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Flavor-Specific Inclusive B Decays to Charm

CLEO Collaboration

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Abstract

We have measured the branching fractions for $B \to \bar{D}X$, $B \to DX$, and $B \to \bar{D}X\ell^+\nu$, where "B" is an average over B^0 and B^+, "D" is a sum over D^0 and D^+, and "$\bar{D}$" is a sum over $\bar{D}^0$ and D^-. From these results and some previously measured branching fractions, we obtain $\mathcal{B}(b \to c\bar{c}s) = (21.9 \pm 3.7)\%$, $\mathcal{B}(b \to sg) < 6.8\%$ @ 90% c.l, and $\mathcal{B}(D^0 \to K^-\pi^+) = (3.69 \pm 0.20)\%$. Implications for the "$B$ semileptonic decay problem" (measured branching fraction being below theoretical expectations) are discussed. The increase in the value of $\mathcal{B}(b \to c\bar{c}s)$ due to $B \to DX$ eliminates 40% of the discrepancy.

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I. INTRODUCTION

There has been a longstanding problem in heavy flavor physics of the measured B semileptonic decay branching fraction [1] being smaller than theoretical expectations [2,3]. One possible explanation [2] is a larger-than-expected flavor-changing neutral current (FCNC) contribution, due to new physics. Another [3] is an enhanced rate for $b \to c\bar{c}s'$ (s' denotes the weak isospin partner of c). An argument against an enhanced $b \to c\bar{c}s'$ rate is that it would conflict with the measured branching fraction for $B \to \bar{D}X$ plus $B \to DX$. That measurement relies on a knowledge of $\mathcal{B}(D^0 \to K^-\pi^+)$, however, and if that is in error, the measurement of the branching fraction of B to charm or anticharm will be also. We address all three issues by measuring the yields of the flavor-specific inclusive B decay processes $B \to DX$, $B \to \bar{D}X$, and $B \to \bar{D}X\ell^+\nu$ in a sample of $B\bar{B}$ events in which at least one B decays semileptonically. (Herein, "B" represents an average over B^0 and B^+, "D" a sum over D^0 and D^+, and "$\bar{D}$" a sum over $\bar{D}^0$ and D^- [4]. We use the term "upper vertex D" for a $\bar{D}$ produced from the charm quark from $W \to \bar{c}s$, and "lower vertex D" for a D produced from the charm quark from $b \to c$.)

These yields, and ratios among them, provide information on the above-mentioned issues as follows:

(i) The fraction of semileptonic B decays that proceed through $B \to \bar{D}X\ell^+\nu$, f_{SL}, differs from 100% only because of small contributions from $b \to u\ell\nu$ and $B \to D_s^- KX\ell^+\nu$ ("lower vertex D_s"). The measured fraction is inversely proportional to the assumed D absolute branching fraction (in our case $\mathcal{B}(D^0 \to K^-\pi^+)$) and scaling the yield to agree with expectations gives a new method to measure that branching fraction.

(ii) The fraction of all B decays that proceed through $B \to \bar{D}X$, f_{all}, differs from 100% because of $b \to u$ decays, lower vertex D_s, formation of $c\bar{c}$ bound states, formation of charmed baryons, and FCNC processes such as $b \to sg$, $b \to dg$, $b \to sq\bar{q}$, $b \to dq\bar{q}$ (which we will refer to collectively as "$b \to sg$"). As all processes except $b \to sg$ have been measured, the ratio f_{all}/f_{SL} provides a measurement of the branching fraction for $b \to sg$. By taking the ratio of f_{all} to f_{SL}, rather than just using f_{all}, we eliminate dependence on the $D^0 \to K^-\pi^+$ branching ratio, and reduce dependence on D detection efficiency.

(iii) The process $B \to DX$ proceeds via the the quark-level process $b \to c\bar{c}s'$, and thus the ratio of the yields for $B \to DX$ and $B \to \bar{D}X$, i.e., ratio of upper to lower vertex charm, provides information on the rate of that process relative to $b \to c\bar{u}d'$.

