

Charged track multiplicity in B meson decay

G. Brandenburg, A. Ershov, Y. S. Gao, D. Y.-J. Kim, and R. Wilson
Harvard University, Cambridge, Massachusetts 02138

T. E. Browder, Y. Li, J. L. Rodriguez, and H. Yamamoto
University of Hawaii at Manoa, Honolulu, Hawaii 96822

T. Bergfeld, B. I. Eisenstein, J. Ernst, G. E. Gladding, G. D. Gollin, R. M. Hans, E. Johnson, I. Karliner, M. A. Marsh,
M. Palmer, C. P. P. P. Plager, C. Sedlack, M. Selen, J. J. Thaler, and J. Williams
University of Illinois, Urbana-Champaign, Illinois 61801

K. W. Edwards
*Carleton University, Ottawa, Ontario, Canada K1S 5B6
and the Institute of Particle Physics, Canada*

R. Janicek and P. M. Patel
*McGill University, Montréal, Québec, Canada H3A 2T8
and the Institute of Particle Physics, Canada*

A. J. Sadoff
Ithaca College, Ithaca, New York 14850

R. Ammar, P. Baringer, A. Bean, D. Besson, R. Davis, S. Kotov, I. Kravchenko, N. Kwak, and X. Zhao
University of Kansas, Lawrence, Kansas 66045

S. Anderson, V. V. Frolov, Y. Kubota, S. J. Lee, R. Mahapatra, J. J. O'Neill, R. Poling, T. Riehle, and A. Smith
University of Minnesota, Minneapolis, Minnesota 55455

S. Ahmed, M. S. Alam, S. B. Athar, L. Jian, L. Ling, A. H. Mahmood,* M. Saleem, S. Timm, and F. Wappler
State University of New York at Albany, Albany, New York 12222

A. Anastassov, J. E. Duboscq, K. K. Gan, C. Gwon, T. Hart, K. Honscheid, H. Kagan, R. Kass, J. Lorenc, H. Schwarthoff,
M. B. Spencer, E. von Toerne, and M. M. Zoeller
Ohio State University, Columbus, Ohio 43210

S. J. Richichi, H. Severini, P. Skubic, and A. Undrus
University of Oklahoma, Norman, Oklahoma 73019

M. Bishai, S. Chen, J. Fast, J. W. Hinson, J. Lee, N. Menon, D. H. Miller, E. I. Shibata, and I. P. J. Shipsey
Purdue University, West Lafayette, Indiana 47907

Y. Kwon,[†] A. L. Lyon, and E. H. Thorndike
University of Rochester, Rochester, New York 14627

C. P. Jessop, K. Lingel, H. Marsiske, M. L. Perl, V. Savinov, D. Ugolini, and X. Zhou
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

T. E. Coan, V. Fadeyev, I. Korolkov, Y. Maravin, I. Narsky, R. Stroynowski, J. Ye, and T. Wlodek
Southern Methodist University, Dallas, Texas 75275

M. Artuso, R. Ayad, E. Dambasuren, S. Kopp, G. Majumder, G. C. Moneti, R. Mountain, S. Schuh, T. Skwarnicki,
S. Stone, A. Titov, G. Viehhauser, J. C. Wang, A. Wolf, and J. Wu
Syracuse University, Syracuse, New York 13244

S. E. Csorna, K. W. McLean, S. Marka, and Z. Xu
Vanderbilt University, Nashville, Tennessee 37235

R. Godang, K. Kinoshita,[‡] I. C. Lai, P. Pomianowski, and S. Schrenk
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

G. Bonvicini, D. Cinabro, R. Greene, L. P. Perera, and G. J. Zhou
Wayne State University, Detroit, Michigan 48202

S. Chan, G. Eigen, E. Lipeles, M. Schmidtler, A. Shapiro, W. M. Sun, J. Urheim, A. J. Weinstein, and F. Würthwein
California Institute of Technology, Pasadena, California 91125

D. E. Jaffe, G. Masek, H. P. Paar, E. M. Potter, S. Prell, and V. Sharma
University of California, San Diego, La Jolla, California 92093

D. M. Asner, A. Eppich, J. Gronberg, T. S. Hill, D. J. Lange, R. J. Morrison, T. K. Nelson, J. D. Richman, and D. Roberts
University of California, Santa Barbara, California 93106

R. A. Briere
Carnegie Mellon University, Pittsburgh, Pennsylvania 15213

B. H. Behrens, W. T. Ford, A. Gritsan, H. Krieg, J. Roy, and J. G. Smith
University of Colorado, Boulder, Colorado 80309-0390

