Title
Measurement of the $B \to X\ell^+\ell^-$ Branching fraction and search for direct CP violation from a sum of exclusive final states

Permalink
https://escholarship.org/uc/item/6d04f81q

Journal
Physical Review Letters, 112(21)

ISSN
0031-9007

Authors
Lees, JP
Poireau, V
Tisserand, V
et al.

Publication Date
2014-05-30

DOI
10.1103/PhysRevLett.112.211802

License
https://creativecommons.org/licenses/by/4.0/ 4.0

Peer reviewed
Measurement of the $B \to X_{\ell\ell} \ell^+\ell^-$ Branching Fraction and Search for Direct CP Violation from a Sum of Exclusive Final States

J. P. Lees, V. Poireau, V. Tisserand, E. Grauges, A. Palano, G. Eigen, B. Stugu, D. N. Brown, L. T. Kerth, Yu. G. Kolomensky, M. J. Lee, G. Lynch, H. Koch, T. Schroeder, C. Hearty, T. S. Mattison, J. A. McKenna, R. Y. So, A. Khan, V. E. Blinov, A. R. Buzylkaev, V. P. Druzhinin, V. B. Golubev, E. A. Kravchenko, A. P. Onuchin, S. I. Seredynakov, Yu. I. Skovpen, E. P. Solodov, K. Yu. Toidsev, A. N. Yushkov, A. J. Lankford, M. Mandelkern, B. Dey, J. W. Gary, O. Long, C. Campagnini, M. Franco Serena, T. M. Hong, D. Kovalskyi, J. D. Richman, C. A. West, A. M. Eisner, W. S. Lockman, B. A. Schumm, A. Seiden, D. S. Chao, P. R. Schwierz, D. Bernard, M. Verden, S. Playfer, D. Bettoni, R. Calabrese, G. Cibinetto, A. M. Lutz, B. Malaescu, P. Roudeau, A. Stocchi, G. Wormser, D. J. Lange, D. M. Wright, V. Prasad, M. Morii, A. Adametz, U. Uwer, H. M. Lacker, P. D. Dauncey, U. Mallik, C. Chen, J. Cochran, W. T. Meyer, S. Prell, H. Ahmed, A. V. Grisian, N. Arnaud, M. Davier, D. Derkach, G. Grosdidier, F. Le Diberder, A. M. Lutz, B. Dey, J. W. Gary, O. Long, C. Campagnari, M. Franco Serena, T. M. Hong, E. M. T. Puccio, M. S. Alam, R. Gorodeisky, N. Guttman, D. R. Peimer, A. Soffer, S. M. Spanier, M. Martinelli, G. Raven, C. H. Cheng, B. Echenard, K. T. Flood, D. G. Hitlin, T. S. Miyashita, F. Ongmongkol, F. C. Porter, R. Andreassen, Z. Huard, B. C. Wray, J. M. Izen, X. C. Lou, F. Bianchi, W. H. Toki, B. Spaan, R. Schwierz, D. Bernard, M. Verden, S. Playfer, D. Bettoni, C. A. West, A. M. Eisner, W. S. Lockman, B. A. Schumm, A. Seiden, D. S. Chao, F. De Mori, A. Filippi, D. Gamba, S. Zambito, L. Lanceri, F. Martinez-Vidal, A. Oyanguren, P. Villanueva-Perez, J. Albert, Sw. Banerjee, F. U. Bernlochner, G. J. King, R. Kowalewski, M. J. Lewczuk, T. Lueck, J. M. Nugent, J. M. Roney, R. J. Sobie, N. Tasneem, T. J. Gershon, P. F. Harrison, T. E. Latham, H. R. Band, S. Dasu, Y. Pan, R. Prepost, and S. L. Wu

(\textit{BABAR} Collaboration)

