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Measurement of the $b\bar{b}$ Fraction in Hadronic Z Decays*

J. F. Kral,(1) G. S. Abrams,(1) C. E. Adolphsen,(2) D. Averill,(3)
J. Ballam,(4) B. C. Barish,(5) T. Barklow,(4) B. A. Barnett,(6) J. Bartelt,(4)
S. Bethke,(1) D. Blockus,(3) G. Bonvicini,(7) A. Boyarski,(4) B. Brabson,(3)
A. Breakstone,(8) F. Bulos,(4) P. R. Burchat,(2) D. L. Burke,(4) R. J. Cence,(8)
J. Chapman,(7) M. Chmeissani,(7) D. Cords,(4) D. P. Coupal,(4) P. Dauncey,(6)
H. C. DeStaebler,(4) D. E. Dorfan,(2) J. M. Dorfan,(4) D. C. Drewer,(6)
R. Elia,(4) G. J. Feldman,(4) D. Fernandes,(4) R. C. Field,(4) W. T. Ford,(9)
C. Fordham,(4) R. Frey,(7) D. Fujino,(4) K. K. Gan,(4) C. Gatto,(2) E. Gero,(7)
G. Gidal,(1) T. Glanzman,(4) G. Goldhaber,(1) J. J. Gomez Cadenas,(2)
G. Gratta,(2) G. Grindhammer,(4) P. Grosse-Wiesmann,(4) G. Hanson,(4)
R. Harr,(1) B. Harral,(6) F. A. Harris,(8) C. M. Hawkes,(5) K. Hayes,(4)
C. Hearty,(1) C. A. Heusch,(2) M. D. Hildreth,(4) T. Himel,(4)
D. A. Hinshaw,(9) S. J. Hong,(7) D. Hutchinson,(4) J. Hylen,(6)
W. R. Innes,(4) R. G. Jacobsen,(4) J. A. Jaros,(4) C. K. Jung,(4)
J. A. Kadyk,(1) J. Kent,(2) M. King,(2) S. R. Klein,(4) D. S. Koetke,(4)
S. Komamiya,(4) W. Koska,(7) L. A. Kowalski,(4) W. Kozanecki,(4)
M. Kuhlen,(5) L. Labarga,(2) A. J. Lankford,(4) R. R. Larsen,(4)
F. Le Diberder,(4) M. E. Levi,(1) A. M. Litke,(2) X. C. Lou,(3) V. Lüth,(4)
J. A. McKenna,(5) J. A. J. Matthews,(6) T. Mattison,(4) B. D. Milliken,(5)
K. C. Moffeit,(4) C. T. Munger,(4) W. N. Murray,(3) J. Nash,(4) H. Ogren,(3)
K. F. O'Shaughnessy,(4) S. I. Parker,(8) C. Peck,(5) M. L. Perl,(4)
M. Petradza,(4) R. Pitthan,(4) F. C. Porter,(5) P. Rankin,(9) K. Riles,(4)
F. R. Rouse,(4) D. R. Rust,(3) H. F. W. Sadrozinski,(2) M. W. Schaad,(1)
B. A. Schumm,(1) A. Seiden,(2) J. G. Smith,(9) A. Snyder,(3) E. Soderstrom,(5)
D. P. Stoker,(6) R. Stroynowski,(5) M. Swartz,(4) R. Thun,(7) G. H. Trilling,(1)
R. Van Kooten,(4) P. Voruganti,(4) S. R. Wagner,(4) S. Watson,(2)
P. Weber,(9) A. J. Weinstein,(5) A. J. Weir,(5) E. Wicklund,(5) M. Woods,(4)
D. Y. Wu,(5) M. Yurko,(3) C. Zaccardelli,(2) and C. von Zanthier(2)

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[1] *Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720*
[2] *University of California, Santa Cruz, California 95064*
[3] *Indiana University, Bloomington, Indiana 47405*
[4] *Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
[5] *California Institute of Technology, Pasadena, California 91125*
[6] *Johns Hopkins University, Baltimore, Maryland 21218*
[7] *University of Michigan, Ann Arbor, Michigan 48109*
[8] *University of Hawaii, Honolulu, Hawaii 96822*
[9] *University of Colorado, Boulder, Colorado 80309*

ABSTRACT

Using isolated leptons reconstructed in the Mark II detector to tag $b\bar{b}$ events, we measure the fraction of $b\bar{b}$ events in hadronic Z^0 decays to be $0.23^{+0.11}_{-0.09}$, in good agreement with the Standard Model prediction of 0.22. We find $\Gamma(Z \rightarrow b\bar{b}) = 0.43^{+0.21}_{-0.17}$ GeV.