J. P. Alexander, R. Baker, C. Bebek, B. E. Berger, K. Berkelman, F. Blanc, V. Boisvert, D. G. Cassel, M. Dickson, S. von Dombrowski, P. S. Drell, K. M. Ecklund, R. Ehrlich, A. D. Foland, P. Gaidarev, R. S. Galik, L. Gibbons, B. Gittelman, S. W. Gray, D. L. Hartill, B. K. Heltsley, P. I. Hopman, C. D. Jones, D. L. Kreinick, T. Lee, Y. Liu, T. O. Meyer, N. B. Mistry, C. R. Ng, E. Nordberg, J. R. Patterson, D. Peterson, D. Riley, J. G. Thayer, P. G. Thies, B. Valant-Spaight, and A. Warburton
Cornell University, Ithaca, New York 14853

P. Avery, M. Lohner, C. Prescott, A. I. Rubiera, J. Yelton, and J. Zheng
University of Florida, Gainesville, Florida 32611

CLEO Collaboration

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We have used the CLEO II detector to study the multiplicity of charged particles in the decays of B mesons produced at the $\Upsilon(4S)$ resonance. Using a sample of 1.5×10^6 B meson pairs, we find the mean inclusive charged particle multiplicity to be $10.71 \pm 0.02^{+0.21}_{-0.15}$ for the decay of the pair. This corresponds to a mean multiplicity of $5.36 \pm 0.01^{+0.11}_{-0.08}$ for a single B meson. Using the same data sample, we have also extracted the mean multiplicities in semileptonic and nonleptonic decays. We measure a mean of $7.82 \pm 0.05^{+0.21}_{-0.19}$ charged particles per $B\bar{B}$ decay when both mesons decay semileptonically. When neither B meson decays semileptonically, we measure a mean charged particle multiplicity of $11.62 \pm 0.04^{+0.24}_{-0.18}$ per $B\bar{B}$ pair.

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I. INTRODUCTION

Measurements of the charged track multiplicity distribution in B meson decay are used to constrain unmeasured or poorly measured branching fractions in Monte Carlo simulations so that generated event samples more closely represent actual data. The CLEO Monte Carlo parametrization of B meson decays has been tuned to agree with our measurements and our model is used by other experimental groups [1]. Charged particle multiplicity in heavy meson decay has been studied by several groups [2–4]. In this paper we

present a measurement of the charged particle multiplicity in inclusive $B\bar{B}$ decays that is an improvement over our previous result [2]. We also present improved measurements of the charged particle multiplicities in semileptonic and nonleptonic decays.

For clarity, we use the term “observed multiplicity” to denote the number of well reconstructed charged particle tracks in a given event. We use the term “decay multiplicity” to denote the number of e^\pm , μ^\pm , π^\pm , K^\pm , and p^\pm that come from the decay of the primary B mesons and also from the subsequent decays of any secondary or tertiary particles other than neutrons, K_L , or π^0 . The decay multiplicity excludes any tracks produced through interactions with the detector or surrounding material. Not all charged decay products will result in reconstructed tracks, and not all observed tracks come from the primary decay, so the observed multiplicity may be less than, equal to, or greater than the decay multiplicity for a given event.

*Permanent address: University of Texas - Pan American, Edinburg, TX 78539.

†Permanent address: Yonsei University, Seoul 120-749, Korea.

‡Permanent address: University of Cincinnati, Cincinnati, OH 45221.

II. INCLUSIVE MULTIPLICITY MEASUREMENT

The CLEO detector is located at the Cornell Electron Storage Ring, a high luminosity e^+e^- collider operated at or near the $Y(4S)$ resonance. The results presented here are derived from a sample of 1.4 fb^{-1} , corresponding to 1.5×10^6 B meson pairs, collected with the CLEO II detector [5]. Charged particle tracks are measured by cylindrical wire drift chambers inside a 1.5 T superconducting solenoid. A CsI crystal calorimeter is also inside the magnet, and energy deposition information from both the calorimeter and the drift chamber is used for particle identification. Muon counters are layered in the steel yoke surrounding the coil.