\textit{PRL} 112, 211802 (2014) PHYSICAL REVIEW LETTERS week ending 30 MAY 2014

0031-9007/14/112(21)/211802(8) 211802-1 © 2014 American Physical Society
We measure the total branching fraction of the flavor-changing neutral-current process \( B \to X_s \ell^+ \ell^- \), along with partial branching fractions in bins of dilepton and hadronic system (\( X_s \)) mass, using a sample of \( 471 \times 10^6 \) \( \Upsilon(4S) \to BB \) events recorded with the BABAR detector. The admixture of charged and neutral \( B \) mesons produced at PEP-II2 are reconstructed by combining a dilepton pair with 10 different \( B \) bins of dilepton mass; over the full dilepton mass range, we find the inclusive branching fraction \( B(B \to X_s \ell^+ \ell^-) = [6.73^{+0.79}_{-0.70}(\text{stat})^{+0.34}_{-0.32}(\text{exp syst}) \pm 0.50(\text{model syst})] \times 10^{-6} \) for \( m_{\ell^+ \ell^-} > 0.1 \text{ GeV}/c^2 \). Restricting our analysis exclusively to final states from which a decaying \( B \) meson’s flavor can be inferred, we additionally report measurements of the direct \( CP \) asymmetry \( A_{CP} \) in bins of dilepton mass; over the full dilepton mass range, we find \( A_{CP} = 0.04 \pm 0.11 \pm 0.01 \) for a lepton-flavor-averaged sample.

$$\text{DOI: 10.1103/PhysRevLett.112.211802}$$

**PACS numbers:** 13.20.He, 11.30.Er

The \( b \to s \ell^+ \ell^- \) transition, where \( b \) is a bottom quark, \( s \) is a strange quark, and \( \ell^+ \ell^- \) is an \( e^+e^- \) or \( \mu^+\mu^- \) pair, is forbidden at lowest order in the standard model (SM) but is allowed at one loop via electroweak penguin and \( W \)-box diagrams. The amplitude for this decay is expressed in terms of perturbatively calculable effective Wilson coefficients, \( C_7^{\text{eff}}, C_9^{\text{eff}}, \) and \( C_{10}^{\text{eff}} \), which represent the electromagnetic penguin diagram and the vector part and axial-vector part of the linear combination of the \( Z \) penguin and \( W^+W^- \) box diagrams, respectively [1]. Non-SM contributions can enter these loops at the same order as the SM processes, modifying the Wilson coefficients from their SM expectations and allowing experimental sensitivity to possible non-SM physics [2–11].

We study the inclusive decay \( B \to X_s \ell^+ \ell^- \), where \( X_s \) is a hadronic system containing exactly one kaon, using a sum over exclusive final states, which provides a basis for extrapolation to the fully inclusive rate. We measure the total branching fraction (BF), as well as partial BFs in five disjoint dilepton mass-squared \( q^2 \equiv m_{\ell^+ \ell^-}^2 \) bins and four
hadronic mass $m_{X_s}$ bins, which are defined in Table I. We additionally search for direct CP violation in the same $q^2$ bins. The relative precision of our results is approximately a factor of 2 better than the combined precision of all previously published measurements [12].

The $X_s$ system in the lowest mass $m_{X_s}$ bin $m_{X_s,1}$ contains a single kaon with no other hadrons present; the $m_{X_s,2}$ bin is populated only up to the $K\pi$ threshold. Results are also reported in an additional $q^2$ region $q^2 \equiv 1 < q^2 < 6$ GeV$^2$/c$^2$, i.e., the perturbative window away from the photon pole at low $q^2$ and the $c\bar{c}$ resonances at higher $q^2$, where theory uncertainties are well controlled [13–24]. The most recent SM predictions in this region are $B^{\text{SM}}(B \to X_s \mu^+ \mu^-) = (1.59 \pm 0.11) \times 10^{-6}$ and $B^{\text{SM}}(B \to X_s e^+ e^-) = (1.64 \pm 0.11) \times 10^{-6}$ [22]. Theory uncertainties in the $q^2$ range above the hadronic mass exclusive final states using only final data set. More recently, both collaborations (along with $q^2$ unreconstructed and bin. The number in parentheses after each result is the multiplier which is applied to the measured semi-inclusive rate to account for $45 \pm 2$ uncertainty in the same region [22]. The SM expectation in the $q^2 > 4m^2$ range is $B(B \to X_s^{\text{eff}} e^+ e^-) = (4.6 \pm 0.8) \times 10^{-6}$ [20]. Direct CP violation, defined as $A_{CP} = (B_{FB} - B_{FB})/(B_{FB} + B_{FB})$, where $b$ ($\bar{b}$) denotes a $B$ ($\bar{B}$) parent, is expected to be suppressed well below the $1\%$ level in both exclusive and inclusive $b \to s\ell^+\ell^-$ transitions [25–28]; however, in beyond-SM models with four quark generations, significant enhancements are possible, particularly in the high-$q^2$ region [10,11].

