Comments on Recent Measurements of $R_c$ and $R_b$

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Abstract

Discrepancies between Standard Model predictions and experimental measurements of the fractions $R_c$ and $R_b$ of hadronic $Z$ decays to charm and bottom are investigated. We show that there exists a discrepancy in two complementary determinations of $B(\overline{B} \to DX)$. Reducing the branching ratio $B(D^0 \to K^-\pi^+)$ by $\sim 15\%$ from currently accepted values to $(3.50 \pm 0.21)\%$ removes the discrepancy. Since $B(D^0 \to K^-\pi^+)$ calibrates most charmed hadron yields, the reduced value also eliminates the discrepancy between the predicted and measured values of $R_c$ and mitigates a problem in semileptonic $B$ decays. A reduction in $B(D^0 \to K^-\pi^+)$ would also mean that roughly $15\%$ of all $D^0$ and $D^+$ decays have not been properly taken into account. It is shown that if the missing decay modes involve multiple charged particles, they would be more likely to pass the requirements for lifetime $B$ tagging at LEP and SLC. This would mean that the charm tagging efficiency in $Z \to c\overline{c}$ has been underestimated. As a consequence $R_b$ would need to be revised downward, potentially bringing it in line with the Standard Model prediction.
I. INTRODUCTION

Recent discrepancies between theoretical predictions and experimental measurements
of the fractions \( R_c \) and \( R_b \) of hadronic Z decays to charm and bottom \[1,2\] could have
very serious implications for the Standard Model. It is therefore extremely important to
determine whether or not there exist possible explanations for these discrepancies which do
not contradict the current paradigm. To this end we show in Section II that there now exist
two complementary determinations of \( B(\overline{B} \to DX) \). After making reasonable adjustments
to charmed baryon yields, we show that the two estimates disagree. We find that a 15%
reduction in \( B(D^0 \to K^-\pi^+) \) to \((3.50 \pm 0.21)\% \) eliminates the problem. We then proceed
to demonstrate that reducing \( B(D^0 \to K^-\pi^+) \) also eliminates the discrepancy between the
predicted and measured values of \( R_c \) and alleviates a problem in semileptonic \( B \) decays.
One further consequence of the change in \( B(D^0 \to K^-\pi^+) \) would be that roughly 15% of
all \( D^0 \) and \( D^+ \) decays have not been properly taken into account. In Section III we show
that if these missing decay modes involve multiple charged particles, they would be more
likely to pass the requirements for lifetime \( B \) tagging at LEP and SLC. In this case, the
charm tagging efficiency in \( Z \to c\bar{c} \) events would have been underestimated. This would
necessitate a downward revision in the measured value of \( R_b \) which would bring it closer
to the Standard Model prediction. The effect could in fact be large enough to completely
eliminate the \( R_b \) discrepancy.

*Throughout this note, CP violation is neglected and for each process its CP-conjugate is implied.
II. \( R_c \) MEASUREMENTS AND \( B(D^0 \to K^-\pi^+) \)

The fraction \( R_c \) of hadronic \( Z \) decays to charm, which is predicted to be 0.172 in the Standard Model, has recently been measured to be \( 0.1598 \pm 0.0069 \) \([1,2]\). Similarly, the number of charm quarks per \( B \) decay \( (n_c) \) was historically measured to be smaller than expected \([3]\), especially in view of the small measured inclusive semileptonic \( B \) decay branching ratio. Furthermore, the sum over all branching ratios of exclusive semileptonic \( B \) decays falls significantly short of the inclusive \( B(B \to X\ell\nu) \) measurements \([4]\).

One possible explanation for these discrepancies is that a systematic under-counting of charm has taken place. In particular, a common thread in these measurements is a significant reliance upon the measured value of \( B(D^0 \to K^-\pi^+) \) to calibrate charm production and decay for a wide range of observable decay modes. The CLEO experiment measures \([5]\)

\[
B(D^0 \to K^-\pi^+) = (3.91 \pm 0.19)\% ,
\]

and the 1994 Particle Data Group \([6]\) cites a world average of

\[
B(D^0 \to K^-\pi^+) = (4.01 \pm 0.14)\% .
\]

These calibrate not only the \( D^0 \) decay modes, but the \( D^+ \) decay modes as well \([7]\), via the ratio

\[
r_+ \equiv \frac{B(D^+ \to K^-\pi^+\pi^+)}{B(D^0 \to K^-\pi^+)} .
\]

The calibration mode for \( D_s \), namely \( B(D_s \to \phi\pi) \), has also recently been tied to \( B(D^0 \to K^-\pi^+) \) in a model-independent fashion \([8]\).

As a result of a recent measurement by CLEO \([9]\) of the wrong-charm production in flavor-tagged \( B \) decays, it is now possible to determine the right-charm branching fraction, \( B(B \to DX) \), in two complementary ways. As one important consequence, we can treat \( B(D^0 \to K^-\pi^+) \) as an unknown which is determined by equating the two results for \( B(B \to DX) \). This exercise is carried out in the next section after we address several concerns related to charmed baryon yields which result in an overall reduction in the estimate for weakly decaying charmed baryon production in \( B \) decays.
A. Inclusive D Yields in $\bar{B}$ Decays and $B(D^0 \to K^-\pi^+)$

The number of charmed hadrons per $B$ decay is defined as

$$n_c \equiv Y_D + Y_{D_s} + Y_{baryon_c} + 2B(\bar{B} \to (c\bar{c})X),$$

where the inclusive production of final states containing an arbitrary charmed hadron $T$ is defined by

$$Y_T \equiv B(\bar{B} \to TX) + B(\bar{B} \to \bar{T}X).$$

The weakly decaying, singly charmed baryon species ($\Lambda_c, \Xi_c^+, \Omega_c^0$) are collectively denoted by $baryon_c$ while $(c\bar{c})$ represents charmonia not seen as open charm. Table I summarizes CLEO measurements with the underlying calibration terms factored out explicitly. Note that the inclusive $D^+$ yield in $B$ decays involves $B(D^+ \to K^-\pi^+\pi^+)$ which is calibrated by $D^0 \to K^-\pi^+$ via the ratio,

$$r_+ \equiv \frac{B(D^+ \to K^-\pi^+\pi^+)}{B(D^0 \to K^-\pi^+)} = 2.35 \pm 0.23.$$

We can thus express $Y_{D^+}$ in terms of $B(D^0 \to K^-\pi^+)$ as

$$Y_{D^+} = \left(0.235 \pm 0.017\right) \frac{9.3\%}{B(D^+ \to K^-\pi^+\pi^+)} =$$

$$= \left(0.235 \pm 0.017\right) \frac{9.3\%}{r_+ \cdot B(D^0 \to K^-\pi^+)} =$$

$$= \left(0.238 \pm 0.029\right) \frac{3.91\%}{B(D^0 \to K^-\pi^+)}. \quad (2.4)$$

The inclusive $D$ yield in $\bar{B}$ decays,

$$Y_D \equiv Y_{D^0} + Y_{D^+},$$

can then be expressed in terms of $B(D^0 \to K^-\pi^+)$ as shown in Table I.

