FERMILAB-CONF-09-301-PPD

B PHYSICS RESULTS FROM THE TEVATRON: LIFETIMES AND RARE DECAYS

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With data samples of up to $2\,\mathrm{fb}^{-1}$ of $p\bar{p}$ interactions at $\sqrt{s} = 1960\,\mathrm{GeV}$, the CDF and DØ experiments are beginning to make precision measurements of the lifetime of bottom hadrons not produced in e^+e^- colliders operating at the $\Upsilon(4S)$ and set limits on the branching ratios of many decay modes that are predicted to be rare or forbidden under the standard model. Both sets of measurements are providing limits on physics beyond the standard model.

1 Introduction

As systems of a heavy quark and a light anti-quark or diquark, bottom hadrons are unique in the ability of theory to predict many of their properties. In Heavy-Quark Effective Theory[1] (HQET), the light degrees of freedom decouple from the heavy-quark decay processes. Thus it is possible to make predictions of total and partial decay widths without a detailed understanding of the "brown muck" that binds quarks to form hadrons. Furthermore, b hadron decays are dominated by spectator decays in which the heavy quarks decay without interacting with the light quarks. The total width of B^+ mesons is expected to be slightly less than that of B^0 and B_s^0 as a result of destructive interference between the two dominant spectator diagrams in the former and the availability of the W-exchange process in the latter two. The width of Λ_b and other b baryons is expected to be yet greater because of the lack of helicity suppression in "internal W" spectator decays. The predicted[2] relationships are:

$$\tau(B^+) = (1.06 \pm 0.02) \cdot \tau(B^0) \tag{1}$$

$$\tau(B_s^0) = (1.01 \pm 0.01) \cdot \tau(B^0) \tag{2}$$

$$\tau(\Lambda_b^0) = (0.85 \pm 0.05) \cdot \tau(B^0) \tag{3}$$

Given precise predictions of lifetimes and branching fractions, deviations provide indication of new physics. Measurements of B lifetimes that are significantly shorter than predictions would indicate that additional processes—perhaps beyond the standard model (SM)—participate in the decays. Similarly, for rare decays of order 10^{-8} or less with final states that cannot be reached by tree-level diagrams in the SM, branching ratios significantly greater than predicted would indicate the presence of new physics.

B physics at the Tevatron benefits from large signals—the b hadron cross section for the central region of order $100\,\mu$b—but must contend with large backgrounds arising from a total

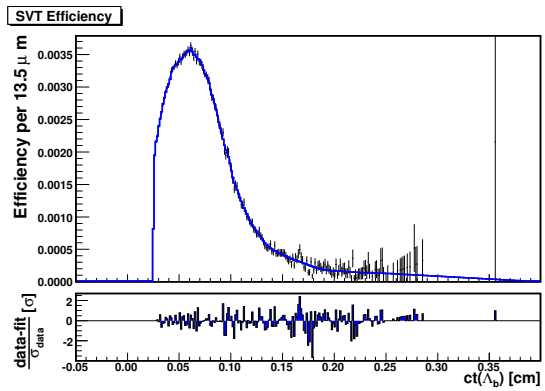

Figure 1: The efficiency as a function of the proper decay distance for $\Lambda_b \to \Lambda_c \pi^+$ decays in the CDF track-trigger sample. A typical b hadron decay distance is about 500 μm.

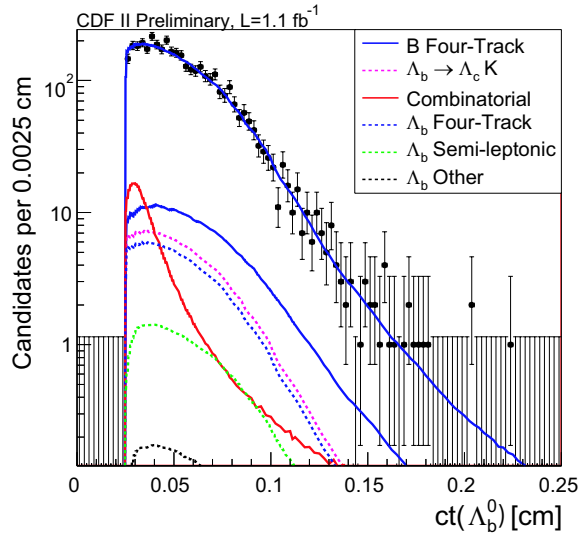

Figure 2: The proper decay distance for $\Lambda_b \to \Lambda_c \pi^+$ decays in the CDF track-trigger sample is shown with the result of the fit for the lifetime overlaid including the properly normalized background distributions used in the fit.

cross section of about 50 mb. The key to collecting events it is a trigger with good background rejection and high efficiency. Three signatures are used.