The BABAR [29] and Belle [30] Collaborations have previously published $B \to X_s e^+ e^-$ BFs based on a sum over exclusive final states using only ~25% of each experiment’s final data set. More recently, both collaborations (along with LHCb and CDF) have published BFs, and time-integrated rate and angular asymmetries, for the exclusive decays $B \to K^{*0} e^+\ell^-$ [31–37]. The present analysis uses the $424.2 \pm 1.8$ fb$^{-1}$ $e^+e^- \to \Upsilon(4S)$ data sample [38], corresponding to $471 \times 10^6 BB$ pairs, collected with the BABAR detector [39,40] at the PEP-II collider at the SLAC National Accelerator Laboratory.

The decays $B \to X_s e^+ e^-$ are reconstructed in 10 separate $X_s$ hadronic final states ($K^+, K^+ \pi^0$, $K^+ \pi^-$, $K^+ \pi^- \pi^0$, $K^+ \pi^- \pi^0$, $K^+ \bar{K}^0\pi^0$, $K^+\pi^0\pi^0$, and $K^0_{S}\pi^0\pi^0$) [41], combining these with an $e^+e^-$ or $\mu^+\mu^-$ pair for a total of 20 final states. The selection of charged and neutral particle candidates, as well as the reconstruction of $\pi^+ \gamma$ and $K^0_S \to \pi^0 \pi^0$, is described in Refs. [31,36]. Based on studies including up to 18 $X_s$ modes with a maximum of four pions and $m_{X_s}$ as large as 2.2 GeV/c$^2$, we limit the number of $X_s$ final states to the 10 listed above and require $m_{X_s} < 1.8$ GeV/c$^2$ since the expected signal-to-background ratio rapidly decreases with increasing $X_s$ pion multiplicity and mass. We assume that the fraction of modes containing a $K^0_S$ is equal to that containing a $K^0_S$ and account for these decays, as well as $K^0_S \to \pi^0\pi^0$ and $\pi^0$ Dalitz decays, in our reconstruction efficiencies. With these efficiencies taken into account, the reconstructed states represent ~70% of the total inclusive rate.

We account for missing hadronic final states, as well as for states with $m_{X_s} > 1.8$ GeV/c$^2$, based on the formalism of Refs. [8,13,22,42–44], with hadronization of the $X_s$ system provided by the JETSET [45] event generator. Given that we observe no statistically significant nonresonant $B \to K\pi e^+ e^-$ decays in our data [31], signal decays with a two-body $X_s$ system and $m_{X_s} < 1.1$ GeV/c$^2$ are assumed.
to proceed through the $K^*(892)$ resonance. The simulation of such events, as well as those with a single kaon and no pions, is similar to that for inclusive events but incorporates the form factor models of Refs. [46,47].

The kinematic variables $m_{ES} = \sqrt{E_{c.m.}^2/4 - p^2}$ and $\Delta E = E_B - E_{c.m.}/2$, where $p^*_B$ and $E^*_B$ are the $B$ momentum and energy in the $\Upsilon(4S)$ center-of-mass (c.m.) frame with $E_{c.m.}$, the total c.m. energy, are used to distinguish signal from background events. We require $m_{ES} > 5.225$ GeV/$c^2$ and $-0.10 < \Delta E < 0.05$ GeV ($-0.05 < \Delta E < 0.05$ GeV) for dielectron (dimuon) final states. Signale-like $B$ backgrounds with $J/\psi$ [$\psi(2S)$] daughters are removed by vetoing events with $6.8 < q^2 < 10.1$ GeV/$c^2$ ($12.9 < q^2 < 14.2$). We reconstruct $X_s h^\pm\mu^\mp$ final states, where $h$ is a track with no particle identification (PID) requirement applied, to characterize backgrounds from hadrons misidentified as muons. Such backgrounds occur only in dimuon final states because of the significantly higher probability to misidentify $K^+$ or $\pi^+$ as a muon rather than an electron. Similarly, backgrounds from $B \rightarrow D(\rightarrow K^{\pm}h)\pi$ decays occur only in dimuon modes and, assigning the pion mass hypothesis to both muon candidates, we reject candidates with $K^{\pm}\pi^\mp$ mass values in the range $1.84 < m_{K^{\pm}\pi^\mp} < 2.04$ GeV/$c^2$.