The typical inclusive B decay branching fraction measurement averages over B and $\bar{B}$ initial states for a given final state, and consequently averages over particle and antiparticle final states for a given initial state (B or $\bar{B}$), losing the flavor-specific information sought here. In 1987 CLEO developed a technique for measuring inclusive B decay branching fractions separately to particle and antiparticle final states, and applied it to inclusive kaon decays [5,6]. Here we apply similar techniques to inclusive charm decays.

The principle underlying the 1987 technique is that if one B from a $B\bar{B}$ pair from the $\Upsilon(4S)$ decays semileptonically, with a high momentum lepton, then the other decay products from that B will have substantial angular correlations with the lepton, tending to come off back-to-back to it, while the decay products from the other B have negligible angular correlations with the lepton. The lepton tags the flavor of its parent B, and thus also the other B (with a correction needed for mixing). By plotting the distribution in the angle between $D\ell^+$ (and $\bar{D}\ell^-$) pairs, and separately the distribution in the angle between $D\ell^-$ (and $\bar{D}\ell^+$) pairs, and extracting an isotropic component and a peaking component from each, yields are obtained for four processes: $B \to \bar{D}X\ell^+\nu$, $B \to DX\ell^+\nu$, $B \to \bar{D}X$, and $B \to DX$. Of these, $B \to DX\ell^+\nu$ should be zero.

For low D momenta, the technique just described loses statistical power and becomes sensitive to the shape assumed in fitting for the peaking component. (In the limit that the D momentum vanishes, the D–lepton angular correlation clearly contains no information.) Consequently, we have developed a second technique, based on charge correlations alone. We measure three yields: the number of $D\ell^-$ (and $\bar{D}\ell^+$) pairs, equal to the sum of $B \to \bar{D}X\ell^+\nu$ and $B \to DX$ yields in the lepton-tagged data sample; the number of $D\ell^+$ (and $\bar{D}\ell^-$) pairs, equal to the sum of $B \to DX\ell^+\nu$ and $B \to \bar{D}X$ yields in the lepton-tagged sample; and the number of D (and $\bar{D}$) mesons in an untagged sample, equal to the sum of $B \to \bar{D}X$ and $B \to DX$ yields in the untagged sample. Using the fact that the rate for $B \to DX\ell^+\nu$ vanishes, and scaling the last-mentioned yield by the ratio of the sizes of the tagged and untagged data samples, these yields give the yields for the other three processes: $B \to \bar{D}X\ell^+\nu$, $B \to \bar{D}X$, and $B \to DX$. Using a combination of the angular correlation and charge correlation techniques, we have obtained those three yields for the sum of D^0 and D^+ mesons.

II. PROCEDURES

The data were taken with the CLEO detector [7] at the Cornell Electron Storage Ring (CESR), and consist of 3.2 fb^{-1} on the Υ(4S) resonance and 1.6 fb^{-1} at a center-of-mass energy 60 MeV below the resonance. The on-resonance sample contains 3.3 million $B\bar{B}$ events and 10 million continuum events. The CLEO detector measures charged particles over 95% of 4π steradians with a system of cylindrical drift chambers. Its barrel and endcap CsI electromagnetic calorimeters cover 98% of 4π. Hadron identification is provided by specific ionization (dE/dx) measurements in the outermost drift chamber and by time-of-flight counters (ToF). Muons are identified by their ability to penetrate iron; electrons by dE/dx, comparison of track momentum with calorimeter cluster energy, and track/cluster position matching.

