Measurement of the production fraction times branching fraction f(b→Λ_{b})·B(Λ_{b}→J/ψΛ)

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Measurement of the production fraction times branching fraction $f(b \to \Lambda_b) \cdot \mathcal{B}(\Lambda_b \to J/\psi \Lambda)$

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The $\Lambda_b(udb)$ baryon is observed in the decay $\Lambda_b \to J/\psi\Lambda$ using 6.1 fb^{-1} of $p\bar{p}$ collisions collected with the D0 detector at $\sqrt{s} = 1.96$ TeV. The production fraction multiplied by the branching fraction for this decay relative to that for the decay $B^0 \to J/\psi K^0_s$ is measured to be 0.345 ± 0.034 (stat.) $\pm$ 0.033 (syst.) $\pm$ 0.003 (PDG). Using the world average value of $f(b \to B^0) \cdot \mathcal{B}(B^0 \to J/\psi K^0_s) = (1.74 \pm 0.08) \times 10^{-5}$, we obtain $f(b \to \Lambda_b) \cdot \mathcal{B}(\Lambda_b \to J/\psi\Lambda) = (6.01 \pm 0.60$ (stat.) $\pm$ 0.58 (syst.) $\pm$ 0.28 (PDG)$) \times 10^{-5}$. This measurement represents an improvement in precision by about a factor of three with respect to the current world average.

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The study of b hadron decays, in particular $b \to s$ decays, offers good opportunities to search for physics beyond the standard model (BSM). For this reason, these decays have been the subject of intensive experimental [1–6] and theoretical [7–9] work. Studies of b baryons at the Fermilab Tevatron Collider and the CERN Large Hadron Collider are a natural extension of these studies which have been mostly performed on B mesons [10–13]. The experimental knowledge of b baryons is currently limited [14]. For the $\Lambda_b(udb)$, the lightest b baryon, only a few decay channels have been studied, and the uncertainties on its branching fractions are large $\sim$(30–60)%. For higher mass b baryon states, even less information is available. Due to its relative abundance, the Λ_b baryon has been used to investigate production and decay properties of heavier b baryons, to search for possible polarization effects [15], for violation of discrete symmetries in the decay (CP [16] and T [17] violation), and to search for BSM effects [18]. There are several models (PQCD [19], relativistic and non-relativistic quark models based on factorization aproximations [20–25] are examples) to describe b baryon decays such as $\Lambda_b \to J/\psi\Lambda$. Increasingly precise measurements of $f(b \to \Lambda_b) \cdot \mathcal{B}(\Lambda_b \to J/\psi\Lambda)$ (where $f(b \to \Lambda_b)$ is the fraction of b quarks which hadronize to Λ_b baryons) will allow better tests of these models. Moreover, these measurements could help in the study of $b \to s$ decays such as $\Lambda_b \to \mu^+\mu^-\Lambda$ [26, 27], which are topologically similar to $\Lambda_b \to J/\psi\Lambda$, where

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J/ψ decays to dimuons.

This Letter reports an improved measurement with respect to the previous Tevatron result [28] of the production fraction multiplied by the branching fraction of the $\Lambda_b \to J/\psi\Lambda$ decay relative to that of the decay $B^0 \to J/\psi K_s^0$. From this measurement we can obtain $f(b \to \Lambda_b) \cdot \mathcal{B}(\Lambda_b \to J/\psi\Lambda)$ with significantly improved precision compared to the current world average [14]. The J/ψ, Λ, and K_s^0 are reconstructed in the $\mu^+\mu^-$, $p\pi^-$, and $\pi^+\pi^-$ modes, respectively. Throughout this Letter, the appearance of a specific charge state also implies its charge conjugate. The study is performed using 6.1 fb^{-1} of $p\bar{p}$ collisions collected with the D0 detector between 2002–2009 at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron Collider.