The central values for $\Xi_c$ and $\Lambda_c$ yields which are typically used in the determination of $n_c$ are both at the 5% level. The inclusive $\Lambda_c$ production in $B$ decays is measured rather well, whereas the $\Xi_c$ yield has large uncertainty. The CLEO experiment has demonstrated
that right-sign $\ell^+\Lambda_c$ correlations dominate over the wrong-sign $\ell^-\Lambda_c$ case [11], (where the lepton comes from the semileptonic decay of one $B$ and the $\Lambda_c$ originates from the other $B$ in an $\Upsilon(4S)$ event). As a consequence, inclusive $\Xi_c$ production in $B$ decays cannot be as large as that of the $\Lambda_c$. This is shown in the Appendix where we relate both $\Xi_c$ and $\Omega_c$ production in $B$ decays to $Y_{\Lambda_c}$ and the ratio

$$r_{\Lambda_c} \equiv \frac{B(B \rightarrow \Xi_c X)}{B(B \rightarrow \Lambda_c X)}.$$  

We neglect $b \rightarrow u$ transitions and use the Cabibbo suppression factor, $\theta^2 = (0.22)^2$, for charmed baryon production in $b \rightarrow c \bar{u} s (b \rightarrow c \bar{d} d)$ versus $b \rightarrow c \bar{u} d (b \rightarrow c \bar{s} s')$. [The prime indicates that the corresponding Cabibbo-suppressed mode is included.] The Appendix also parametrizes $s\bar{s}$ fragmentation from the vacuum, and predicts

$$\frac{Y_{\Xi_c}}{Y_{\Lambda_c}} = 0.38 \pm 0.10,$$  

$$\frac{Y_{baryon_c}}{Y_{\Lambda_c}} = 1.41 \pm 0.12,$$  

$$\frac{B(B \rightarrow baryon_c X)}{Y_{\Lambda_c}} = 1.22 \pm 0.07,$$  

$$\frac{B(B \rightarrow baryon_c X)}{Y_{\Lambda_c}} = 0.20 \pm 0.10.$$

As discussed in the Appendix, $\Xi_c$ production in $\overline{B}$ decay is probably overestimated. Inclusive $baryon_c$ production thus lies somewhere in the range

$$1 < \frac{Y_{baryon_c}}{Y_{\Lambda_c}} < 1.41 \pm 0.12.$$  

Variation over this range has negligible effect on the value of $n_c$. We therefore use the values given in Eqs. (2.7) - (2.10). We also prefer not to use the 1994 PDG value [3] of $B(\Lambda_c \rightarrow pK^-\pi^+) = (4.4 \pm 0.6)\%$, because it relies upon a flawed model of baryon production in $B$ decays. We instead follow the approach outlined in Ref. [12] and use $B(\Lambda_c \rightarrow pK^-\pi^+) = (6.0 \pm 1.5)\%$. Thus $n_c$ in Eq. (2.1) can be written:
\[ n_c = (0.883 \pm 0.038) \left[ \frac{3.91\%}{B(D^0 \to K^-\pi^+)} \right] + (0.1211 \pm 0.0096) \left[ \frac{3.5\%}{B(D_s \to \phi\pi)} \right] + \\
+ (0.042 \pm 0.008) \left[ \frac{6\%}{B(\Lambda_c \to pK^-\pi^+)} \right] + 2B(B \to (c\bar{c})X). \] (2.12)

Inserting the branching fractions in Table II and estimating \[ [13],
\]
\[ B(B \to (c\bar{c})X) = 0.026 \pm 0.004, \] (2.13)

one obtains
\[ n_c = 1.10 \pm 0.06 \] (2.14)

which is below the currently accepted value of 1.18 \( \pm 0.06 \) \[ [10].

Very recently, the CLEO experiment has completed the direct measurement of \( B(b \to c\bar{c}s') \) which allows one to use the following, alternative expression for the number of charm quarks per \( B \) decay \[ [13],
\]
\[ \hat{n}_c = 1 - B(b \to \text{no charm}) + B(b \to c\bar{c}s'). \] (2.15)

This expression is much less sensitive to either \( B(B \to \text{baryon}_cX) \) or \( B(D^0 \to K^-\pi^+) \). We take \( B(b \to \text{no charm}) \) to be \[ [13],
\]
\[ B(b \to \text{no charm}) = (0.25 \pm 0.10) \ (0.1049 \pm 0.0046) = \\
= 0.026 \pm 0.010. \] (2.16)

The inclusive wrong charm \( B \) decay branching fraction is expressed as \[ [13], [15]
\]
\[ B(b \to c\bar{c}s') = B(B \to \overline{D}X) + B(B \to D_\pi^0 X) + \\
+ B(B \to \overline{baryon}_c X) + B(B \to (c\bar{c})X). \] (2.17)

From Tables I and III, Eq. (2.17) and the charmed baryon correlations discussed in the Appendix, we thus obtain
\[ B(b \to c\bar{c}s') = (0.085 \pm 0.025) \left[ \frac{3.91\%}{B(D^0 \to K^-\pi^+)} \right] + \\
+ (0.100 \pm 0.012) \left[ \frac{3.5\%}{B(D_s \to \phi\pi)} \right] + (0.0059 \pm 0.0031) \left[ \frac{6\%}{B(\Lambda_c \to pK^-\pi^+)} \right] + \\
+ B(B \to (c\bar{c})X). \] (2.18)
Using the absolute charm branching fractions of Table II we obtain

\[ B(b \rightarrow c\bar{c}s') = 0.22 \pm 0.03 , \]  
(2.19)

\[ \tilde{n}_c = 1.19 \pm 0.03 . \]  
(2.20)

The quantities \( n_c \) and \( \tilde{n}_c \) must be equal. Their difference can be traced to a significant discrepancy in two alternative determinations of \( B(\mathcal{B} \rightarrow DX) \). On the one hand, one can write

\[ B(\mathcal{B} \rightarrow DX) = 1 - B(\mathcal{B} \rightarrow \text{no charm}) - B(\mathcal{B} \rightarrow D_s^+ X) + \]
\[ - B(\mathcal{B} \rightarrow \text{baryon}_c) - B(\mathcal{B} \rightarrow (c\bar{c}) X) . \]  
(2.21)