We suppress $e^+e^- \rightarrow q\bar{q}$ events (where $q$ is a $u,d,s$, or $c$ quark) and $B\bar{B}$ combinatoric backgrounds using boosted decision trees (BDTs) [48,49] identical in construction to those used in our $B \rightarrow K^{(*)}\ell^+\ell^-$ analysis [31]. These BDTs are, respectively, trained with simulated $udsc$ or $BB$ backgrounds and correctly reconstructed signal events. Ensembles of simulated event samples are used to simultaneously optimize the $\Delta E$ windows and selection on the $udsc$ BDTs for each individual $q^2$ and $m_{X_s}$ bin. After all selection criteria are applied, the average multiplicity of $B$ candidates per event is $\sim$2.6 ($\sim$2.2) for $e^+e^- (\mu^+\mu^-)$ final states. We allow only one candidate per event, selecting the candidate with the smallest $|\Delta E|$. Signal efficiencies after event selection range from about 1% to 30% depending on mode and the $q^2$ or $m_{X_s}$ bin.

In each $q^2$ and $m_{X_s}$ bin, we extract the signal yield with a two-dimensional maximum likelihood fit using $m_{ES}$ and a likelihood ratio $L_R$ based on the $B\bar{B}$ BDT, $L_R \equiv P_S/(P_S + P_B)$, where $P_S$ and $P_B$ are, respectively, probabilities for genuine-signal and $BB$ backgrounds. For correctly reconstructed signal events, $L_R$ sharply peaks near one, while $BB$ backgrounds peak at zero. Events with $L_R > 0.42$ are selected. This selection rejects $\geq95\%$ of the $B\bar{B}$ background events remaining after all other event selections have been applied, with only a trivial reduction in signal efficiency.

Five (six) event classes contribute to the dielectron (dimuon) maximum likelihood fit: (1) correctly reconstructed signal; (2) events that contain a partially or incorrectly reconstructed $B \rightarrow X_s, e^+\ell^-$ decay (signal cross feed); (3) $udsc$ and (4) $B\bar{B}$ combinatoric backgrounds; (5) charmonium backgrounds; and, for dimuon modes, (6) events with hadrons misidentified as muons.

There is no correlation between $m_{ES}$ and $L_R$ for correctly reconstructed signal events. Therefore, the probability distribution function (PDF) for these events is chosen as a product of two 1D PDFs, with $m_{ES}$ parametrized with a Crystal Ball function [50–52] and $L_R$ described by a nonparametric histogram PDF. The Crystal Ball shape parameters are fixed using simulated signal events, as is the $L_R$ PDF. These PDFs describe well the $m_{ES}$ and $L_R$ distributions derived from the high-statistics control samples of vetoed signal-like charmonium events. The signal cross feed is modeled as a 2D $m_{ES}$ versus $L_R$ histogram PDF using simulated signal samples, with normalization $N_{\bar{X}_t}$ scaled as a fixed fraction of the fit signal yield $N_{sig}$.

The $udsc$ combinatoric background PDF is derived from simulated events using a 2D nonparametric kernel density estimator with adaptive bandwidth [49,53,54], which is validated using data collected with $e^+e^-$ center-of-mass energy 40 MeV below the $\Upsilon(4S)$ resonance. The $udsc$ normalization $N_{udsc}$ is obtained by scaling the 43.9 $\pm$ 0.2 fb$^{-1}$ of off-resonance data [38] by the ratio of on- to off-resonance integrated luminosity.