A detailed description of the D0 detector can be found in [29]. The components most relevant to this analysis are the central tracking system and the muon spectrometer. The central tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT) that are surrounded by a 2 T superconducting solenoid. The SMT is optimized for tracking and vertexing for the pseudorapidity region $|\eta| < 3.0$ (where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle), while the CFT has coverage for $|\eta| < 2.0$. Liquid-argon and uranium calorimeters in a central and two end-cap cryostats cover the pseudorapidity region $|\eta| < 4.2$. The muon spectrometer is located outside the calorimeter and covers $|\eta| < 2.0$. It comprises a layer of drift tubes and scintillator trigger counters in front of 1.8 T iron toroids followed by two similar layers after the toroids.

We closely follow the data selection for $J/\psi \to \mu^+\mu^-$, $\Lambda \to p\pi^-$ and $K_s^0 \to \pi^+\pi^-$ used in the measurement [30] of the ratio of the lifetimes, $\tau(\Lambda_b)/\tau(B^0)$, that used the same decay products of the Λ_b and B^0. Events satisfying muon or dimuon triggers are used. At least one $p\bar{p}$ interaction vertex must be identified in each event, determined by minimizing a χ^2 function that depends on all reconstructed tracks in the event and a term that represents the average beam position constraint. We begin by searching for $J/\psi \to \mu^+\mu^-$ decays reconstructed from two oppositely charged muons that have a common vertex with a χ^2 probability greater than 1%. Muons are identified by matching tracks reconstructed in the central tracking system with track segments in the muon spectrometer. The requirements of transverse momentum $p_T > 2.0$ GeV/c and $|\eta| < 2.0$ are imposed on these matched tracks, and each of them must be associated to at least two hits in the SMT and two hits in the CFT. In addition, at least one muon track must have segments in the muon system both inside and outside the toroid. The dimuon transverse momentum $p_T(\mu^+\mu^-)$ is required to be greater than 3.0 GeV/c, and its invariant mass $M_{\mu^+\mu^-}$ must be in the range $2.8 - 3.35$ GeV/c^2. In these dimuon events we search for $\Lambda \to p\pi^-$ and $K_s^0 \to \pi^+\pi^-$ candidates formed from two oppositely charged tracks with a common vertex with a χ^2 probability greater than 1% and invariant mass between $1.102 < M_\Lambda < 1.130$ GeV/c^2 and $0.466 < M_{K_S^0} < 0.530$ GeV/c^2. To reduce the contribution from fake vertices reconstructed from random track crossings, the two tracks are required to have at most two hits associated to them in the tracking detectors located between the reconstructed $p\bar{p}$ interaction vertex and the common two-track vertex. The impact parameter significance (the impact parameter with respect to the $p\bar{p}$ vertex divided by its uncertainty) for the tracks forming Λ or K_S^0 candidates must exceed 3 for both tracks and 4 for at least one of them. To reconstruct Λ candidates, the track with the higher p_T is assumed to be a proton. Monte Carlo studies show that this is always the correct assignment, given the track p_T detection threshold. To suppress contamination from cascade decays of more massive baryons such as $\Sigma^0 \to \Lambda\gamma$ and $\Xi^0 \to \Lambda\pi^0$, we require the cosine of the angle between the p_T of the Λ and the vector from the J/ψ vertex to the Λ decay vertex in the plane perpendicular to the beam direction to be larger than 0.999. For Λ candidates coming from Λ_b decays, the cosine of this angle is typically greater that 0.9999.

The Λ_b (B^0) is reconstructed by performing a constrained fit to a common vertex for the Λ (K_S^0) candidate and the two muon tracks, with the muons constrained to the nominal J/ψ mass of 3.097 GeV/c^2 [14]. The p_T of the Λ_b or B^0 candidate is required to be greater than 5 GeV/c. The invariant mass of the J/ψ and the two additional tracks is required to be within the range 5.0–6.2 GeV/c^2 for Λ_b candidates and within 4.8–5.8 GeV/c^2 for B^0 candidates.