To obtain a clean sample of candidate $B\bar{B}$ events, we select hadronic events by requiring that an event have three or more reconstructed tracks, energy deposition in the calorimeter greater than 15% of the center of mass energy, and an event vertex consistent with the interaction region. For additional background suppression, the total reconstructed event energy, including charged and neutral particles, is required to be between 4 GeV and 12 GeV, and the total reconstructed vector momentum of the event is required to have a magnitude less than $3 \text{ GeV}/c$. This hadronic event sample contains events from both $B\bar{B}$ and continuum processes such as $q\bar{q}$ and $\tau^+\tau^-$ production. We remove the continuum contribution by rescaling and subtracting the observed multiplicity distribution of a separate 0.7 fb^{-1} data sample collected $65 \text{ MeV}/c^2$ below the $Y(4S)$ resonance.

To be counted in our observed multiplicity, drift chamber tracks are required to be well reconstructed and consistent with having originated from the event vertex. Tracks must not be within 25.8 degrees of the e^+e^- beam axis. Once the event selection, continuum subtraction, and track selection are completed, we count the selected tracks in each event to obtain the *observed* charged track multiplicity distribution in Fig. 1. There are events with fewer than three selected tracks because not all reconstructed tracks pass the track selection criteria.

To obtain the true decay multiplicity distribution from the observed multiplicity distribution, we must account for detector effects. If the number of events with observed multiplicity j is O_j and the number of events with decay multiplicity i is D_i , these quantities are related by Eq. (1):

$$O_j = \sum_{i=2,4,\dots}^n \epsilon_{ij} D_i, \quad (1)$$

where ϵ_{ij} is the probability that an event with decay multiplicity i will be reconstructed with observed multiplicity j . We have assumed that charge is conserved, so the index i can only take even values. In principle, there can be events with decay multiplicity of zero, where two neutral B mesons decay to all neutral final states. However, we do not include zero decay multiplicity events in our analysis both because of the very low branching ratio for such events and also because our event selection criteria make detection of such events extremely unlikely. The upper bound in Eq. (1) is, in principle, the maximum decay multiplicity in a $B\bar{B}$ event,

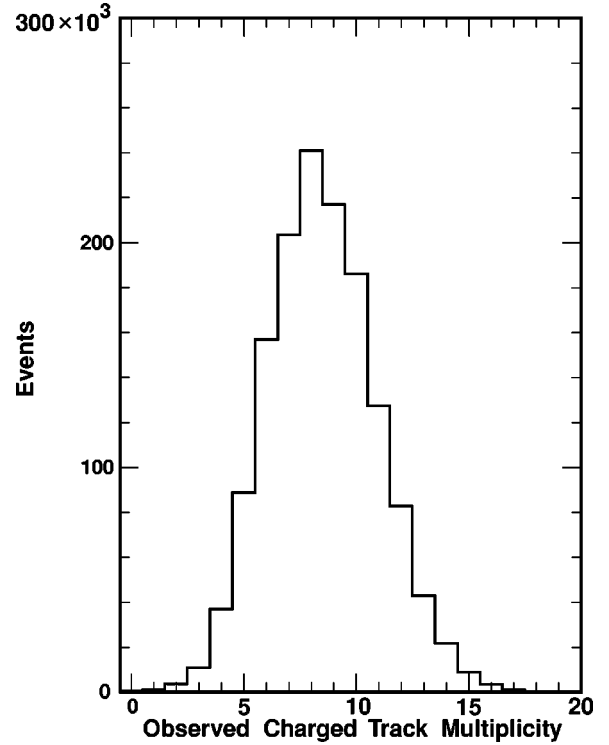


FIG. 1. Observed charged track multiplicity for $B\bar{B}$ events, after continuum subtraction.

which is not known. We vary the maximum decay multiplicity in our analysis as described below. The fact that the sum of D_i and the sum of O_j are both equal to the total number of events is used to constrain the values of the D_i , as expressed in Eq. (2):

$$\sum_{i=2,4,\dots}^n D_i = \sum_{j=0}^m O_j, \quad (2)$$

where the upper bound m is the maximum value of our observed multiplicity, which is 20.

The coefficients ϵ_{ij} in Eq. (1) are obtained from Monte Carlo simulation and depend primarily on the detector's track finding efficiency and also on the probability of producing extra charged particles that pass the track selection cuts and that are counted. While these coefficients depend on accurate simulation of detector response and processes such as photon conversion and decays in flight, they do not depend significantly on the exact tuning of the branching fractions or the decay multiplicity distribution in the simulation.