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We measure the fraction of $b\bar{b}$ events in hadronic events produced through e^+e^- annihilation near the Z^0 peak.[1] The Standard Model[2] (SM) predicts that for five kinematically accessible quarks, this fraction $r_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to had)}$ is 0.22, considerably larger than 0.09, the predicted fraction of $b\bar{b}$ in hadronic events produced by the single photon exchange process which dominates e^+e^- annihilation at lower energies. The SM couplings are determined by the doublet structure of quarks which come in three generations, $\binom{u}{d}$, $\binom{c}{s}$ and $\binom{t}{b}$, with the upper (lower) members of the doublets having weak isospin $T_3 = +\frac{1}{2}$ $(-\frac{1}{2})$ and electrical charge $Q = +\frac{2}{3}$ $(-\frac{1}{3})$ units of the positron charge. We have seen no evidence for quarks heavier than the fifth, b, quark.[3] The rates of production of quarks from e^+e^- annihilation are proportional to the sums of the squares of vector and axial coupling constants. At tree level, single photon exchange has a vector coupling proportional to Q while Z^0 exchange has an axial coupling $a = 2T_3$ and a vector coupling $v = 2T_3 - 4Q\sin^2\theta_W$, where θ_W is the weak angle. Previous measurements of the b quark neutral current coupling constants have come from electroweak interference experiments,[4] which are more sensitive to a_b than v_b. We estimate the v_b coupling constant from the measured number of $b\bar{b}$ events in our data.

We extract r_b from a sample of $b\bar{b}$ events tagged with isolated leptons, defined to be leptons having high transverse momenta with respect to the nearest cluster formed by the other particles in the event. The larger rest mass of the b quark, compared to u, d, s and c ($udsc$) quark masses, results in higher transverse momenta of leptons in b jets than in $udsc$ jets. For this measurement we count the number of hadronic events observed and the number of these events that are tagged by an isolated lepton. We determine r_b from these numbers and the respective efficiencies for observing $udsc$ and $b\bar{b}$ events in the hadronic event sample as well as the tagged subsample. Our measurement of the number of produced $b\bar{b}$ events is then used to determine the width $\Gamma(Z \to b\bar{b})$, from which we derive v_b.

The data, taken with the Mark II detector at the SLAC Linear Collider, amount to 19.7 nb^{-1} over a small range of energies on either side of the Z^0 pole.[5] The detector has been described elsewhere,[6] and we indicate here the elements used for lepton identification. The momenta of charged particles are measured in the central drift chamber (DC) in the angular region $|\cos\theta| < 0.92$, where θ is the polar angle measured with respect to the beam axis. We identify electrons in the liquid argon barrel calorimeters (LA), which sample 14 radiation lengths of lead over a solid angle of 64% of 4π. Muons are identified over a solid angle of 45% of 4π after penetrating the iron hadron absorbers of the muon system, which has an outer instrumented layer of proportional tubes that is 7 interaction lengths from the center of the Mark II. There are four layers of tubes preceded by iron plates with thicknesses of 22 to 30 cm each.

We select hadronic events with seven or more charged tracks and a visible energy greater than 15% of the center-of-mass energy, E_{cm}. The visible energy is the sum of the energies from both the momentum measurements of charged particles and the energy measurements of neutral particles. Charged tracks in the DC are selected if they originate within a cylinder of radius 1 cm and length 6 cm along the beam axis, centered at the e^+e^- collision point. These tracks are used only if they are measured to have $|\cos\theta| < 0.85$, momenta transverse to the beam axis greater than 0.150 $\text{Ge}V/c$ and total momenta, p, less than the beam energy. Showers in the LA and endcap calorimeters are required to have an energy greater than 1 $\text{Ge}V$ and to satisfy $|\cos\theta| < 0.68$ in the LA and $0.70 < |\cos\theta| < 0.95$ in the endcaps. We do not include energy deposits which have been associated with a charged track if the energy of the shower corresponds to less than twice the momentum of the charged track.

These cuts select 413 hadronic events with efficiencies of 0.86 ± 0.02 for $udsc$ events and 0.88 ± 0.02 for $b\bar{b}$ events, according to Monte Carlo (MC) simulations with the Lund parton shower model with string fragmentation (JETSET 6.3 shower)[7] and the Webber-Marchesini parton shower model with cluster fragmentation (BIGWIG 4.1).[8] Throughout this analysis we use the average of the two models as the prediction to be compared with data, and we account for differences between the models in the systematic errors. Using other Monte Carlo simulations,[9] we estimate the numbers of events from non-hadronic Z^0 decays and two-photon interactions in the sample to be 0.04 and 0.01, respectively. All the generated MC events have been passed through a simulation of the trigger and the detector. To mimic the effect of beam induced backgrounds, we mix the signals from each MC event with the signals from one of many background events recorded at random beam crossings during the same time period as Z^0 candidates. We estimate that the number of events due to beam-gas interactions and cosmic rays in the sample is < 0.4, based on observing no events when we displace the center of the cylinder defined for the origin of charged tracks by more than its full length along the beam axis.