To determine the final selection criteria, we maximize $N_S/\sqrt{N_S + N_B}$, where N_S is the number of signal (Λ_b or B^0) candidates determined by Monte Carlo and N_B is the number of background candidates estimated by using data events in the sidebands of the expected signal. For the Monte Carlo, we use PYTHIA [31] and EVTGEN [32] for the production and decay of the simulated particles, respectively, and GEANT3 [33] to simulate detector effects. As a result of this optimization, for the Λ (K_S^0) we require the transverse decay length to be greater than 0.8 (0.4) cm, the p_T to be greater than 1.6 (1.0) GeV/c and the significance of its transverse proper decay length (transverse decay length corrected by the boost in the transverse plane) to be greater than 4.0 (9.0). For the Λ_b (B^0) candidate, the significance of the proper decay length is required to be greater than 2.0 (3.0). In addition, the Λ_b and B^0 vertices must be well reconstructed.

A track pair can be simultaneously identified as both Λ and K_S^0 due to different mass assignments to the same tracks. Events containing such track pair ambiguities are removed. Finally, if more than one candidate is found in the event, the candidate with the best vertex χ^2 probability is selected as the Λ_b (B^0).

The invariant mass distributions of the final Λ_b and B^0 candidates passing our selection criteria are shown in Fig. 1. To extract the yields of the observed Λ_b and B^0 hadrons, we perform an unbinned likelihood fit to each mass distribution assuming a double Gaussian function

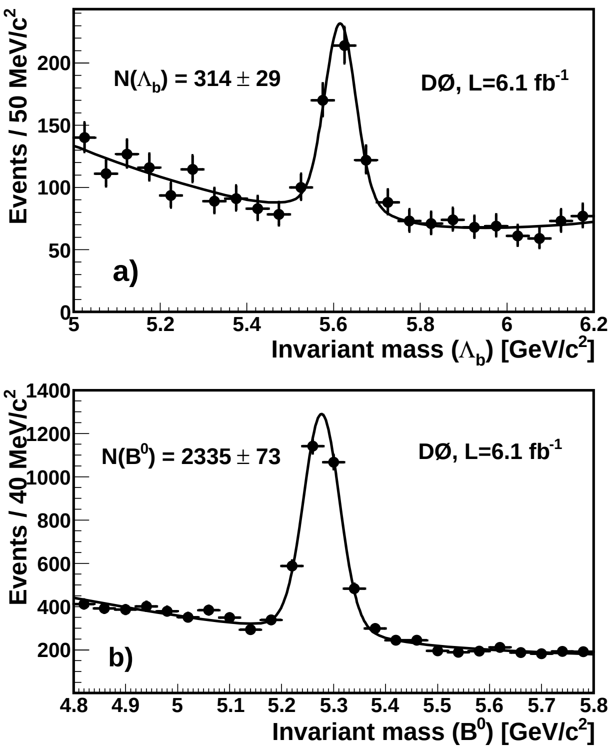

FIG. 1: Invariant mass distribution in data for (a) $\Lambda_b \to J/\psi\Lambda$ and (b) $B^0 \to J/\psi K_s^0$ decays. Fit results are superimposed.

for signal and a second order polynomial distribution for background. The fits yield $N_{\Lambda_b \to J/\psi\Lambda} = 314 \pm 29$ events and $N_{B^0 \to J/\psi K_S^0} = 2335 \pm 73$ events.

The relative production fraction times branching fraction for $\Lambda_b \to J/\psi\Lambda$ decays to that of $B^0 \to J/\psi K_s^0$ decays is given by

$$\sigma_{\rm rel} \equiv \frac{f(b \to \Lambda_b) \cdot \mathcal{B}(\Lambda_b \to J/\psi\Lambda)}{f(b \to B^0) \cdot \mathcal{B}(B^0 \to J/\psi K_s^0)} = \frac{N_{\Lambda_b \to J/\psi\Lambda}}{N_{B^0 \to J/\psi K_S^0}} \cdot \frac{\mathcal{B}(K_s^0 \to \pi^+\pi^-)}{\mathcal{B}(\Lambda \to p\pi^-)} \cdot \epsilon. \qquad (1)$$