The parameters D_i in Eq. (1) are determined by a χ^2 fit. This fit unfolds the detector effects to give the decay multiplicity distribution of events that pass the event selection criteria. These selection criteria are biased against very low decay multiplicity events, particularly because of the requirement of three or more reconstructed tracks. We remove the event selection bias using Monte Carlo simulation to determine the probability for events of a given decay multiplicity to pass the event selection cuts. After unfolding detector and reconstruction effects, we obtain the decay multiplicity distribution in Fig. 2. The error bars represent the statistical

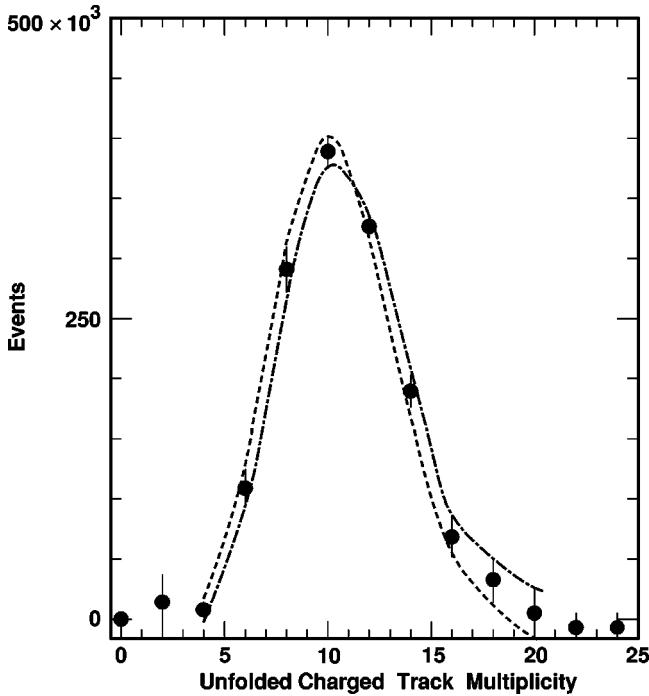


FIG. 2. Unfolded charged track decay multiplicity for $B\bar{B}$ events. The dashed lines represent the high multiplicity and low multiplicity fluctuations in the fit.

uncertainty in both the χ^2 fit and the event bias correction, but do not include systematic errors. The dashed lines represent the high multiplicity and low multiplicity statistical fluctuations in the fit. The large error bar on the $i=2$ point is due to the event bias correction.

From the distribution in Fig. 2, we obtain a mean of 10.71 ± 0.02 charged particles for inclusive $B\bar{B}$ decay, where the error is statistical only. The points with $i > 20$ show no evidence for events with such high multiplicities. We have tested our fitting procedure by varying the maximum decay multiplicity included in the fit between 20 and 28. The fit is stable and the unfolded mean decay multiplicity does not change significantly when decay multiplicities of 22 and higher are included or excluded from the fit.

The most important systematic effect in this analysis is the accuracy of modeling the detector's track finding efficiency. We determine the detector's efficiency by studying the decays of τ lepton pairs where we identify a tag hemisphere with one track and count the observed tracks in the opposite hemisphere. Our Monte Carlo simulations are carefully tuned to reproduce the observed track finding efficiency. These studies indicate that the overall efficiency for finding a single track is known to within $\pm 1\%$ for tracks with momentum greater than 250 MeV/ c and with decreasing accuracy as track momentum decreases. We have repeated our analysis after making artificial changes in the track finding efficiency of our Monte Carlo simulations and we find a $^{+1.6}_{-0.9}\%$ variation in the measured mean decay multiplicity. Because the track finding efficiency depends on the momentum of the track, we account separately for the uncertainty due to this dependence. This analysis uses all tracks

TABLE I. Systematic errors for the inclusive decay multiplicity measurement for $B\bar{B}$ pairs.

Systematic error source	Effect on mean decay multiplicity (charged tracks)
Overall track finding efficiency	+0.17 -0.09
Event selection bias	± 0.07
Low momentum tracking efficiency	± 0.06
K_S modeling	+0.05 -0.03
Hadronic interactions and photon conversion	± 0.03
Contamination by non $B\bar{B}$ events	± 0.02
Decays in flight	± 0.01
All other sources	± 0.01
Total systematic error	+0.21 -0.15

without regard to momentum. When we add a track selection cut requiring a reconstructed momentum of at least 150 MeV/ c , both for data and for Monte Carlo simulation, we observe a shift in the decay multiplicity of -0.6% . We assign an additional $\pm 0.6\%$ uncertainty due to this momentum dependence.