- Dimuons are extremely clean, especially in events that contain a $J/\psi \to \mu^+\mu^-$ decay. However, product branching ratios are typically of order 10^{-5}.
- Single muon triggers attempt to collect events from semileptonic decays. These samples are less pure, and lifetime measurement precision suffers from the missing momentum of the unreconstructed neutrino.
- CDF uses a fast processor system (SVT) to find pairs of tracks that are displaced from the beamline, a characteristic of decay products of the long-lived b hadrons. This sample has large yields of fully reconstructed events. The only drawback for the measurement of lifetimes is that it is necessary to account for the sculpting by the trigger of the decay-length distribution.

2 Lifetimes

2.1 Λ_b

CDF has measured[3] the lifetime of the lightest bottom baryon in a 1.1 fb^{-1} data sample using the decay mode[a] $\Lambda_b \to \Lambda_c \pi^+, \Lambda_c \to pK^-\pi^+$ and an SVT-based trigger selection that requires two charged particle tracks with impact parameters $120\mu\text{m} < d_0 < 1\text{mm}$ and opening angle $2^\circ < \Delta\phi < 90^\circ$ with an intersection distance from the beamline $L_{xy} > 200\mu\text{m}$ and kinematic cuts that vary according to running conditions. In order to determine the effect of the trigger on the decay-length distribution, the Monte Carlo simulation has been carefully tuned to match kinematic distributions in the data. The efficiency as a function of the proper decay distance is shown in Fig. 1. The event sample includes backgrounds from other bottom hadron decays as well as random combinations. The composition of the sample is determined by fitting the candidate mass distribution using template distributions for each component found from simulations.

[a] Unless explicitly stated otherwise, charge-conjugate modes are included in all decays modes discussed here.

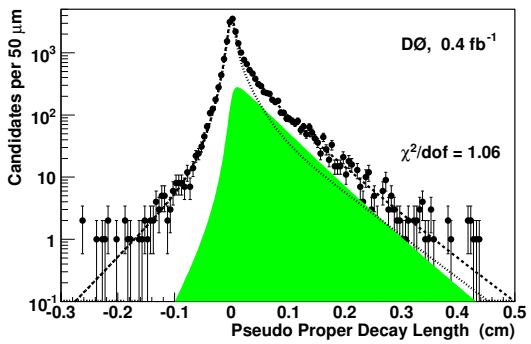

Figure 3: The decay-length distribution for $B_s^0 \to D_s^- \mu^+ X$ events from DØ. The dashed line shows the fit projection with the background distribution as the dotted line and the signal as the green filled area.

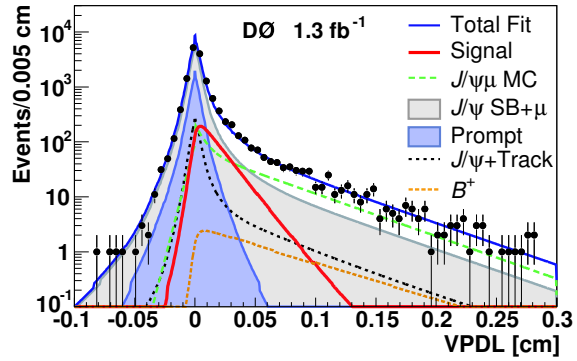

Figure 4: Distribution of the pseudo proper decay length for $B_c^+ \to J/\psi\, \mu^+$ candidates from DØ. The projections of the signal and background components of the lifetime fit are shown.

The signal yield is 2927 ± 58 events. The lifetime is fit from the proper decay-length ct distribution with components for the signal and the backgrounds. The background distributions are determined from simulations. The signal probability distribution function (PDF) is a convolution of an exponential, the ct resolution PDF, and the trigger efficiency distribution. The result of the fit is shown in Fig. 2. The mean decay length is found to be $c\tau = 422.8 \pm 13.3 \pm 8.8\mu$m where the systematic uncertainty is dominated by the trigger modeling. This result is as good as the previous world average[4] of $414.6 \pm 14.7\mu$m. While the new result is quite similar to the previous average, that average was dominated by results from CDF and DØ that had poor agreement among themselves. The ratio of lifetimes $\tau(\Lambda_b)/\tau(B^0) = 0.922 \pm 0.039$ is quite consistent with theoretical expectations.