Inserting the values from Eqs. (2.13) and (2.16) and the current CLEO results,

\[ B(\mathcal{B} \rightarrow D_s^+ X) = (0.021 \pm 0.010) \left[ \frac{3.5\%}{B(D_s \rightarrow \phi\pi)} \right] , \]  
(2.22)

\[ B(\mathcal{B} \rightarrow \text{baryon}_c) = (0.0365 \pm 0.0065) \left[ \frac{6\%}{B(\Lambda_c \rightarrow pK^-\pi^+)} \right] , \]  
(2.23)

into the right hand side of Eq. (2.21) we obtain

\[ B(\mathcal{B} \rightarrow DX) = (0.89 \pm 0.02) . \]  
(2.24)

On the other hand, current CLEO measurements of \( Y_D \) and \( r_D \) (see Tables I and III) yield,

\[ B(\mathcal{B} \rightarrow DX) = (0.798 \pm 0.042) \left[ \frac{3.91\%}{B(D^0 \rightarrow K^-\pi^+)} \right] . \]  
(2.25)

Equating the two determinations of \( B(\mathcal{B} \rightarrow DX) \),

\[ (0.89 \pm 0.02) = (0.798 \pm 0.042) \left[ \frac{3.91\%}{B(D^0 \rightarrow K^-\pi^+)} \right] , \]  
(2.26)

it follows that either the coefficient \( (0.798 \pm 0.042) \), or \( B(D^0 \rightarrow K^-\pi^+) = (3.91 \pm 0.19)\% \), or both, are incorrect. Let us assume for the moment that only \( B(D^0 \rightarrow K^-\pi^+) \) is incorrect. We can then solve Eq. (2.26) for \( B(D^0 \rightarrow K^-\pi^+) \) to obtain,
\[ B(D^0 \rightarrow K^-\pi^+) = (3.50 \pm 0.21)\% . \] 

(2.27)

This is considerably smaller than currently accepted values but compatible with the most recent measurement from ARGUS \[14\],

\[ B(D^0 \rightarrow K^-\pi^+) = (3.41 \pm 0.12 \pm 0.28)\% . \]

Eq. (2.27), in turn, yields

\[ B(b \rightarrow c\bar{c}s') = (22.7 \pm 3.5)\% , \] 

(2.28)

\[ n_c = \bar{n}_c = 1.20 \pm 0.04 . \] 

(2.29)

Our result must of course be corroborated by additional precision studies. In the meantime we have investigated some consequences of a lower value for \( B(D^0 \rightarrow K^-\pi^+) \).

B. The Low \( R_c \) Measurement

Whereas theory predicts

\[ R_c \equiv \frac{\Gamma(Z^0 \rightarrow c\bar{c})}{\Gamma(Z^0 \rightarrow \text{hadrons})} = 0.172 , \] 

(2.30)

experiments yield a combined result which is \( \sim 2\sigma \) lower \[1\]

\[ R_c|_{\text{exp}} = 0.1598 \pm 0.0069 . \] 

(2.31)

To analyze this result one must make distinctions among the various contributing measurements. Those which fully reconstruct a primary \( D^{*+} \) are calibrated by \( B(D^0 \rightarrow K^-\pi^+) \). These are \[17,18\]

\[ R_c(DELPHI \: D^*) = 0.148 \pm 0.007 \pm 0.011 , \] 

(2.32)

\[ R_c(OPAL \: D^*) = 0.1555 \pm 0.0196 , \] 

(2.33)
with a world-average of
\[ R_c(D^*) = 0.150 \pm 0.011 . \] (2.34)

Unfortunately, the uncertainty in \( R_c \) measurements due to \( B(D^o \to K^- \pi^+) \) has not been explicitly reported. We therefore conservatively retain the full error on \( R_c \) to write
\[ 0.172 = (0.150 \pm 0.011) \left[ \frac{3.84\%}{B(D^o \to K^- \pi^+)} \right] . \] (2.35)
(Note that the calibration factor is different than that used previously because these measurements have taken the updated PDG value \[ B(D^o \to K^- \pi^+) = (3.84 \pm 0.13)\% . \])

This yields
\[ B(D^o \to K^- \pi^+) = (3.35 \pm 0.25)\% , \] (2.36)
which is near to the value we extracted in Eq. (2.27).

Note that DELPHI has also measured \( R_c \) via an inclusive double tag method, where only the daughter pion of the \( D^{*\pm} \) is identified. This method does not involve \( B(D^o \to K^- \pi^+) \) and the result \[ R_c(\pi^+ \pi^-) = 0.171^{+0.014}_{-0.012} \pm 0.015 \] (2.37)
agrees well with the Standard Model.

Other measurements of \( R_c \) include a lepton method which has very large systematic uncertainties, and measurements from both OPAL and DELPHI that involve direct charm counting \[ R_c(\text{charm counting}) = 0.167 \pm 0.011 (stat) \pm 0.011 (sys) \pm 0.005 (br) . \] (2.38)

OPAL measures
\begin{align*}
R_c f(c \to D^0) \; B(D^0 \to K^-\pi^+) &= (0.389 \pm 0.037)\% , \\
R_c f(c \to D^+) \; B(D^+ \to K^-\pi^+\pi^+) &= (0.358 \pm 0.055)\% , \\
R_c f(c \to D_s^+) \; B(D_s^+ \to \phi\pi^+) &= (0.056 \pm 0.017)\% , \\
R_c f(c \to \Lambda_c^+) \; B(\Lambda_c^+ \to pK^-\pi^+) &= (0.041 \pm 0.020)\% . \tag{2.39}
\end{align*}

The fractions are summed by using the updated PDG branching fractions \[21\] as reference:

\begin{align*}
B(D^0 \to K^-\pi^+) &= (3.84 \pm 0.13)\% , \\
B(D^+ \to K^-\pi^+\pi^+) &= (9.1 \pm 0.6)\% , \\
B(D_s^+ \to \phi\pi^+) &= (3.5 \pm 0.4)\% , \\
B(\Lambda_c \to pK^-\pi^+) &= (4.4 \pm 0.6)\% . \tag{2.40}
\end{align*}

They assume that the undetected primary \( \Xi_c \) and \( \Omega_c \) production is \((15 \pm 5)\% \) of the primary \( \Lambda_c \) production, and thus obtain Eq. (2.38).