We tag $b\bar{b}$ event candidates in the hadronic event sample with isolated charged tracks identified as leptons. We define the transverse momentum of each track with respect to the nearest cluster formed by the other charged and neutral particles in the event, $p_t = p \sin\theta_j$, where θ_j is the angle between the track and the cluster (j) closest to the track. The Lund cluster algorithm is used to find the clusters.[10] We call a track isolated if it has $p_t > 1.25$ GeV/c.

For electron and muon identification, we consider all isolated charged tracks defined above which have momenta greater than 2 GeV/c and which point from the DC to either the LA calorimeter or the muon system.

Electrons are identified as having large energy deposits in all three orientations of strips in the front section of the LA calorimeter.[11] We have calibrated the identification algorithm on known electrons from Bhabha scattering recorded in the Mark II Upgrade detector at the PEP storage ring. We require each value $r_i = E_i/p$, where E_i is the energy deposit in a particular strip orientation of the front of the calorimeter and i = 1–3, to be at least 55% of the median value for the calibration electrons and $\sum r_i$ to be at least 65% of the median value for the sum. The energies E_i are calculated by adding the energies deposited in a narrow road around the DC track extrapolation, typically 2 strips (8 cm) wide. We find that with this algorithm, the efficiency for identifying isolated electron tracks pointing to the LA in hadronic events is 0.83 ± 0.05. The main source of contamination of the electron sample is a combination of interacting hadrons and overlapping neutral deposits. We simulate this background in our MC hadronic events by using signals from known pions in tau pair events, recorded with the Mark II detector at PEP. We determine that the probability is 0.007 ± 0.004 for isolated non-electron tracks to be identified as electrons. The p_t spectrum for tracks identified as electrons is shown in Fig. 1(a) together with predictions for the contributions from real electrons and hadrons misidentified as electrons.

Muons are selected by requiring hits in all four layers of the muon system within 3σ of the extrapolated DC track.[12] We use cosmic rays to calibrate σ, which depends on the expected amount of material traversed in each layer and the resolutions of the DC and the muon system. We also require correlated hits in the outer three layers of the muon system by demanding that the hit in the fourth layer be within a three standard deviation width of the path defined by the associated hits in the second and third layers. The width was determined from muon chamber signals recorded in muon pair events at PEP. Because it allows for a narrow search region in the fourth layer, this requirement is quite effective for reducing misidentification from beam-induced noise in the outer layers of the muon system. Isolated muons tracks pointing to the muon system in hadronic events are identified with an efficiency of 0.79 ± 0.05. Misidentification in the muon system comes from track overlap, noise hits and hadron punchthrough. Using tracks in the data which penetrate to the inner three layers, we determine hadron punchthrough probabilities to these layers. Our simulation of punchthrough to the fourth layer agrees with a detailed hadronic interaction simulation (FLUKA87)[13] which was found to describe well the punchthrough in hadronic events recorded with the Mark II detector at PEP. The estimated probability for identifying an isolated non-muon track as a muon is $0.006^{+0.006}_{-0.003}$. This probability does not include muons from π or K decays in flight, which are categorized as real muons. The p_t spectrum for tracks identified as muons is shown in Fig. 1(b) together with predictions for the contributions from real muons and hadrons misidentified as muons.

To determine the efficiencies for tagging $b\bar{b}$ and $udsc$ events with an isolated lepton, we use the Lund and Webber parton shower models whose parameters were optimized with hadronic events produced in e^+e^- annihilation at $E_{cm} = 29$ GeV using the Mark II detector at PEP.[14] We have modified the Lund model so that at the end of the shower process, typically at a mass of a few GeV/c^2, b and c quark fragmentation is parameterized by the Peterson function.[15] The MC simulation of uds events contains electrons and muons from π and K decays as well as electrons from photon conversions. The $c\bar{c}$ events contain leptons from semi-leptonic decays of charmed hadrons in addition to the above sources. Similarly, the additional sources of electrons and muons in $b\bar{b}$ events are from primary semi-leptonic decays of bottom hadrons and from secondary cascade decays via charmed hadrons or τ leptons. The simulation includes hadrons misidentified as leptons for events of all flavors. For this analysis, we take the branching fractions for primary B meson decay to electrons and muons to be 0.11 ± 0.01 each, where the error represents the precision of measurements of this quantity.[16]

We separate $b\bar{b}$ events from $udsc$ events by tagging events that have a high p_t track identified as a lepton. We assign a p_t value to each event containing an identified lepton, and, if an event contains more than one lepton track, we choose the highest p_t value. The overall efficiency for tagging produced $b\bar{b}$ events is 0.100 ± 0.012, resulting from the semi-leptonic branching ratios, the fiducial acceptance of the detector, the lepton identification efficiencies and the isolation cut,[17] $p_t > 1.25$ GeV/c. The cuts retain only a small fraction, $0.011^{+0.004}_{-0.003}$, of produced $udsc$ events.

