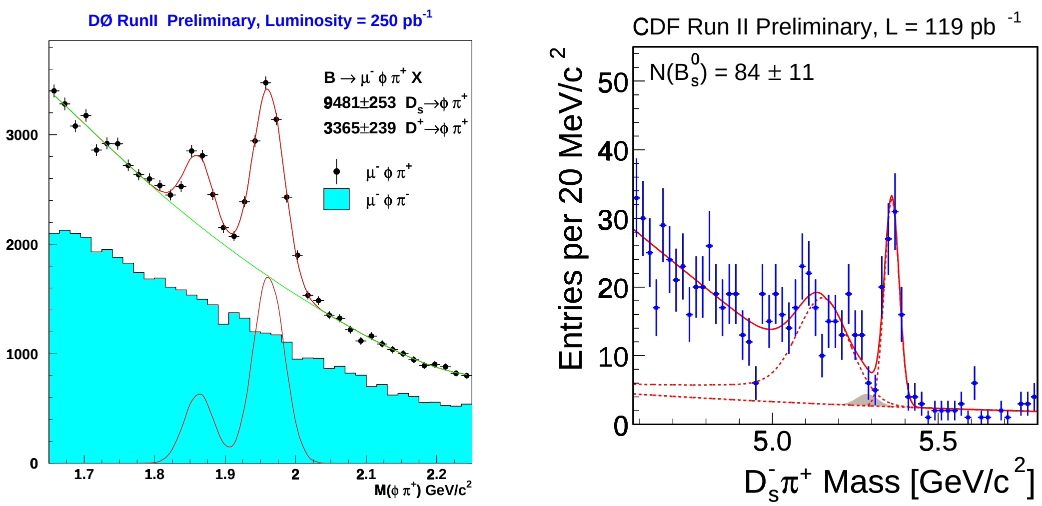

Figure 3: *semileptonic B_s^0 yields from DØ (left) and fully hadronic yields from CDF (right).*

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 ε 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 εD^2. Contrary to B physics at the $\Upsilon(4S)$, where values of $\varepsilon D^2 \approx 30\%$ are readily achieved, the flavor taggers at hadron colliders rarely exceed an εD^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 particles associated with the B_u^+. However, for the B_s^0, the flavor information is typically carried by a kaon, and it requires good π/K separation to use same-side taggers for the B_s^0.

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

10 Conclusions

The physics of the B_s and Λ_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_s^0 mixing parameters Δm_s and Γ_s will determine the physics opportunities at the next generation hadron B physics experiments at hadron colliders.

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