When the event selection bias is removed, the measured mean decay multiplicity shifts by $+0.7\%$, which we also take as the systematic uncertainty for event selection bias. Charged pions produced by the decays of K_S will have lower track finding efficiency than average charged pions, so our result depends on the rate of K_S production in our simulation. Based on our studies of inclusive K_S production in B meson decay, we assign a systematic uncertainty of $^{+0.5}_{-0.3}\%$ from this source. Interactions of neutral and charged decay products with the detector material produce additional charged tracks, some of which satisfy the track selection criteria. We study the effect of these extra tracks by varying the rates of photon conversion and hadronic interactions in our Monte Carlo sample. Misidentification of these extra tracks contributes an additional $\pm 0.3\%$ systematic uncertainty. Extra tracks also come from the decay of particles in the detector volume, adding another $\pm 0.1\%$ uncertainty. Additional uncertainty comes from contamination by non- $B\bar{B}$ events, most notably from beam-gas interactions. We study the effect of non- $B\bar{B}$ events by varying the size of the continuum subtraction by 1% , which is the uncertainty in our measured luminosity, and we find a $\pm 0.2\%$ uncertainty in our mean decay multiplicity.

We have looked for other potential systematic effects by varying our track selection cuts but do not observe any significant change in mean decay multiplicity. When all systematic errors are added in quadrature, we obtain a total systematic uncertainty of $^{+1.9}_{-1.4}\%$, which gives a final result of $10.71 \pm 0.02^{+0.21}_{-0.15}$ for the mean inclusive charged particle decay multiplicity in the decay of a $B\bar{B}$ pair. Systematic errors are summarized in Table I.

The results presented here are a significant improvement over the previous CLEO result [2]. The earlier analysis

found a mean multiplicity of $11.5 \pm 0.2 \pm 0.4$. In addition to using a much larger sample of $B\bar{B}$ events, the present analysis uses a substantially different method. The former analysis treated the coefficients ϵ_{ij} in Eq. (1) as a matrix and used matrix inversion to solve for the D_i . Such matrix inversion is very sensitive to singularities and can produce unstable results. In the current analysis, we do not attempt to invert the ϵ_{ij} matrix, but instead we perform a more stable χ^2 fit for the parameters D_i .

III. SEMILEPTONIC AND NONLEPTONIC MULTIPLICITY MEASUREMENT

We have further analyzed the same data sample to measure multiplicities separately for semileptonic and nonleptonic decays. We define semileptonic to include only decays of B mesons into an electron or muon plus a neutrino and any number of hadrons. All other decays are classified as nonleptonic. Decays involving tau leptons are counted as nonleptonic because approximately 65% of taus decay hadronically [6] and such events cannot be distinguished easily from purely hadronic B decays.

We use the same event and track selection criteria as in the inclusive analysis and sort the events by the number of leptons identified. We identify electrons by combining information on energy deposition in the drift chamber, the shape of the shower observed in the calorimeter, and the ratio of the calorimeter energy to the track momentum. Muons are required to traverse at least three pion nuclear interaction lengths of material. We also require all lepton candidates to have momentum between 1.4 GeV/ c and 2.5 GeV/ c to suppress false lepton identification and secondary leptons.

Once we have sorted the events by the number of leptons found, we correct for misidentified and secondary leptons. We move these misidentified events from the sample with one identified lepton to the sample of events with no identified lepton by using the observed multiplicity distributions of Monte Carlo generated events that are similarly misidentified in the reconstruction. The fake and secondary observed multiplicity distributions are scaled using our best estimates of the fake and secondary lepton rates and are added to the sample with no identified lepton and subtracted from the sample with one identified lepton. Uncertainties in the rates and observed multiplicity distributions of these events are treated as systematic errors.

We use the same methods as in the inclusive analysis to extract the mean decay multiplicity from the corrected observed multiplicity distributions for the samples with zero or one identified lepton. For events with no reconstructed leptons, we obtain a mean decay multiplicity of 11.02 ± 0.01 , and for the sample with one reconstructed lepton, we find a mean of 9.28 ± 0.02 charged tracks, where the errors are statistical only.

Not all semileptonic decays will produce a detected lepton because not all electrons and muons will enter the fiducial tracking volume of the detector and pass the track selection and lepton identification criteria. To obtain the true decay multiplicities for semileptonic and nonleptonic $B\bar{B}$ decays, we use simulation to unfold the migration between the num-

ber of leptons generated by the decay of the B mesons and the number of leptons actually identified. If the migration probability for a given event were independent of the event's decay multiplicity, we could write:

$$M^i = a^i M_{n-n} + b^i M_{s-s}, \quad (3)$$

where the M^i are the mean decay multiplicities of the sample with i identified leptons, M_{n-n} and M_{s-s} are the mean decay multiplicities of events where both B mesons decay nonleptonically and semileptonically, respectively, and a^i and b^i are migration coefficients determined from Monte Carlo simulation. These multiplicities include the lepton tracks.