We assume the standard model value \( R_c = 0.172 \) and again use the more accurate estimate for \( B(\Lambda_c \to pK^-\pi^+) \) of \((6.0 \pm 1.5)\% \), rather than \((4.4 \pm 0.6)\% \), in order to solve for \( B(D^0 \to K^-\pi^+) \). We correlate the inclusive primary production fraction of \( baryon_c \) to that of \( \Lambda_c \) via

\[ f(c \to baryon_c) = f(c \to \Lambda_c) / (1 - p)^2 , \tag{2.41} \]

where \( p \) models the production fraction of \( s\bar{s} \) fragmentation relative to \( f\bar{f} \) fragmentation from the vacuum, \((f = u,d \text{ or } s) \) \[21\]. The solution for \( B(D^0 \to K^-\pi^+) \) is

\begin{equation}
B(D^0 \to K^-\pi^+) = \frac{(0.00389 \pm 0.00037) + \frac{0.00058 \pm 0.000055}{r_+}}{R_c - \frac{B(D_s \to \phi\pi^+)}{(1 - p)^2 B(\Lambda_c \to pK^-\pi^+)}} . \tag{2.42}
\end{equation}

Inserting,

\begin{equation}
r_+ = 2.35 \pm 0.23, \quad R_c = .172, \quad B(D_s \to \phi\pi^+) = (3.5 \pm 0.4)\% , \tag{2.43}
\end{equation}

and \( B(\Lambda_c \to pK^-\pi^+) = (6.0 \pm 1.5)\% \), \( \tag{2.44} \)

11
we obtain

\[ B(D^0 \to K^-\pi^+) = (3.67 \pm 0.36)\% \quad (2.45) \]

C. Semileptonic B Decays

Semileptonic B transitions are among the most intensively studied B decays. They consist almost entirely of \( b \to c\ell^-\bar{\nu} \) transitions, since \( |V_{ub}/V_{cb}| \approx 0.1 \). Thus a primary lepton in B decay is typically accompanied by a charmed hadron. Inclusive semileptonic B decay measurements detect the lepton without reconstructing the accompanying charmed hadron. As a result, uncertainties from charm are minimal. These measurements also usually involve very high statistics and so they are generally very precise [2,22–24].

A variety of semileptonic B decay measurements, where the accompanying charm was also seen, have been reported [22]. These include the dominant exclusive \( \bar{B} \to D^{(*)}\ell^-\bar{\nu} \) processes, \( \bar{B} \to D^{**}(X)\ell^-\bar{\nu} \) transitions, and non-resonant \( \bar{B} \to D^{(*)}\pi X\ell^-\bar{\nu} \) processes. Combining all information about semileptonic B decay measurements where the associated charm is also seen, one finds a significant shortfall relative to the inclusive measurements [4]. Decreasing \( B(D^0 \to K^-\pi^+) \) would alleviate this shortfall, because the semileptonic branching fractions with reconstructed charm are inversely proportional to \( B(D^0 \to K^-\pi^+) \) and would therefore increase. With some theoretical input we estimate that the value \( B(D^0 \to K^-\pi^+) = (2.9 \pm 0.4)\% \) eliminates the discrepancy [25].

D. Summary and Implications

We have demonstrated that currently accepted values for \( B(D^0 \to K^-\pi^+) \), namely

\[
B(D^0 \to K^-\pi^+) = \begin{cases} 
(4.01 \pm 0.14)\% & (1994 \text{ PDG}) \\
(3.91 \pm 0.19)\% & (CLEO II) \\
(3.84 \pm 0.13)\% & (1995 \text{ PDG update}) 
\end{cases}
\quad (2.46)
\]

could be too high. The recent wrong charm $B(B \to DX)$ measurement of CLEO opened up a second way to determine right charm $B(B \to DX)$. By equating the two determinations, we solved for $B(D^0 \to K^−\pi^+)$ to obtain the smaller value,

$$B(D^0 \to K^−\pi^+) = (3.50 \pm 0.21)\% .$$  \hspace{1cm} (2.47)

We then demonstrated that reducing the value of $B(D^0 \to K^−\pi^+)$ enables experimental results for $R_c$ to agree with theory and diminishes the excess of inclusive semileptonic $B$ decays relative to the combined exclusive yields. Table IV lists the values of $B(D^0 \to K^−\pi^+)$ required to eliminate the discrepancy in each of these cases. Combining these values one obtains the weighted mean value:

$$\langle B(D^0 \to K^−\pi^+) \rangle = (3.40 \pm 0.14)\% .$$

Additional consequences of a lower value for $B(D^0 \to K^−\pi^+)$ are discussed in Ref. [25]. We note here that it is possible for a reduction in $B(D^0 \to K^−\pi^+)$ to affect the discrepancy between theory and measurement for $R_b$, the fraction of hadronic $Z$ decays to bottom quarks. This connection follows by noting that since $B(D^0 \to K^−\pi^+)$ calibrates almost all charmed meson branching fractions, a lower value for $B(D^0 \to K^−\pi^+)$ means that a significant fraction of $D^0$ and $D^+$ decays have not been observed or properly counted. One hypothesis is that these missed decays involve high track multiplicities [26] since such decays are more difficult to fully reconstruct due to tracking inefficiencies, particle identification errors, combinatoric backgrounds and the presence of undetected neutrals. On the other hand, high charged multiplicity decays are more likely to generate a lifetime $B$ tag at LEP and SLC since they will more likely yield the high number of significantly displaced tracks expected for $B$ decays. We explore this possibility further in the next section.

**III. $R_b$ MEASUREMENTS**

Recently the fraction $R_b$ of $Z$ hadronic decays to $b\bar{b}$ has been measured at LEP [27–31] and SLC [32] using a variety of methods including shape variables, multivariate techniques,
high $p_T$ leptons, and lifetime tags to distinguish the decays of $b$ quarks from those of lighter quarks. While each measurement is consistent, within uncertainties, with the Standard Model expectation of $R_b = 0.2155$, they combine to yield $R_b = 0.2205 \pm 0.0016$ which represents a three standard deviation discrepancy. As seen in Table [1], the highest precision contributions to this average are those which use lifetime $B$ tagging. Indeed, the lifetime measurements (including the lepton + lifetime result from OPAL) yield a simple weighted mean value of $R_b = 0.2200 \pm 0.0017$ which dominates the overall result.

The procedure used for measuring $R_b$ is to tag $Z \rightarrow b\bar{b}$ events using any of the above-mentioned methods, then subtract backgrounds as estimated from Monte Carlo (MC), and estimate the $B$ tag efficiency either by MC or directly from data. Obtaining the $B$ tag efficiency from data is more reliable and is possible in all cases where double tagging (tagging two $B$ hadron decays in one event) is used. As an illustration of the procedure, if we were to ignore backgrounds, the number of tagged hemispheres $N_t$, (where the sphere axis is defined by the direction of the highest energy jet) and the number of double tagged events $N_{tt}$ would be expressed as

$$N_t = 2\epsilon_b R_b N_Z$$  \hspace{1cm} (3.1) \\
$$N_{tt} = C_b \epsilon_b^2 R_b N_Z$$  \hspace{1cm} (3.2)

For a given $B$ tagging algorithm one counts $N_t$ and $N_{tt}$. $N_Z$ is the total number of hadronic $Z$ decays. $C_b$ is a correlation factor which takes into account the fact that the probability of tagging a hemisphere may be correlated with whether or not the other hemisphere is tagged. Eqs. (3.1) and (3.2) can be solved for $R_b$ and $\epsilon_b$:

$$\epsilon_b = \frac{2N_{tt}}{C_b N_Z}$$  \hspace{1cm} (3.3) \\
$$R_b = \frac{C_b N^2}{4N_{tt} N_Z}$$  \hspace{1cm} (3.4)