We select hadronic events containing at least 4 charged tracks. We require a value of the ratio of Fox-Wolfram parameters [8] $R_2 \equiv H_2/H_0 < 0.5$, to suppress continuum events. Events containing at least one lepton with momentum between 1.5 and 2.8 GeV/c and surviving a $\psi \to \ell^+\ell^-$ veto are scanned for D^0, D^+, and charge conjugates. (For the untagged sample, we drop the lepton requirement.) We detect D^0 and D^+ via the $K^-\pi^+$ and $K^-\pi^+\pi^+$ decay mode, respectively. Tracks used as candidate D decay products must have dE/dx and/or ToF values within 2σ of expectations for the particle assignment made (K or π). For $D^0 \to K^-\pi^+$, particle identification must rule out the $\bar{D}^0 \to \pi^-K^+$ option.

For candidate D's, we histogram the $K\pi$ ($K\pi\pi$) mass for four intervals in $\cos\theta_{D-\ell}$ and four intervals in D momentum, separately for the two charge correlations with the lepton. These 64 mass distributions are fit to double-Gaussian signal peaks and polynomial backgrounds, to extract D yields. These are corrected for detection efficiency, determined by Monte Carlo simulation augmented by studies of particle ID efficiency that use data (a sample of $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ events). We perform small subtractions for continuum background (using below-Υ(4S)-resonance data) and for hadrons misidentified as leptons (using hadrons in place of leptons and weighting by the "faking probability"). Small corrections are made to the D^0 yields for the singly-Cabibbo-suppressed decays $D^0/\bar{D}^0 \to K^-K^+$ and $D^0/\bar{D}^0 \to \pi^-\pi^+$ which combine with a single failure of particle ID to make satellite peaks, for the doubly-Cabibbo-suppressed decay $D^0 \to K^+\pi^-$ [9], and for double failures of particle ID, with π^-K^+ treated as $K^-\pi^+$. A small correction is made to D^+ yields for the decay $D_s^+ \to K^-K^+\pi^+$ with the K^+ misidentified as a π^+.

The D yields for each momentum interval, charge correlation, and D type, are histogrammed vs. $\cos\theta_{D-\ell}$, 16 distributions in all. For the high D momentum intervals 1.3 – 1.95 and 1.95 –2.6 GeV/c, we fit the $\ell^- D$ angular distributions to an isotropic component and a backward-peaking component, with fitting functions obtained from Monte Carlo simulation. We fit the $\ell^+ D$ angular distributions to an isotropic component alone. For the low D momentum intervals 0.0 – 0.65 and 0.65 – 1.3 GeV/c, we use the charge correlation technique, summing over $\cos\theta_{D-\ell}$. We sum the yields so obtained over D momentum intervals, and over charged and neutral D's, correcting for D^0 and $D^\pm$ branching fractions, using $\mathcal{B}(D^0 \to K^-\pi^+) = 3.91\%$ [10], and $\mathcal{B}(D^+ \to K^-\pi^+\pi^+)/\mathcal{B}(D^0 \to K^-\pi^+) = 2.35$ [11]. We obtain yields for D and lepton from the same B, and from different B's, as follows. $N(D\ell^- + \bar{D}\ell^+, \mathrm{same}B) = (3.75 \pm 0.11) \times 10^5$, $N(D\ell^- + \bar{D}\ell^+$, different B's)$= (6.66 \pm 0.77) \times 10^4$, and $N(D\ell^+ + \bar{D}\ell^-$, different B's)$= (3.18 \pm 0.08) \times 10^5$, in a sample containing 4.24×10^5 leptons. For illustrative purposes, we show $\cos\theta_{D-\ell}$ distributions summed over momentum intervals and over D^0 and D^+, as Fig. 1. The $\ell^- D + \ell^+ \bar{D}$ distribution shows strong back-to-back peaking from $B \to \bar{D}X\ell^+\nu$, while the $\ell^-\bar{D} + \ell^+ D$ shows no such peaking, due to the nonexistence of $B \to DX\ell^+\nu$. One also notes a much larger isotropic component in $\ell^-\bar{D} + \ell^+ D$, because of the large rate for $B \to \bar{D}X$ and a small rate for $B \to DX$ (and a small rate for mixing $B^0 \to \bar{B}^0 \to DX$).