Here, $\epsilon = \epsilon_{B^0 \to J/\psi K_S^0}/\epsilon_{\Lambda_b \to J/\psi\Lambda}$ is the relative detection efficiency of $B^0 \to J/\psi K_S^0$ to $\Lambda_b \to J/\psi\Lambda$ decays. This relative efficiency is determined from Monte Carlo (MC) simulation to be $\epsilon = 2.37 \pm 0.05$ (MC stat.). Using $\mathcal{B}(K_s^0 \to \pi^+\pi^-) = 0.6920 \pm 0.0005$ and $\mathcal{B}(\Lambda \to p\pi^-) = 0.639 \pm 0.005$ [14], we obtain $\mathcal{B}(K_s^0 \to \pi^+\pi^-)/\mathcal{B}(\Lambda \to p\pi^-) = 1.083 \pm 0.009$. With these inputs and the reconstructed Λ_b and B^0 yields, the relative production fraction is found to be $\sigma_{\rm rel} = 0.345 \pm 0.034$ (stat.) $\pm$ 0.003 (PDG), where (PDG) denotes the uncertainty due to the inputs from [14].

The sources of systematic uncertainty on $\sigma_{\rm rel}$ are: (i) uncertainties in the determination of the Λ_b and B^0 yields, (ii) the determination of the relative efficiency ϵ, (iii) contamination from Λ_b in B^0 and conversely, and (iv) Λ_b polarization effects on the relative efficiency ϵ. Many other systematic uncertainties common to both $\Lambda_b \to J/\psi\Lambda$ and $B^0 \to J/\psi K_s^0$ decays, such as b quark production, integrated luminosity, trigger and selection efficiencies, cancel in the ratio. The models used for describing signal and background in data are varied, and the resulting changes in the Λ_b and B^0 yields introduce a maximum deviation of $\sigma_{\rm rel}$ from its central value of 5.5%, which is included as systematic uncertainty. The simulation used to estimate ϵ uses a phase space model in EVTGEN to decay Λ_b and B^0 particles. For B^0 decays we can also use the SVS_CP (Scalar-Vector-Scalar with CP violation) model [32]. When using this alternative model, we observe a deviation of 2.0% in $\sigma_{\rm rel}$. Given the similar topologies of the $\Lambda_b \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ and $B^0 \to J/\psi(\mu^+\mu^-)K_s^0(\pi^+\pi^-)$ decays, the Λ_b sample may be contaminated with B^0 events that pass the Λ_b selection, or vice versa. We quantify this effect in simulation and find a deviation of 2.3% in $\sigma_{\rm rel}$, which we include as a systematic uncertainty. Finally, the effect of the unknown polarization and decay parameters of the Λ_b baryon on the relative efficiency is studied following the formalism of [15, 34]. The main effect of the polarization is observed through Θ, the emission angle of the Λ baryon with respect to the polarization direction in the Λ_b rest frame. This angle follows the distribution $I(\Theta) \propto 1 + \alpha_{\Lambda_b} P_{\Lambda_b} \cos(\Theta)$, where α_{Λ_b} and P_{Λ_b} are the asymmetry parameter and polarization of the Λ_b baryon. We study the extreme cases $\alpha_{\Lambda_b} P_{\Lambda_b} = \pm 1$ in simulations. The maximum deviation found in $\sigma_{\rm rel}$ is 7.2%, which is included as a systematic uncertainty due to the unknown Λ_b polarization. All of these systematic uncertainties are combined assuming no correlations, giving a total systematic uncertainty of 9.6%.