When the $B$ purity of the tagging algorithm is high, so that backgrounds are small, Eqs. (3.3) and (3.4) are relatively good approximations. Including backgrounds, one arrives at the following generalizations of Eqs. (3.1) and (3.2):
\[
\frac{N_t}{2N_Z} = \epsilon_b R_b + \epsilon_c R_c + \epsilon_{uds}(1 - R_b - R_c)
\] (3.5)

\[
\frac{N_{tt}}{N_Z} = C_b \epsilon_b^2 R_b + C_c \epsilon_c^2 R_c + C_{uds} \epsilon_{uds}^2(1 - R_b - R_c)
\] (3.6)

As input to these equations one can use either the SM value \( R_c = 0.172 \) or a value measured in a separate analysis, and MC predictions for \( \epsilon_c \) and \( \epsilon_{uds} \). A variety of data and MC-based studies are performed to estimate the correlation factor \( C_b \). \( C_c \) and \( C_{uds} \) differ negligibly from unity.

We have asked whether there could be an explanation for the experimental result which does not contradict the Standard Model. Under the assumption that there could be an error in the result obtained for the dominant lifetime measurement technique, it follows that this error would have to be common to a number of different measurements and, as indicated by equation (3.4), would likely result from an excess of single hemisphere tags relative to double-tagged events, or from an overestimate of \( C_b \). Due to the many subtle differences in the experiments and analyses, it is unlikely that a common error could have occurred in the estimates of \( C_b \). There could however be a missed or incorrectly estimated background that enhances \( N_t \) and/or suppresses \( N_{tt} \). Since the \( b \) tagging algorithms used by the experiments are of high purity, as shown in Table VI, we conclude that events with two tagged hemispheres should have extremely small non-\( b \) backgrounds. By process of elimination, one is therefore led to the possibility that some non-\( b \) source of single hemisphere tags could have been overlooked. From Eqs. (3.4) and (3.5) this would imply that one or both of \( \epsilon_c \) and \( \epsilon_{uds} \) are wrong.

The light quark tagging efficiency \( \epsilon_{uds} \) can be studied directly with data even for the added complication of gluon radiation with splitting to \( b \bar{b} \) or \( c \bar{c} \) \[34\]. The charmed tagging efficiency \( \epsilon_c \) is more difficult to determine since it depends upon the relative populations of \( D^0, D^+, D_s, \Lambda_c \ldots \), and their decays. We can investigate the sensitivity of \( R_b \) to \( \epsilon_c \) and \( \epsilon_{uds} \) by plotting the variation in \( R_b \) as a function of each efficiency with all other quantities fixed at their nominal values. For simplicity we set \( C_b = 1 \) which then results in the following
simple expression for $R_b$:

$$R_b = \frac{\left(\frac{N_t}{2N_Z} - R_c(\epsilon_c - \epsilon_{uds}) - \epsilon_{uds}\right)^2}{\frac{N_t}{N_Z} - \frac{N_t}{N_Z}\epsilon_{uds} - R_c(\epsilon_c - \epsilon_{uds})^2 + \epsilon_{uds}^2}$$

(3.7)

For nominal values we choose $\epsilon_{uds} = 1.7 \times 10^{-3}$ and $\epsilon_c = 1.4 \times 10^{-2}$ which are in the mid-range of the values used by the LEP experiments (see Table VI). We assume the value $R_c = 0.172$. Finally we use $\frac{N_t}{2N_Z} = 0.055$ and $\frac{N_t}{N_Z} = 0.012$ which are comparable to the values in Ref. [31] and result in $R_b = 0.22$ as quoted above for the combined lifetime measurements. Figure 1 plots $R_b$ as a function of the change in $\epsilon_c$ and $\epsilon_{uds}$. The discrepancy between measured and predicted values for $R_b$ is seen to correspond to roughly a 50% increase in $\epsilon_{uds}$ from its nominal value or a 20% increase in $\epsilon_c$. (The discrepancy is of course also removed by smaller but simultaneous upward shifts in both efficiencies.)

A review of the various measurements of $\epsilon_{uds}$ yields no obvious oversights. Our initial concern was that there could be some contribution from gluon radiation followed by splitting to $b\bar{b}$ or $c\bar{c}$. However, $g \to b\bar{b}$ occurs in only about (0.2 - 0.3)% of Z hadronic decays while $g \to c\bar{c}$ occurs in roughly 2.5% of Z hadronic decays [34–37]. Furthermore, the experiments have explicitly studied the effect of $g \to b\bar{b}, c\bar{c}$ in Z decays to light quarks and find no significant enhancement in $\epsilon_{uds}$. Even under the assumption of a large uncertainty in the probability for this phenomenon to occur, it is not possible to achieve anywhere near the 50% shift required in $\epsilon_{uds}$ to explain the $R_b$ discrepancy.

We next consider $\epsilon_c$. We were unable to find explicit consideration of the possible effect of gluon radiation and splitting to $b\bar{b}$ and $c\bar{c}$ in $Z \to c\bar{c}$ events. The effect of gluon splitting in these events could be more important than in the light quark Z decays since: (i) the $R_b$ discrepancy is removed by a smaller change in $\epsilon_c$ than would be required for $\epsilon_{uds}$ and (ii) $Z \to c\bar{c}g$ with $g \to c\bar{c}$ results in events with typically three heavy flavors in one hemisphere. Such hemispheres could be expected to have a higher than average multiplicity of significantly displaced charged tracks. The primary charm quark from the Z decay will typically remain fairly energetic in spite of having radiated a gluon, and it is then only necessary for one of the charm quarks from $g \to c\bar{c}$ to be energetic in order to have two
significantly displaced heavy flavor decays similar to that expected for $B$ decay.

To study this phenomenon we have used the PYTHIA Monte Carlo (version 5.7) with JETSET (version 7.4) [38]. To cross-check these results we have written a toy MC based upon the differential relative rate for the process $Z^0 \to c\bar{c}g, \ g \to c\bar{c}$ calculated using an $O(\alpha_s^3)$ cross section. Our calculation is more precise than the leading-log approximation at $O(\alpha_s^3)$ valid only at small angles, because we wanted to also consider large-angle gluon emission. We neglected terms proportional to $k^2/M_Z^2$, with $k^2$ denoting the virtuality of the gluon.

As anticipated, we find that the fraction of those hemispheres with $g \to c\bar{c}$ that contain a large number of displaced charged tracks (e.g. $N_{\text{displaced}} \geq 4$) increases dramatically. These however represent only a small fraction of all hemispheres with $g \to c\bar{c}$ and upon applying the jet probability $B$ tag algorithm [29] we found that, on average, the tagging efficiency was not significantly higher than for hemispheres which do not contain $g \to c\bar{c}$.