If the lepton and D come from the same B, then the lepton tags *that* B correctly. The lepton can't be from decay of D, because the D was *detected* via a hadronic decay mode. It can't be from ψ, because the rate for $B \to \psi\bar{D}X$ is negligible. If there are two D's from the same B, leptons from either will be below our 1.5 GeV/c momentum cut. If the B has mixed, nonetheless the lepton correctly tags the b flavor at the instant of decay, which is what is relevant for understanding the D from the same B. But, if the lepton and D come from different B's, then the tagging of *both* B's is now imperfect: the ancestor of the lepton because leptons from charm decay and leptons from ψ now contribute; and the ancestor of the D for those reasons and in addition because of $B^0 - \bar{B}^0$ mixing. Corrections are thus required when using the yields involving lepton and D from different B's. These corrections depend on f_m (the probability that a lepton mistags its ancestor B), and χ (the mixing parameter).

III. RESULTS AND INTERPRETATION

We extract three distinct pieces of physics from the three yields given above. For each, we have considered systematic errors due to uncertainties in each of the previously-mentioned corrections, uncertainties from fitting mass peaks and $\cos\theta_{D-\ell}$ distributions, and uncertainties in efficiency and D branching fractions.

(i) First consider $\Gamma(B \to DX)/\Gamma(B \to \bar{D}X)$, the ratio of "upper vertex" charm to "lower vertex" charm. This ratio U/L is obtained from $x = N(D\ell^- + \bar{D}\ell^+$, different B's$)/N(D\ell^+ + \bar{D}\ell^-$, different B's), by correcting for mixing and mistags. $U/L = (x - F_m)/(1 - xF_m)$, where $F_m = (f_m + f')/(2 - f_m - f')$, and $f' = f_m + \chi - 2f_m\chi$. We use $\chi = 0.157$ as measured by CLEO with dileptons [12], and $f_m = 0.027$ as found there, thereby achieving cancellation of some systematic errors in F_m, giving $F_m = 0.112 \pm 0.011$. From the yields given above, $x = 0.210 \pm 0.025$, leading to

$$\frac{\Gamma(B \to DX)}{\Gamma(B \to \bar{D}X)} = 0.100 \pm 0.026 \pm 0.016, \tag{1}$$

where the first error is statistical and the second is systematic, dominated by the uncertainties in mixing correction($\pm$ 0.012) and the $\cos\theta_{D-\ell}$ fitting function ($\pm$ 0.008). This result is surprisingly large, as conventional wisdom held that $b \to c\bar{c}s$ would hadronize dominantly into D_s. However, Buchalla *et al.* [3] have argued that the D^0, D^+ component should be substantial.

In Fig. 2 we plot the momentum distribution of these "upper vertex" D^0, D^+, obtained by applying the analysis just described to each of the four D momentum bins. The spectrum is softer than that for "lower vertex" D's, also shown. It is well described by 3-body $D^{(*)}D^{(*)}K^{(*)}$ phase space, if one allows one or two of the particles to be the vector states. CLEO has observed such decay modes [13].

(ii) Next consider the fraction of all B decays to $\bar{D}$, f_{all}, divided by the fraction of semileptonic B decays to $\bar{D}$, f_{SL}, i.e., the double-ratio of widths $\frac{\Gamma(B\to\bar{D}X)}{\Gamma(B\to all)}/\frac{\Gamma(B\to\bar{D}X\ell^+\nu)}{\Gamma(B\to X\ell^+\nu)}$. We obtain this from the ratio of yields $N(D\ell^+ + \bar{D}\ell^-$, different B's$)/N(D\ell^- + \bar{D}\ell^+, \text{same}B) \equiv z_{raw}$. Corrections are required to the "different B's" yield for mixing and mistags. Also, leptons from unvetoed ψ and from secondary decays ($3.3 \pm 0.7\%$ of all leptons) don't contribute to the peaking yield, and so a correction is required for that, leading to $z_{cor} = 0.967z_{raw}/[(1 - 0.5f_m - 0.5f')(1 + F_mU/L)]$, where $U/L = 0.100$, as found above. Applying all corrections, we have

$$\frac{\Gamma(B \to \bar{D}X)}{\Gamma(B \to all)}/\frac{\Gamma(B \to \bar{D}X\ell^+\nu)}{\Gamma(B \to X\ell^+\nu)} \equiv f_{all}/f_{SL} = 0.901 \pm 0.034 \pm 0.015. \tag{2}$$