Among the 413 hadronic events in the data, we observe 15 high p_t events, 9 tagged by electrons and 6 by muons. Figure 1(c) shows the observed p_t spectrum together with the expected quark flavor composition of events with a track identified as a lepton. Using the number of observed hadronic events and the number of tagged events, together with the hadronic event selection efficiencies and the isolated lepton tagging efficiencies described above, we solve for the $b\bar{b}$ fraction, obtaining $r_b = 0.23^{+0.10}_{-0.08}{}^{+0.05}_{-0.04} \pm 0.02$, where the errors are, in the order quoted, the statistical errors, the systematic errors from the uncertainties in the event efficiencies and the systematic error from the uncertainty in the B hadron semi-leptonic branching ratio.

With r_b equal to the SM value of 0.22, we predict a total of 14.7 events with $p_t > 1.25$ GeV/c for a data sample normalized to the number of hadronic events observed, with 9.0 (5.7) events tagged by electrons (muons). The prediction is the average of the prediction from the Lund (12.8) and Webber (16.7) models. Most of the tagged events are expected to be from $b\bar{b}$ events, with 6.3 (4.0) tagged as electrons (muons), 4.5 (3.6) of which come from primary B hadron decays. The majority of the remaining expected events are due to 1.8 (1.0) hadrons misidentified as electrons (muons). Thus, as shown in Fig. 1(c), our measurements are in agreement with the SM predictions.

We extend the measurement of r_b to a measurement of the $b\bar{b}$ partial width and coupling constants, $\Gamma(Z \rightarrow b\bar{b}) \propto a_b^2 + v_b^2$, using the number of produced $b\bar{b}$ events. We calculate $\Gamma(Z \rightarrow b\bar{b})$ from the measured values of the integrated luminosity[5] and the Z^0 resonance line shape formulas listed in Reference 18. Recently measured values for the mass and width of the Z^0, $M_Z = 91.10 \pm 0.05$ GeV/c^2 and $\Gamma_Z = 2.58 \pm 0.08$ GeV are used[19] as well as the SM values for the e^+e^- couplings. We find $\Gamma(Z \rightarrow b\bar{b}) = 0.43^{+0.18}_{-0.15}{}^{+0.10}_{-0.08}$ GeV, where the second error is the systematic error dominated by the uncertainties in the number of produced $b\bar{b}$ events. The measured partial width is in good agreement with the SM width $\Gamma(Z \rightarrow b\bar{b}) = 0.38$ GeV. To estimate v_b, we set the axial coupling constant equal to its SM value, $a_b = -1$, as suggested by measurements[4] at lower E_{cm}, and arrive at $v_b^2 = 0.66^{+0.69}_{-0.59}{}^{+0.40}_{-0.31}$. Our measured value is consistent with the SM value of $v_b^2 = 0.48$. The experimental value of v_b from electroweak interference experiments at lower E_{cm} is $v_b = -0.35 \pm 0.95$, obtained from a fit to data from many experiments.[20]

In summary, we have measured the fraction of $b\bar{b}$ events in hadronic events produced near the Z^0 peak to be $0.23^{+0.11}_{-0.09}$, in good agreement with the Standard Model value for Z^0 decays to five quarks. We have estimated the Z^0 vector coupling to b quarks, $v_b^2 = 0.66^{+0.80}_{-0.67}$, from our measurement of the partial width $\Gamma(Z \rightarrow b\bar{b}) = 0.43^{+0.21}_{-0.17}$ GeV.

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FIGURE CAPTION

FIG. 1. The p_t spectra for tracks identified as (a) electrons and (b) muons. The shaded and unshaded regions show the expected contributions from real leptons and hadrons misidentified as leptons, respectively. (c) The p_t distribution for leptons ($e^{\pm}$ or $\mu^{\pm}$) with one entry per event. The shaded region is the expected contribution from $b\bar{b}$ events with real leptons. Also indicated are the contributions from $c\bar{c}$ and uds events, as well as events tagged by hadrons misidentified as leptons. The prediction for the number of events with $p_t > 5.0$ GeV/c is 1.1. We observe one such event with $p_t = 14.8$ GeV/c, consistent with a $b\bar{b}$ event in the tail of the p_t distribution. The above predictions come from Monte Carlo simulations. They are normalized to 413 observed events and assume $r_b = 0.22$.