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

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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 $\Gamma(Z \to b\bar{b}) = 0.43^{+0.21}_{-0.17}$ 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 $r_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{had})$ 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. The rates of production of quarks from e^+e^- annihilation are proportional to the sums of the squares of vector and axial-vector coupling constants. At tree level, single-photon exchange has a vector coupling proportional to Q while Z^0 exchange has an axial-vector coupling $a = 2T_3$ and a vector coupling $v = 2T_3 - 4Q\sin^2\theta_W$, where θ_W is the weak angle. Using the measured number of produced $b\bar{b}$ events in our data, we determine the width $\Gamma(Z \to b\bar{b})$ and estimate the neutral-current vector coupling constant v_b.

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 relatively large mass of the b quark 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 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.

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.[3] The detector has been described elsewhere,[4] 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 contain 14 radiation lengths of lead over a solid angle of 64% of 4π. They are arranged in alternating layers of lead sheets and lead strips, whose orientations can be along the beam axis, perpendicular to it, or at 45° to it. Groups of layers with the same strip orientation are ganged together to form readout channels. Muons are identified over 45% of 4π after penetrating through iron absorbers to the outer layer of proportional tubes which is separated from the center of the Mark II detector by 7 interaction lengths. There are a total of four layers of tubes preceded by iron plates with thicknesses of 22–30 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 $E_{\text{c.m.}}$. 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 a 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 GeV/c, and total momenta p less than the beam energy. Showers in the LA and end-cap calorimeters are required to have an energy greater than 1 GeV and to satisfy $|\cos\theta| < 0.68$ in the LA and $0.70 < |\cos\theta| < 0.95$ in the end caps. 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. The corresponding efficiencies are estimated by Monte Carlo (MC) simulations based on the Lund parton-shower model with string fragmentation (JETSET 6.3 shower)[5] and the Webber-Marchesini parton-shower model with cluster fragmentation (BIGWIG 4.1).[6] We use the average of the two models as the prediction to be compared with data, and account for differences between them in the systematic errors. The resulting efficiencies are 0.86 ± 0.02 for detecting produced *udsc* events and 0.88 ± 0.02 for produced $b\bar{b}$ events. Using other Monte Carlo simulations,[7] we estimate the numbers of events from nonhadronic 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.[8] 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.[9] We have calibrated the identification algorithm on known electrons from Bhabha scattering recorded in the Mark II Upgrade detector at the SLAC storage ring PEP. We require each value $r_i = E_i/p$, where E_i is the energy deposit in a particular strip orientation of the front half 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 two strips (8 cm) wide. Our 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 represent this background in our MC hadronic events by combining signals from pions in τ-pair events recorded at PEP with simulations of electron-photon cascades (EGS4).[10] The probability for isolated nonelectron tracks to be misidentified as electrons is 0.007 ± 0.004. 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.[11] 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

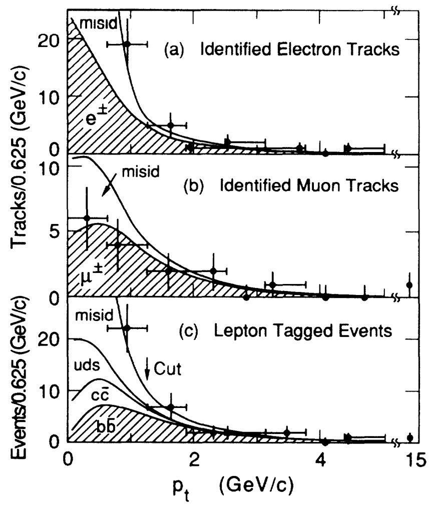

FIG. 1. The p_t spectra for tracks identified as (a) electrons and (b) muons. The shaded and unshaded regions show the expected contributions from real leptons and hadrons misidentified as leptons, respectively. (c) The p_t distribution for leptons ($e^\pm$ or $\mu^\pm$) with one entry per event. The 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. These predictions come from Monte Carlo simulations normalized to 413 observed events, assuming $r_b=0.22$.

hit in the fourth layer be within a 3-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 muon tracks pointing to the muon system in hadronic events are identified with an efficiency of 0.79 ± 0.05. Misidentification comes from track overlap, noise hits, and hadron punch through. Using tracks which penetrate to the inner three layers, we determine hadron punch-through probabilities to these layers. Our simulation of punch through to the fourth layer agrees with a detailed hadronic interaction simulation (FLUKA87)[12] which was found to describe well the punch through in hadronic events recorded with the Mark II detector at PEP. The estimated probability for misidentifying an isolated non-muon track as a muon is $0.006^{+0.006}_{-0.003}$, not including 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 $E_{\text{c.m.}}=29$ GeV using the Mark II detector at PEP.[13] We have modified the Lund model so that at the end of the shower process, b- and c-quark fragmentation are parametrized by the Peterson function.[14] 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 also contain leptons from semileptonic decays of charmed hadrons. Similarly, the additional sources of electrons and muons in $b\bar{b}$ events are from primary semileptonic 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. We take the branching fraction[15] for primary B-meson decay to electrons or muons to be 0.11 ± 0.01.

To separate $b\bar{b}$ events from *udsc* events, 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 semileptonic branching ratios, the fiducial acceptance of the detector, the lepton identification efficiencies, and the isolation cut[16] $p_t>1.25$ 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. The SM prediction is 14.7 tagged events, with 10.3 events expected from $b\bar{b}$ events containing real leptons. 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. From the observed numbers of hadronic events and tagged events, together with the efficiencies described above, we construct two equations to be solved for the unknown *udsc* and $b\bar{b}$ populations. The resulting value of $r_b=0.23^{+0.10}_{-0.08}{}^{+0.05}_{-0.04}\pm0.02$, where the errors are, in the order quoted, the statistical errors, the systematic errors from uncertainties in the event efficiencies, and the systematic error from the uncertainty in the B semileptonic branching ratio. As shown in Fig. 1, our measurements are in good agreement with the SM predictions.

We determine the $b\bar{b}$ partial width and coupling constants, $\Gamma(Z\to b\bar{b})\propto a_b^2+v_b^2$, from the number of produced $b\bar{b}$ events, assuming the SM values for the e^+e^- couplings. We obtain the average $b\bar{b}$ cross section from our measured values of the luminosity.[3] From the Z^0 line-shape formula,[17] applied to our set of running energies, we find $\Gamma(Z\to b\bar{b})=0.43^{+0.18}_{-0.15}{}^{+0.10}_{-0.08}$ 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 $\Gamma(Z\to b\bar{b})=0.38$ GeV. To estimate v_b, we set the axial-vector coupling constant equal to its SM value $a_b=-1$, as suggested by measurements[18] at lower $E_{\text{c.m.}}$, and arrive at $v_b^2=0.66^{+0.69}_{-0.59}{}^{+0.40}_{-0.31}$, consistent with the SM value of 0.48. The experimental value of v_b from electroweak interference experiments at lower $E_{\rm c.m.}$ is $v_b = -0.35 \pm 0.95$, obtained from a fit to data from many experiments.[18]

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 $\Gamma(Z \to b\bar{b}) = 0.43^{+0.21}_{-0.17}$ GeV.

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