One expects both f_{all} and f_{SL} to be close to 1.0. The first ratio will be less than 1.0 because of $b \to u$ transitions ($2|V_{ub}/V_{cb}|^2$, where the 2 is a phase space factor), lower vertex D_s (2%), bound $c\bar{c}$ states ($3.0 \pm 0.5\%$ [14]), baryons ($6.5 \pm 1.5\%$ [15]), and $b \to sg$ (to be extracted). The second ratio will be less than 1.0 because of $b \to u$ transitions ($3|V_{ub}/V_{cb}|^2$, enhanced by the 1.5 GeV/c lepton momentum requirement), and lower vertex D_s ($1.0 \pm 0.5\%$, suppressed by the lepton momentum requirement). These lead to

$$f_{all}/f_{SL} = 1.0 + |V_{ub}/V_{cb}|^2 - (0.010 \pm 0.005) - (0.030 \pm 0.005) - (0.065 \pm 0.015) - \mathcal{B}(b \to sg) \tag{3}$$

Here $b \to sg$ is symbolic for all FCNC processes. Using $|V_{ub}/V_{cb}|^2 = 0.008 \pm 0.003$, we obtain $\mathcal{B}(b \to sg) = (0.2 \pm 3.4 \pm 1.5 \pm 1.7)\%$, where the first error is statistical, the second systematic on z, and the third the uncertainties in Expression (3). From this we obtain an upper limit

$\mathcal{B}(b \to sg) < 6.8\%$, @ 90% C.L. The dominant components of the systematic error on z are from mixing ($\pm 1.2\%$) and unvetoed and secondary leptons ($\pm$ 0.6%).

(iii) Finally consider the fraction of semileptonic B decays to $\bar{D}^0$ or D^-, i.e., $f_{SL} \equiv \Gamma(B \to \bar{D}X\ell^+\nu)/\Gamma(B \to X\ell^+\nu)$. We obtain this fraction by dividing the yield $N(D\ell^- + \bar{D}\ell^+, \mathrm{same}B)$ by the number of leptons from B semileptonic decay, 96.7% of the total of 4.24×10^5 leptons in our sample. We find $0.914 \pm 0.027 \pm 0.042$. This number is inversely proportional to the value used for $\mathcal{B}(D^0 \to K^-\pi^+)$. The expected value of the ratio of widths is $\Gamma(B \to \bar{D}X\ell^+\nu)/\Gamma(B \to X\ell^+\nu) = 1.0 - 3|V_{ub}/V_{cb}|^2 - 0.010 \pm 0.005(\mathrm{for}\, \bar{B} \to D_s^+ K X \ell^- \nu)$. Taking $3|V_{ub}/V_{cb}|^2 = 0.023 \pm 0.008$, we find the expected ratio of widths to be 0.968 ± 0.010, differing from the measured value by one standard deviation. We set measured and expected values of the ratio equal to each other, and solve for the D^0 branching fraction, finding $\mathcal{B}(D^0 \to K^-\pi^+) = (3.69 \pm 0.11 \pm 0.16 \pm 0.04)\%$, where the first error is statistical, the second systematic in the measured ratio, and the third systematic in the predicted ratio. The dominant systematic errors are from uncertainties in D detection efficiency ($\pm$ 0.10%), mass peak fitting ($\pm$ 0.09%), and the ratio of D^+ to D^0 branching ratios ($\pm$ 0.08%). This value for the branching fraction, (3.69 $\pm$ 0.20)%, is to be compared with recent measurements by CLEO of (3.91 $\pm$ 0.19)% [10] and (3.81 $\pm$ 0.22)% [16], by ALEPH of (3.90 $\pm$ 0.15)% [17] and the PDG value of (3.83 $\pm$ 0.12)% [18].