Finally, as mentioned in the previous section, the accepted value for the branching ratio $B(D^0 \to K^-\pi^+)$ could be too high. One consequence would be that roughly 15% of $D^0$ decays would be missing. A similar argument applies to $D^+$ decays since the most accurate measurement of $B(D^+ \to K^-\pi^+\pi^+)$ is tied to $B(D^0 \to K^-\pi^+)$ [7]. A number of different scenarios could be proposed for the missing decays. We consider here one which could link the reduced value for $B(D^0 \to K^-\pi^+)$ to the discrepancy between the measured value of $R_b$ and the value predicted by the Standard Model. In particular, if the missing decays were predominantly multiple charged particle modes, then it can be demonstrated that this would increase the value of $\epsilon_c$ relative to that currently assumed in recent measurements of $R_b$.

To demonstrate this we have performed a simple Monte Carlo study of the process $e^+e^- \to Z \to c\bar{c}$, again using the PYTHIA MC with JETSET. We have chosen the DELPHI detector for the purpose of creating a simple model of detector effects such as silicon detector acceptance and impact parameter resolution. The results would however be qualitatively the same if we were to use OPAL or ALEPH detector acceptances and resolutions. For each stable charged particle we have calculated the impact parameter ($d$) relative to the
$e^+e^-$ interaction vertex. The calculated impact parameter is smeared according to the measured DELPHI resolution function \cite{1}. The impact parameter significance is then defined as $S \equiv d/\sigma$ where $\sigma$ depends on transverse momentum \cite{39}.

For lifetime $B$ tagging we again apply the jet probability algorithm which uses impact parameter significance values of charged particle tracks to detect the presence of long-lived particles. The resulting hemisphere probability distribution we obtain for $e^+e^- \rightarrow Z \rightarrow c\bar{c}$ is shown in Figure 2 where it is compared to that obtained by ALEPH \cite{29}. The distributions are not expected to be in strict agreement since we have not modelled detector efficiencies and acceptances in detail. Nevertheless, the agreement is good and should be adequate for this discussion. Figure 3 plots the hemisphere tagging efficiencies for all $D^0$ decays containing 4 or more charged particles, and for all $D^+$ decays containing 3 or more charged particles (normalized to the tagging efficiency for all charm hemispheres), as a function of $P_{H} = \log_{10}(P_{\text{cut}}^{H})$, where $P_{H}$ is the jet probability obtained for all charged tracks in the hemisphere. In measurements of $R_b$ using this algorithm, a $B$ tag is defined as a hemisphere satisfying $P_{H} \leq P_{\text{cut}}^{H}$ where $10^{-4} \leq P_{\text{cut}}^{H} \leq 10^{-2.9}$ for the various experiments. It is clear from Figure 3 that the multiple charged track modes have a significantly higher value of $\epsilon_c$ in this range of $P_{\text{cut}}^{H}$ values. Despite the presence of fewer charged tracks, the $D^+$ efficiency is much higher than that of the $D^0$ in Figure 3, because of its significantly longer lifetime.

From our previous discussion, we found that the $R_b$ discrepancy is removed by a 20% increase in $\epsilon_c$. Relative to a nominal value of $\epsilon_c = 0.014$, this corresponds to $\epsilon_c = 0.017$. Since the charm quark hadronizes as a $D^0$ or $D^+$ roughly 60% and 25% of the time, respectively, the $\sim 15\%$ of missing decays corresponds to $\sim 13\%$ of all charm hemispheres. Let us assume that the remaining $\sim 87\%$ of charm hemispheres have efficiency $\epsilon_c = 0.014$. We will take $P_{\text{cut}}^{H} = 10^{-3.5}$ and assume that all missing decays are high multiplicity decays for which the efficiencies are given by Figure 3. This allows us to estimate the maximum impact on $R_b$. From Figure 3 at $P_{\text{cut}}^{H} = 10^{-3.5}$, $D^+$ decays to three or more charged particles have a tagging efficiency $\epsilon_c^+ = 5 \cdot \epsilon_c$ while $D^0$ decays to four or more charged particles have
efficiency $\epsilon'^c_c = 1.5 \cdot \epsilon_c$. The adjusted charm efficiency is therefore given by:

$$\epsilon'^c_c = 0.87 \cdot \epsilon_c + 0.15 \cdot (0.6 \cdot \epsilon'^0_c + 0.25 \cdot \epsilon'^+_c) = 1.20 \cdot \epsilon_c = 0.017$$

Thus, in the extreme where all missing decays are multiple charged particle modes, the $R_b$ discrepancy is completely eliminated. We hasten to add that, in reality, charged modes may not represent all of the missing decays so that the effect on $R_b$ could be smaller. In fact, at the opposite extreme, if the missing decay modes involve few or no charged particles this would lead to an increase in the final value of $R_b$.

**IV. CONCLUSIONS**

We have demonstrated that complementary determinations of $B(\overline{B} \to DX)$ can be reconciled by a downward revision in the branching ratio $B(D^0 \to K^-\pi^+)$. This revision, together with the central role played by $B(D^0 \to K^-\pi^+)$ in calibrating almost all charmed hadron yields, explains the $R_c$ discrepancy and diminishes a problem in semileptonic $B$ decays. We have speculated that it could also be linked to the $R_b$ puzzle. In particular, a reduction in $B(D^0 \to K^-\pi^+)$ would mean that roughly 15% of all $D^0$ and $D^+$ decays have not been properly seen or counted. In the case where all of the missing decays involve multiple charged particle final states, we demonstrated that this leads to a higher than anticipated lifetime tag efficiency in $Z \to c\overline{c}$ events which would be adequate to bring the measured value of $R_b$ into line with the Standard Model value of 0.2155. We have also explicitly considered $g \to c\overline{c}$ in $Z \to c\overline{c}$ events but find that it does not enhance the lifetime tagging efficiency.