2.2 B_s^0

CDF has measured the B_s lifetime[5] in a $1.3\,\mathrm{fb}^{-1}$ track-trigger sample using a similar method to that of the Λ_b. The sample includes ~ 1100 fully reconstructed events in the decay $B_s^0 \to D_s^- \pi^+, D_s^- \to \phi\pi^-$ and ~ 2200 partially reconstructed events in the modes $B_s^0 \to D_s^{*-}\pi^+$ and $B_s^0 \to D_s^- \rho^+$ where the photon (π^0) from the D_s^{*-} (ρ^+) decay is not detected. The mean decay length is $c\tau = 455.0 \pm 12.2 \pm 8.2\mu$m.

DØ has measured the lifetime[6] using the semileptonic decays $B_s^0 \to D_s^- \mu^+ X, D_s^- \to \phi\pi^-$ in a $0.4\,\mathrm{fb}^{-1}$ data sample. The measurement must account for missing neutrino momentum. The quantity $p_T(D_s\mu)/p_T(B_s)$ is known as the K-factor, where p_T is the component of momentum perpendicular to the beamline. The signal PDF is a convolution of an exponential, the K-factor distribution found in simulations, and a resolution function. The background PDF includes Gaussian and exponential terms. The fit actually uses the pseudo proper decay length $m(D_s\mu)L_{xy}/p_T(D_s\mu)$. The result of the fit is shown in Fig. 3. The measured lifetime is $c\tau = 419.1 \pm 13.2^{+8.4}_{-7.5}\mu$m where the systematic uncertainty is dominated by the background and resolution models and the K-factor distribution.

As a result of mixing, the flavor eigenstates B_s^0 and $\bar{B}_s^0$ are not mass eigenstates. Rather, they are the CP-even and CP-odd superpositions of the flavor eigenstates. By measuring the decay amplitudes of $B_s^0 \to J/\psi\,\phi, \phi \to K^+K^-$ decays in the transversity basis[7], it is possible to measure the separate lifetimes of the CP-even and CP-odd components. A description of the extraction of the amplitudes and measurement of the lifetime difference $\Delta\Gamma_s$ can be found elsewhere in these Proceedings[8]. Both CDF[9] and DØ[10] have measured the mean lifetime in their analyses. DØ finds $c\tau = 445.8 \pm 18.0 \pm 8.4\mu$m while CDF finds $c\tau = 459 \pm 12 \pm 3\mu$m. The

mean lifetime is insensitive to the value of $\Delta\Gamma_s$. Varying $\Delta\Gamma_s$ in the fit within the allowed range changes the value of $c\tau$ by much less than its statistical uncertainty.

2.3 B_c

CDF in a $1\,\mathrm{fb}^{-1}$ sample[11] and DØ in a $1.3\,\mathrm{fb}^{-1}$ sample[12] have both measured the lifetime of the B_c meson in the decay mode $B_c^+ \to J/\psi\,\ell^+X, J/\psi \to \mu^+\mu^-$ using similar techniques to those for the DØ measurement of the B_s lifetime in the semileptonic channel described above. The CDF measurement includes both the $J/\psi\,e$ and $J/\psi\,\mu$ channels, while DØ uses only $J/\psi\,\mu$ but benefits from substantially larger muon detector acceptance. The B_c measurement has the added complexity of a signal with a short lifetime that must be distinguished from both prompt backgrounds and those from light B meson decays. Fig. 4 shows the pseudo proper decay length distribution from DØ including the results of the fit with the signal and background distributions. CDF finds a mean lifetime $\tau = 0.475^{+0.053}_{-0.049}\pm0.018\,\mathrm{ps}$, and DØ measures $\tau = 0.448^{+0.038}_{-0.036}\pm0.032\,\mathrm{ps}$. The naïve mean of these two measurements is $0.460 \pm 0.036\,\mathrm{ps}$ which agrees well with the expectation for the B_c width $\Gamma(B_c) \simeq \Gamma(b) + \Gamma(c)$. With this 8% uncertainty, measurements of this heaviest of mesons are reaching a high level of precision.