IV. THE B SEMILEPTONIC DECAY BRANCHING FRACTION PROBLEM

In Table I we list all the components of B decay, give their branching fractions (based on measurement or theory), and see if they sum to 100%. We express some in terms of b_{SL}, the B semileptonic decay branching fraction, for which we use [1] (10.49 $\pm$ 0.46)%. The factor of 0.25 for $b \to (c \text{ or } u)\tau\nu$ is a phase space factor. The factor r_{ud} for $b \to (c \text{ or } u)ud'$ would be 3 from color counting, but with QCD corrections [19] is 4.0 $\pm$ 0.4. This analysis has two pieces of information to add to Table I. First, the upper vertex $\bar{D}^0, D^-$ contribution of (7.9 $\pm$ 2.2)% is obtained from our measured value of $\Gamma(B \to D^0 \,\mathrm{or}\, D^+ X)/\Gamma(B \to \bar{D}^0 \,\mathrm{or}\, D^- X)$ combined with the rate for inclusive $D^0 + D^+$ (63.6% + 23.5%) [20], and leads to a branching fraction for $b \to (c \,\mathrm{or}\, u)\bar{c}s'$ of (21.9 $\pm$ 3.7)%. Second, we have a value (with large errors) for the FCNC term. One sees that the upper vertex $\bar{D}^0, D^-$ contribution accounts for close to half of the shortfall of the sum of all modes from unity. The remaining shortfall is less than 2 standard deviations. If we adjust r_{ud} to bring the sum to 100%, we find $r_{ud} = 5.2 \pm 0.6$.

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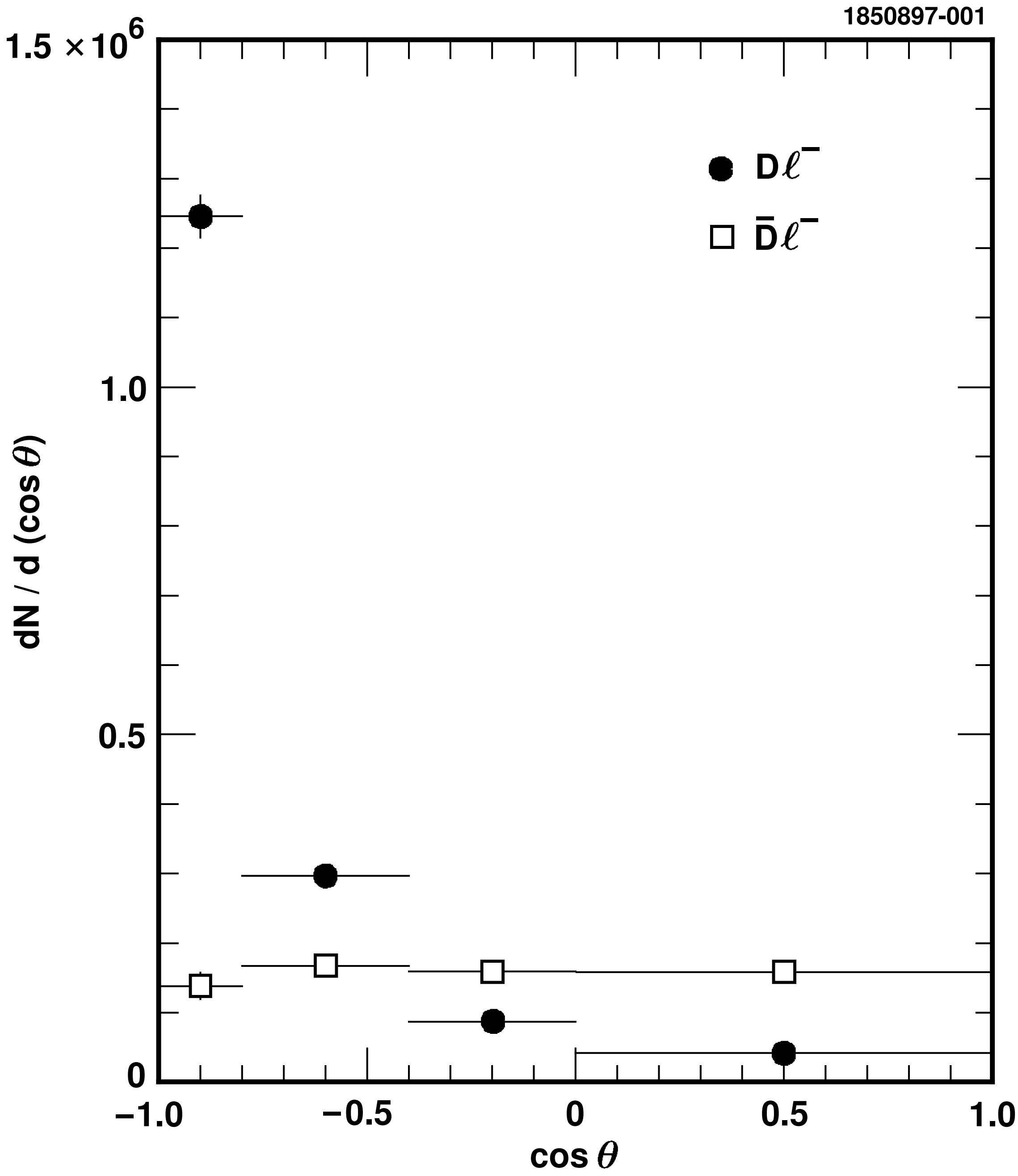