We study the stability of the measurement by performing cross checks on the two main inputs to the computation of $\sigma_{\rm rel}$: the ratio between the numbers of observed Λ_b and B^0 candidates extracted from data and the relative efficiency determined from Monte Carlo. We investigate the possibility that the number of Λ_b and B^0 candidates is affected by time or kinematics dependent changes in the detection and selection efficiency. We divide the data in subsamples and determine the value of $\sigma_{\rm rel}$ in each individual subsample without observing any significant deviation from the measurement based on the full sample. We split the sample based on different data taking periods, in different p_T, η regions, Λ and K_S^0 decay lengths and also investigated differences between Λ_b and $\bar{\Lambda}_b$ rates. To test for any mismodeling of the detector efficiency that could affect the determination of $\sigma_{\rm rel}$, decay length distributions are compared between data and Monte Carlo, as well as proper decay length significance, χ^2 vertex distributions, and other variables used in the selection. In all these comparisons, the data and Monte Carlo distributions are found to be in good agreement. One such example is Fig. 2, which shows the proper decay length [35] distribution of K_S^0 candidates. As a final cross-check, lifetime measurements are performed for the Λ and K_S^0 with results in agreement with the world av-

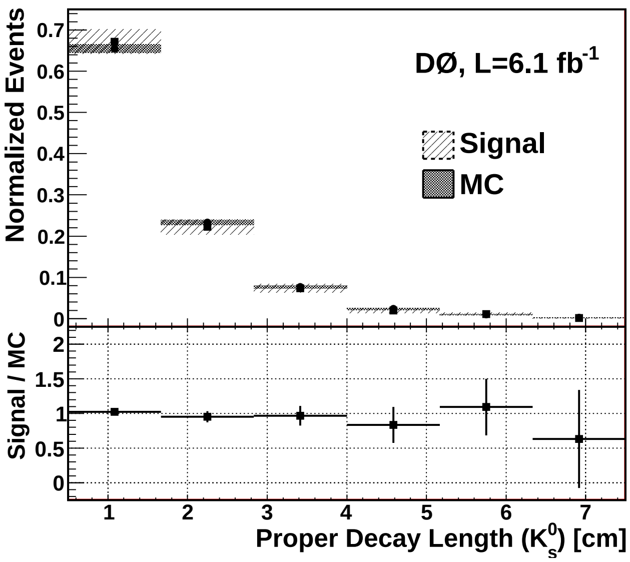

FIG. 2: Proper decay length distributions for K_s^0 candidates in the decay $B^0 \to J/\psi K_s^0$ for background subtracted signal compared to the full Monte Carlo (MC) simulation. The ratio Signal/MC is given in the bottom panel.

erage values [14].

In summary, using an integrated luminosity of 6.1 fb^{-1} collected with the D0 detector, we measure the production fraction multiplied by the branching fraction for the decay $\Lambda_b \to J/\psi\Lambda$ relative to that for the decay $B^0 \to J/\psi K_s^0$,

$$\sigma_{\rm rel} = 0.345 \pm 0.034 \text{ (stat.)} \\ \pm 0.033 \text{ (syst.)} \pm 0.003 \text{ (PDG)}. \tag{2}$$

Combining the uncertainties in quadrature, we obtain $\sigma_{\rm rel} = 0.345 \pm 0.047$. Our measurement is the most precise to date and exceeds the precision of the current value reported as the world average, 0.27 ± 0.13 [14]. Using the PDG value $f(b \to B^0) \cdot \mathcal{B}(B^0 \to J/\psi K_s^0) = (1.74 \pm 0.08) \times 10^{-4}$ (from [14]), we obtain

$$f(b \to \Lambda_b) \cdot \mathcal{B}(\Lambda_b \to J/\psi\Lambda) = \\ [6.01 \pm 0.60 \text{ (stat.)} \pm 0.58 \text{ (syst.)} \\ \pm 0.28 \text{ (PDG)}] \times 10^{-5} = (6.01 \pm 0.88) \times 10^{-5}, \tag{3}$$

which can be compared directly to the world average value of $(4.7 \pm 2.3) \times 10^{-5}$ [14]. This result represents a reduction by a factor of $\sim$3 of the uncertainty with respect to the previous measurement [28].

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