3 Rare Decays

3.1 $B_s \to \mu^+\mu^-$

Flavor-changing neutral currents are forbidden in the SM at tree level. However, they can occur via diagrams with heavy particles in loops. Thus, measuring a branching ratio significantly greater than the SM prediction[13] $\mathcal{B}(B_s \to \mu^+\mu^-) = 3.5 \pm 0.5 \times 10^{-9}$ would be a strong indication of the existence of new physics. The same is true for $B_d \to \mu^+\mu^-$; however, in the latter case, the decay rate is suppressed by a CKM factor $|V_{td}/V_{ts}|^2$ giving a value of order 10^{-10}. The two Tevatron experiments use similar techniques. $B \to \mu\mu$ candidates are separated from background using a multivariate selection including kinematic, vertex quality and displacement and isolation quantities. DØ uses a likelihood ratio,[14] while CDF uses a neural network (NN).[15] Both normalize to the branching ratio $B^+ \to J/\psi\,K^+, J/\psi \to \mu^+\mu^-$ which has been measured[4] precisely at e^+e^- B factories and which has the two muons and other properties similar to the signal mode so systematic uncertainties cancel. Selecting on the dimuon mass, DØ finds three candidates in the signal region in a $2\,\mathrm{fb}^{-1}$ sample, and after estimating backgrounds from the mass sidebands, find a 95% confidence level limit $\mathcal{B}(B_s \to \mu^+\mu^-) < 9.8\times10^{-8}$. CDF constructs a signal region in the two-dimension distribution of $\mu\mu$ mass and NN output. The mass resolution is sufficient to construct distinct regions for B_s and B_d. In a $2\,\mathrm{fb}^{-1}$ sample, the CDF 95% CL upper limit for B_s is 5.8×10^{-8} and for B_d is 1.5×10^{-8}. Each of these is a world's best limit.

Results from both experiments should improve substantially in the near future. Each experiment now has accumulated $5\,\mathrm{fb}^{-1}$. In addition to the simple statistical scaling, the larger data set also allows the development of tighter selections, reducing the background. DØ also has improved sensitivity resulting from detector improvements that were included only for the last part of the data used in the measurement described above. Therefore, by the end of Run II, one may expect a combined limit from the two groups of order 10^{-8}. While the current measurement is just starting to exclude new physics scenarios, a limit of 10^{-8} would be quite restrictive. For example, it would exclude nearly all of the allowed region[16] for mSUGRA with $\tan\beta = 50$.

3.2 $B_{d,s} \to e^\pm\mu^\mp$

The charged-lepton flavor-violating decay $B \to e\mu$ is essentially forbidden in the SM. However, it can be allowed in various models of supersymetry, extra dimensions, or leptoquarks. CDF has

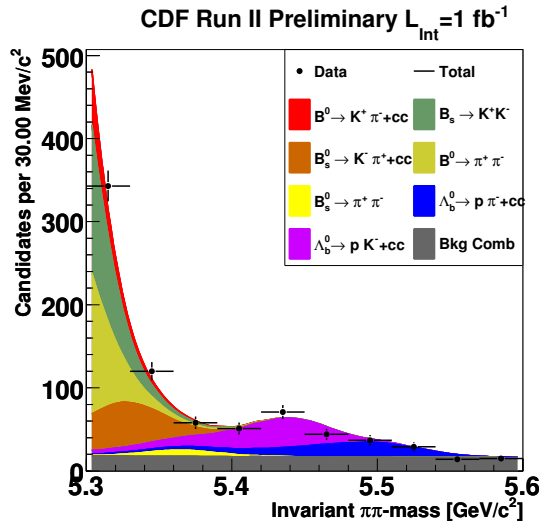

Figure 5: Projection on the two-particle mass of the fit for the yield of the various b hadron decay modes. A large peak for $B_{d,s}$ at lower mass has been suppressed

searched[17] for this decay in the first $2\,\mathrm{fb}^{-1}$ of Run II using the SVT track-trigger data sample with stringent lepton identification, candidate isolation, and decay vertex requirements. There is one candidates in the mass range consistent with a B_s meson and two consistent with B_d. The expected combinatorial background is less than one event for each. Using the yield of $B_d^0 \to K^+\pi^-$ found in the same sample with similar selections (except for lepton identification) as a reference, the 95% CL limits are $\mathcal{B}(B_s^0 \to e^\pm\mu^\mp) < 2.6 \times 10^{-7}$ and $\mathcal{B}(B_d^0 \to e^\pm\mu^\mp) < 7.9 \times 10^{-8}$ These limits can be interpreted a limits on the mass of Pati-Salam leptoquarks[18] as $M_{LQ} > 44\,\mathrm{TeV}/c^2$ and $M_{LQ} > 55\,\mathrm{TeV}/c^2$, respectively.