There are many factors that affect the number of leptons that will be reconstructed for a given event. Lepton identification depends strongly on particle momentum not only because of the explicit momentum requirements but also because a particle's momentum determines the probability that it will penetrate the muon chambers sufficiently to be classified as a muon candidate. Because of phase space limitations, events with one or more high momentum (above 1.4 GeV/ c) particles will tend to have fewer charged tracks than events without a high momentum particle, so events with an identified lepton tend to have lower multiplicities than those where the lepton was not identified.

In addition to assuming that migration probability is independent of decay multiplicity, Eq. (3) also assumes that the mean decay multiplicity of events where only one B meson decays semileptonically is simply the average of M_{n-n} and M_{s-s} . This assumption would be valid if the mean true decay multiplicities of B^- and B^0 mesons were equal, but this may not be the case. To account for the possibility of unequal B^- and B^0 multiplicities and the effect of multiplicity dependent migration, we can introduce another term into Eq. (3):

$$M^i + \Delta^i = a^i M_{n-n} + b^i M_{s-s}. \quad (4)$$

The correction terms Δ^i and migration coefficients are determined from Monte Carlo simulation, and we can solve Eq. (4) for M_{n-n} and M_{s-s} . We obtain mean true decay multiplicities of 11.62 ± 0.04 charged particles for events where neither B meson decays semileptonically and 7.82 ± 0.05 charged particles for events where both B mesons decay semileptonically, where the errors are statistical and include analytic propagation of the uncertainty in each of the parameters in Eq. (4).

All of the systematic uncertainties that affect the inclusive analysis are also present in these semileptonic and nonleptonic results. This $^{+1.9\%}_{-1.4\%}$ uncertainty in unfolding the decay multiplicity from the observed multiplicity is the largest systematic effect for these results. The next largest uncertainty comes from lepton identification, including inefficiencies, false particle identification, and acceptance of secondary leptons not directly produced in the B meson decay. We have studied these effects by varying all of our lepton identification criteria. We have also varied the rates of fake and secondary lepton identification directly in simulation. All of the lepton identification systematics combine to give a ± 0.06 charged track uncertainty in the nonleptonic result and a cor-

TABLE II. Systematic error for the charged track multiplicity in nonleptonic and semileptonic events.

Systematic error source	Nonleptonic events (charged tracks)	Semileptonic events (charged tracks)
Inclusive unfolding	+0.23 -0.16	+0.15 -0.11
Lepton identification	± 0.06	± 0.11
Branching fractions	± 0.05	± 0.08
Fake and secondary leptons	± 0.01	± 0.06
All other sources	$< \pm 0.01$	± 0.01
Total uncertainty	+0.24 -0.18	+0.21 -0.19

responding uncertainty of ± 0.11 charged tracks in the mean decay multiplicity of semileptonic decays. Our result is also sensitive to the modeling of semileptonic decays in our simulation, including the inclusive rate of semileptonic decays and the exclusive branching fractions of semileptonic decays that produce the various resonances of the D meson. We have varied both the inclusive and exclusive branching fractions within their uncertainties and find ± 0.05 uncertainty in the nonleptonic mean decay multiplicity and ± 0.08 uncertainty for the semileptonic result. Uncertainty in the observed multiplicity of events with fake and secondary leptons contributes ± 0.06 charged tracks uncertainty to the semileptonic result. The systematic uncertainties are summarized in Table II.

Combining all errors, we find mean multiplicities of $11.62 \pm 0.04^{+0.24}_{-0.18}$ charged tracks when both B mesons decay nonleptonically and $7.82 \pm 0.05^{+0.21}_{-0.19}$ charged tracks when both B mesons decay semileptonically. As a further check on our systematic errors, we have repeated this analysis by using only electron identification or only muon identification. In both cases, the results are statistically consistent with the means stated above and with each other. Our present results are a significant improvement over the previous CLEO results [2], in which mean multiplicities of $12.6 \pm 0.4 \pm 0.4$ and $8.2 \pm 0.7 \pm 0.4$ were obtained for events where both B mesons decay nonleptonically and semileptonically, respectively.

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