FIG. 1. Yield of $D\ell$ events vs $\cos\theta_{D-\ell}$. $D^0\ell^- + D^+\ell^-$ plus charge conjugate, summed over D momentum are shown as solid circles, while $\bar{D}^0\ell^- + D^-\ell^-$ plus charge conjugate, summed over D momentum are shown as open squares.

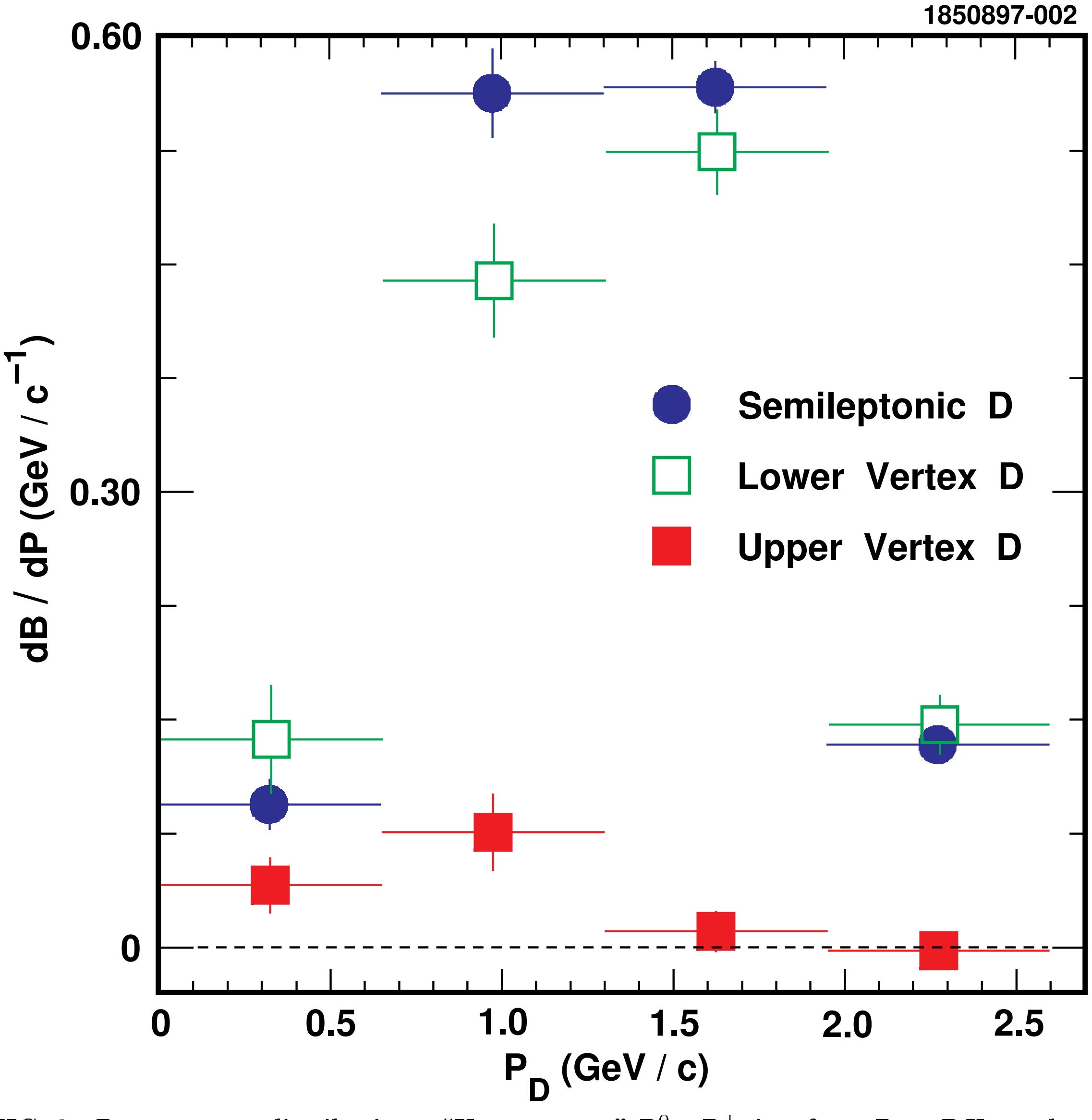

FIG. 2. D momentum distributions. "Upper vertex" D^0+D^+, i.e., from $B \to DX$ are shown as solid squares, while "lower vertex" D^0+D^+, from $\bar{B} \to DX$ are shown as open squares and "lower vertex" D^0+D^+, from $\bar{B} \to DX\ell\nu$ are shown as solid circles. Vertical scale gives branching fraction per unit momentum, for upper and lower vertex D's, and same divided by total semileptonic decay branching fraction for semileptonic D's.