3.3 $\Lambda_b^0 \to pK^-, p\pi^-$

In a $1\,\mathrm{fb}^{-1}$ two-track trigger sample, CDF has studied charmless, two-body Λ_b decays,[19] measuring both branching ratios and CP asymmetries. The trigger selection is somewhat different from the multibody case used for the lifetime measurement, requiring two charged particle tracks with impact parameters $100\mu\mathrm{m} < d_0 < 1\mathrm{mm}$ and opening angle $20^\circ < \Delta\phi < 135^\circ$ with an intersection distance from the beamline $L_{xy} > 200\mu\mathrm{m}$ and kinematic cuts that vary according to running conditions. Furthermore, the impact parameter of trajectory of the two-track combination must within $140\,\mu\mathrm{m}$ of the beamline. In the analysis, the sample is purified with requirements on kinematic quantities, decay vertex reconstruction and pointing, and candidate isolation. In addition to the desired $\Lambda_b^0 \to pK^-$ or $p\pi^-$ signal and combinatorial background, the sample includes real two-body $B_{d,s} \to \pi^+\pi^-, K^\mp\pi^\pm$, and K^+K^- decays.

The mass of the two-particle combinations are found with the pion mass assigned to both tracks. Pairs with a mass $5.0 < m_{\pi\pi} < 5.8\,\mathrm{GeV}/c^2$ are retained for further analysis. The yields of the various decay modes are found using a likelihood fit that includes the pair mass, the signed momentum imbalance of the pair, and the measured ionization (dE/dx) of the two tracks. The momentum imbalance is defined as $\alpha = (1 - p_1/p_2)q_1$ where p_1 (p_2) is the momentum of the particle with lower (higher) momentum and q_1 is the charge of the lower momentum particle. This quantity helps to discriminate which of the decay products are not pions and in separating protons and anti-protons which is key to determining the CP asymmetry. The projection of the fit on the $\pi\pi$ mass axis is shown in Fig. 5. The figure includes only the high-side tail of interest for the Λ_b. The branching ratio is found by normalizing to the well-measured[4] mode

$B^0 \to K^-\pi^+$. The measured branching ratios are $\mathcal{B}(\Lambda_b^0 \to p\pi^-) = 3.5 \pm 0.6 \pm 0.9 \times 10^{-6}$ and $\mathcal{B}(\Lambda_b^0 \to pK^-) = 5.6 \pm 0.8 \pm 1.5 \times 10^{-6}$ where the fragmentation fraction f_Λ/f_d taken from LEP data[4] has been used. If the value measured in a CDF analysis[20] is used, the results are about a factor of 2 lower. This result excludes some MSSM models[21] that predict values of order 10^{-4}

Because of the large difference between the proton and kaon or pion masses, the momentum imbalance distinguishes on a statistical basis between $\Lambda_b^0 \to ph^-$ and $\bar{\Lambda}_b^0 \to \bar{p}h^+$ decays where h refers to a pion or kaon. By measuring the separate particle and anti-particle yields, it is possible to determine the asymmetry:

$$A_{CP}(\Lambda_b^0 \to ph^-) \equiv \frac{\mathcal{B}(\Lambda_b^0 \to ph^-) - \mathcal{B}(\bar{\Lambda}_b^0 \to \bar{p}h^+)}{\mathcal{B}(\Lambda_b^0 \to ph^-) + \mathcal{B}(\bar{\Lambda}_b^0 \to \bar{p}h^+)}. \tag{4}$$

CDF finds $A_{CP}(\Lambda_b^0 \to p\pi^-) = 0.03 \pm 0.17 \pm 0.05$ and $A_{CP}(\Lambda_b^0 \to pK^-) = 0.37 \pm 0.17 \pm 0.03$. These results are consistent with SM predictions of ~ 0.3.

4 Conclusions

With versatile detectors and large datasets, CDF and DØ have begun to make precision measurements of the properties of B_s, B_c, and Λ_b particles. These results exclude many possible models for physics beyond the standard model. The results presented at this meeting were based on samples of 1-2 fb^{-1}. CDF and DØ each have samples of of about 5 fb^{-1} already collected and continue to accumulate about 50 pb^{-1} per week, so much more stringent results can be expected in the near future.

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