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V. APPENDIX: CHARMED BARYON PRODUCTION IN B MESON DECAYS

Accurate accounting of inclusive charm yields in $B$ decays requires a consistent description of charmed baryon production, which is lacking in the existing literature. Several years ago it was hypothesized that the soft inclusive momentum spectrum of inclusive $\Lambda_c$ production indicates that $b \to c\bar{s}s$ is the dominant source of $\Lambda_c$’s in $B$ decays [40]. The hypothesis predicted (i) large wrong-sign $\ell^-\Lambda_c$ correlations, where the lepton comes from the semileptonic decay of one $B$ and the $\Lambda_c$ from the other $B$ in an $\Upsilon(4S)$ event; and (ii) large $\Xi_c$ production in $B$ decays, which at that time had not been observed and was believed to be highly suppressed [41]. Shortly afterwards, CLEO observed the first evidence of $\Xi_c$ production in $B$ decays (see Table I), but also found that the right-sign $\ell^+\Lambda_c$ correlations are dominant (see Table III) [11]. CLEO measured [11]

$$r_{\Lambda_c} \equiv \frac{B(B \to \overline{\Lambda}_cX)}{B(B \to \Lambda_cX)} = 0.20 \pm 0.14 . \quad (5.1)$$

Because the CLEO measurements of inclusive $\Xi_c$ production in $B$ decays involve large uncertainties, and their central values appear to us to be too high, this Appendix correlates $\Xi_c$ and $\Omega_c$ production in tagged $B$ decays to that of the more accurately measured $\Lambda_c$. We neglect $b \to u$ transitions and use the Cabibbo suppression factor $\theta^2 = (0.22)^2$ for charmed baryon production in $b \to c\bar{u}s(b \to c\bar{c}d)$ versus $b \to c\bar{u}d'(b \to c\bar{s}s')$ transitions. The parameter $p = 0.15 \pm 0.05$ models the fraction of $s\bar{s}$ fragmentation relative to $f \bar{f}$ fragmentation from the vacuum, where $f = u, d$ or $s$. (This value for $p$ was chosen to demonstrate that even a large value yields a significant reduction in $\Xi_c$ production in $\overline{B}$ decays.)
We denote by $C_{\bar{u}d}$ the fraction of $\bar{B}$’s which decay to weakly decaying charmed baryons which come from $b \to c\bar{u}d$, and define $C_{\bar{s}s}, C_{\bar{c}d}, C_{\bar{u}s}$ analogously. Because our model allows for substantial charmless-baryon, charmless-anti-baryon production in $B$ decays, $C_{\bar{u}d}$ is smaller, or at most equal to $B_{\bar{u}d}$ as defined in Ref. [40]. Similar comments can be made for $C_{\bar{s}s}, C_{\bar{c}d}$, and $C_{\bar{u}s}$ relative to $B_{\bar{s}s}, B_{\bar{c}d}$, and $B_{\bar{u}s}$. The simplest version of the model predicts

\[
B(\bar{B} \to \Lambda_c X) = (1 - p)(C_{\bar{u}d} + C_{\bar{c}d}) \quad (5.2)
\]

\[
B(\bar{B} \to \bar{\Lambda}_c X) = (1 - p)(C_{\bar{s}s} + C_{\bar{c}d}) \quad (5.3)
\]

\[
B(\bar{B} \to \Xi_c X) = p C_{\bar{u}d} + (1 - p) C_{\bar{u}s} + (1 - p) C_{\bar{s}s} + p C_{\bar{c}d} \quad (5.4)
\]

\[
B(\bar{B} \to \bar{\Xi}_c X) = p (C_{\bar{s}s} + C_{\bar{c}d}) \quad (5.5)
\]

\[
B(\bar{B} \to \Omega_c X) = p(C_{\bar{u}s} + C_{\bar{s}s}) \quad (5.6)
\]

\[
B(\bar{B} \to \bar{\Omega}_c X) = 0 \quad (5.7)
\]

The Cabibbo structure

\[
C_{\bar{c}d}/(C_{\bar{c}d} + C_{\bar{s}s}) = C_{\bar{c}d}/C_{\bar{s}s} = \theta^2 \quad (5.8)
\]

\[
C_{\bar{u}s}/(C_{\bar{u}s} + C_{\bar{u}d}) = C_{\bar{u}s}/C_{\bar{u}d} = \theta^2 \quad (5.9)
\]

allows us to express the six observables listed on the left-hand sides of Eqs. (5.2)-(5.7) in terms of the two unknowns $C_{\bar{u}d}$ and $C_{\bar{s}s}$. The latter are in turn obtained from the two measurements involving inclusive $\Lambda_c$ production in $B$ decays, namely $Y_{\Lambda_c}$ and $r_{\Lambda_c}$, as follows:

\[
\frac{C_{\bar{u}d}}{Y_{\Lambda_c}} = \frac{(1 + \lambda^2 - \lambda^2 r_{\Lambda_c})}{(1 - p)(1 + \lambda^2)(1 + r_{\Lambda_c})}, \quad (5.10)
\]

\[
\frac{C_{\bar{s}s}}{C_{\bar{u}d}} = \frac{r_{\Lambda_c}}{1 + \lambda^2(1 - r_{\Lambda_c})}, \quad (5.11)
\]
where
\[
\lambda^2 = \frac{\theta^2}{|V_{cs}|^2} = \frac{\theta^2}{\left(1 - \frac{1}{2}\theta^2\right)^2}.
\] (5.12)

The inclusive \(^{(-)}\Xi_c, \Omega_c\) yields in \(\bar{B}\) decays are thus correlated to inclusive \(^{(-)}\Lambda_c\) production,
\[
\frac{B(\bar{B} \to \Lambda_c X)}{Y_{\Lambda_c}} = \frac{1}{1 + r_{\Lambda_c}},
\] (5.13)
\[
\frac{B(\bar{B} \to \bar{\Xi}_c X)}{Y_{\Lambda_c}} = \frac{r_{\Lambda_c}}{1 + r_{\Lambda_c}},
\] (5.14)
\[
\frac{B(\bar{B} \to \Xi_c X)}{Y_{\Lambda_c}} = \frac{C_{\bar{u}d}}{Y_{\Lambda_c}} \left\{ p + (1 - p)\lambda^2 + \frac{C_{\bar{c}s}}{C_{\bar{u}d}}(1 - p + p\lambda^2) \right\},
\] (5.15)
\[
\frac{B(\bar{B} \to \bar{\Xi}_c X)}{Y_{\Lambda_c}} = \frac{C_{\bar{u}d}}{C_{\bar{c}s}} \frac{C_{\bar{u}d}}{C_{\bar{u}d}} p(1 + \lambda^2),
\] (5.16)
\[
\frac{B(\bar{B} \to \Omega_c X)}{Y_{\Lambda_c}} = \frac{p}{Y_{\Lambda_c}} \left(\lambda^2 + \frac{C_{\bar{c}s}}{C_{\bar{u}d}}\right),
\] (5.17)
\[
B(\bar{B} \to \Omega_c X) = 0.
\] (5.18)