TABLE I. All components of B decay, with their branching fractions. Upper vertex $\bar{D}^0$ and D^-, and $b \to s/d\ g$, $s/d\ q\bar{q}$, are from this analysis. The branching fractions for the separate components making up $b \to (c \text{ or } u)\ \bar{c}s'$ are shown parenthetically.

b decay modes		Branching fraction (%)	
$b \to (c \text{ or } u)\ e\nu$	b_{SL}		10.5 ± 0.5
$b \to (c \text{ or } u)\ \mu\nu$	b_{SL}		10.5 ± 0.5
$b \to (c \text{ or } u)\ \tau\nu$	$0.25b_{SL}$		2.6 ± 0.1
$b \to (c \text{ or } u)\ \bar{u}d'$	$r_{ud}b_{SL}$		$42.0 \pm 2.0 \pm 4.2$
$b \to (c \text{ or } u)\ \bar{c}s'$			21.9 ± 3.7
D_s		(10.0 ± 2.7)	
$(c\bar{c})$		(3.0 ± 0.5)	
baryons		(1.0 ± 0.6)	
upper vertex $\bar{D}^0, D^-$		(7.9 ± 2.2)	
$b \to s/d\ g,\ s/d\ q\bar{q}$			0.2 ± 4.1
TOTAL			87.7 ± 7.4