We have taken \(p\) to be a universal quantity and have assumed that the initially produced charmed baryon retains its charm [and when applicable, strange] quantum number[s] through to its weakly decaying offspring. This is not justified but is conservative in that it yields an upper limit for \(\Lambda_c\) production in \(B\) decays. We typically expect the initially produced charmed baryons (via \(b \to c\)) to be highly excited, while this is not expected of their pair-produced antibaryons (via \(b \to \bar{u}\) or \(b \to \bar{c}\)) [42]. That a sizable fraction of these highly excited charmed baryons could break up into a charmed meson, a charmless baryon, and additional debris is irrelevant to our discussion which focuses on weakly decaying charmed baryon production in \(B\) decays. In contrast, it is important to note that \(\Xi_c^r \to \Lambda_c K X\) could occur significantly [the superscript \(r\) denotes excited resonances]. This introduces an additional mechanism for \(\Lambda_c\) production in \(\bar{B}\) decays, which may help explain the small measured value of \(r_{\Lambda_c}\). It also decreases the naive estimate for weakly decaying \(\Xi_c\) production. Because our predictions have not incorporated such effects, they should be viewed strictly as upper limits for \(\Xi_c\) production in \(\bar{B}\) decays.
### TABLE I. Inclusive Charmed Hadron Production in $B$ Decays as Measured by CLEO

| $T$     | $Y_T \equiv B(\bar{B} \rightarrow TX) + B(\bar{B} \rightarrow \bar{T}X)$ | Reference |
|---------|---------------------------------------------------------------------|-----------|
| $D^0$   | $(0.645 \pm 0.025) \left[ \frac{3.91\%}{B(D^+ \rightarrow K^- \pi^+)} \right]$ | [13]      |
| $D^+$   | $(0.235 \pm 0.017) \left[ \frac{9.3\%}{B(D^+ \rightarrow K^- \pi^+ \pi^+)} \right]$ | [13]      |
| $D$     | $(0.883 \pm 0.038) \left[ \frac{3.91\%}{B(D^0 \rightarrow K^- \pi^+)} \right]$ |           |
| $D_s$   | $(0.1211 \pm 0.0096) \left[ \frac{3.5\%}{B(D_s \rightarrow \phi \pi)} \right]$ | [14]      |
| $\Lambda_c$ | $(0.030 \pm 0.005) \left[ \frac{6\%}{B(\Lambda_c \rightarrow pK^- \pi^+)} \right]$ | [15]      |
| $\Xi^+_c$ | $0.020 \pm 0.007$ | [16]      |
| $\Xi^0_c$ | $0.028 \pm 0.012$ | [16]      |

### TABLE II. Absolute Branching Ratios of Key Charm Decays

| Mode                  | BR [in %] | Reference |
|-----------------------|-----------|-----------|
| $D^0 \rightarrow K^- \pi^+$ | $3.91 \pm 0.19$ | [1]       |
| $D_s \rightarrow \phi \pi$ | $3.5 \pm 0.4$ | [8]       |
| $\Lambda_c \rightarrow pK^- \pi^+$ | $6.0 \pm 1.5$ | [12]      |

### TABLE III. Inclusive Charmed Hadron Production in Tagged $B$ Decays as Measured by CLEO

| Observable | Value         | Reference |
|------------|---------------|-----------|
| $r_{\Lambda_c}$ | $\frac{B(\bar{B} \rightarrow \bar{\Lambda}_c X)}{B(\bar{B} \rightarrow \bar{\Lambda}_c X)}$ | $0.20 \pm 0.14$ | [11] |
| $r_D$      | $\frac{B(\bar{B} \rightarrow \bar{D} X)}{B(\bar{B} \rightarrow \bar{D} X)}$ | $0.107 \pm 0.034$ | [9] |
| $f_{D_s}$  | $\frac{B(\bar{B} \rightarrow D_s^+ X)}{Y_{D_s}}$ | $0.172 \pm 0.083$ | [17] |
TABLE IV. Extracted Values of $B(D^0 \rightarrow K^-\pi^+)$.  

| Analysis                      | $B(D^0 \rightarrow K^-\pi^+)$ |
|-------------------------------|--------------------------------|
| $B(\overline{B} \rightarrow DX)$ | $(3.50 \pm 0.21)$%             |
| $R_c(D^{*+})$                 | $(3.35 \pm 0.25)$%             |
| $R_c$(charm counting)         | $(3.67 \pm 0.36)$%             |
| Semileptonic BR’s            | $(2.9 \pm 0.4)$%               |
| **ALL**                      | $(3.40 \pm 0.14)$%             |

TABLE V. $R_b$ Results as of the Brussels EPS-HEP-95 Conference  

| Experiment | Data Set(s) | Measurement Type | $R_b \ (R_c = 0.172 \text{ Fixed})$ |
|------------|-------------|------------------|-------------------------------------|
| ALEPH      | 1992        | Lifetime         | $0.2192 \pm 0.0022 \pm 0.0026$      |
| DELPHI     | 1992-3 prel.| Lifetime         | $0.2216 \pm 0.0017 \pm 0.0027$      |
| DELPHI     | 1992-3 prel.| Mixed            | $0.2231 \pm 0.0029 \pm 0.0035$      |
| DELPHI     | 1992-3 prel.| Multivariate     | $0.2186 \pm 0.0032 \pm 0.0022$      |
| OPAL       | 1992-4 prel.| Lifetime + lepton| $0.2197 \pm 0.0014 \pm 0.0022$      |
| ALEPH      | 1990-1      | Event Shape      | $0.228 \pm 0.005 \pm 0.005$         |
| SLD        |             | Lifetime         | $0.2171 \pm 0.0040 \pm 0.0037$      |
| L3         | 1991        | Event Shape      | $0.222 \pm 0.003 \pm 0.007$         |
| LEP        |             | Lepton Fits      | $0.2219 \pm 0.0039$                  |
| LEP+SLD    |             | Lifetime Fits    | $0.2200 \pm 0.0017$                  |
| **ALL**    |             |                  | $0.2205 \pm 0.0016$                  |
| Experiment | $B$ Purity | $\epsilon_b$ | $\epsilon_c$ | $\epsilon_{uds}$ | $C_b$ |
|------------|------------|--------------|--------------|-----------------|------|
| ALEPH      | 0.96       | 0.26         | $1.18 \times 10^{-2}$ | $0.88 \times 10^{-3}$ | 0.943 |
| DELPHI     | 0.92       | 0.21         | $1.60 \times 10^{-2}$ | $2.52 \times 10^{-3}$ | 0.952 |
| OPAL       | 0.94       | 0.23         | $1.37 \times 10^{-2}$ | $1.01 \times 10^{-3}$ | 1.006 |
| SLD        | 0.94       | 0.31         | $2.30 \times 10^{-2}$ | $0.87 \times 10^{-3}$ | 0.995 |
FIG. 1. $R_b$ as a function of the change in the efficiencies $\epsilon_{uds}$ and $\epsilon_c$ varied separately.
FIG. 2. The tag efficiency versus the Log of the probability cut ($\log_{10}(P_H)$) for Monte Carlo $e^+e^- \rightarrow Z \rightarrow c\bar{c}$ events used in this paper (open circles) as compared with that obtained by ALEPH (solid squares).
FIG. 3. The ratio of the tagging efficiency for $D^0$ hadronic decays containing at least 4 charged particles to the decays of all charmed hadrons (black squares) and the similar ratio for $D^+$ hadronic decay modes containing at least 3 charged particles (open circles) as a function of $\log_{10}$ of the cut on hemisphere jet probability $P_H^{cut}$.
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