The shape of the 2D PDF for the $B\bar{B}$ combinatoric background is modeled similarly to the $udsc$ background. Its normalization in the $5.225 < m_{ES} < 5.270$ GeV/$c^2$ sideband, where no correctly reconstructed signal events are expected, is obtained by subtracting the $N_{\bar{X}_t}^{SB}$, $N_{udsc}^{SB}$, $N_{chm}^{SB}$, and $N_{had}^{SB}$ (for dimuon events) contributions from the total number of sideband events, giving the $BB$ yield in the sideband region $N_{BB}^{SB}$. We use simulated events to obtain the ratio of the number of $B\bar{B}$ combinatoric events in the $m_{ES} > 5.27$ GeV/$c^2$ signal region to the number in the sideband region to scale $N_{BB}^{SB}$ into the expected contribution $N_{BB}^{sig}$ in the full fit region.

Charmonium backgrounds escaping the vetoed $q^2$ regions are similarly described by a 2D kernel estimator, with normalization $N_{chm}^{SB}$ derived from a fit to the data in the vetoed regions that is extrapolated into the nonvetoed regions. The normalization $N_{had}^{SB}$ and shape of the 2D PDF for misidentified dimuon events are characterized by a weighted 2D histogram taken directly from data using event-by-event weights obtained from PID control samples [31,55].

We extract the $N_{sig}^{SB}$ central value and associated upper and lower limits using the negative log-likelihood for $N_{sig}$. We calculate partial BFs taking into account the efficiency for each final state in each $q^2$ and $m_{X_s}$ bin, as well as the multiplicative factors that provide extrapolation to the fully inclusive BFs. The results are shown in Table I, where the fully inclusive total rate and the $m_{X_s}$ binned results include estimated signal contributions in the vetoed charmonium $q^2$ regions. Fit projections for all $q^2$ and $m_{X_s}$ bins are available in the Supplemental Material [56], along with a table giving the raw numerical results from our fits. Figure 1 shows our $q^2$ binned results overlaid on the nominal SM expectations.
derived from our $B \rightarrow X_s e^+ e^-$ signal model. A similar plot for $m_{X_s}$ is included in the Supplemental Material [56].

We consider systematic uncertainties associated with purely experimental systematic uncertainties and the model-dependent extrapolation to the fully inclusive rate. The experimental systematics can either be additive, affecting the extraction of the signal yield from the data, or multiplicative, affecting the calculation of a BF from an observed signal yield. Sources of multiplicative systematic uncertainty include BB counting as well as tracking, PID, and reconstruction efficiencies. The only significant additive systematic uncertainties are associated with the PDF parameterizations and normalizations. The total experimental systematic uncertainty is the sum in quadrature of the above terms, with the exception that uncertainties related to charged particle tracking efficiencies are assumed to be fully correlated among all charged particles. The evaluation of all experimental systematics is fully described in Ref. [31]. Tables quantifying each individual contribution to the experimental and model-dependent extrapolation systematic uncertainties are available in the Supplemental Material [56].

The uncertainty in the extrapolation to the inclusive rate is characterized through variations that attempt to quantify our lack of knowledge of the true dilepton mass-squared distribution and hadronization of the $X_s$ system beyond the specific final states and $m_{X_s}$ range that we observe. We average the most recent $B \rightarrow K^{(*)} e^+ e^-$ BFs [57], excluding BABAR results, and use the latest BABAR result [58] for the ratio of charged-to-neutral $\Upsilon(4S) \rightarrow h\bar{h}$ decays, $\Gamma(B^+ B^-)/\Gamma(B^0\bar{B}^0) = 1.006 \pm 0.036 \pm 0.031$. Each of these terms is varied by its one-standard-deviation uncertainty. We examine an alternate $m_{X_s}$ transition point of 1.0 GeV/c$^2$ between the $B \rightarrow K^{(*)} e^+ e^-$ and $B \rightarrow X_s e^+ e^-$ models. To account for hadronization uncertainties in $m_{X_s} > 1.1$ GeV/c$^2$ events, we generate 20 simulated data sets with varied jet set tunings, two different values for the $B$-meson Fermi motion, and two different $b$-quark mass values. We take the full spread of the extrapolation factors derived from these variations to estimate this systematic uncertainty. Additionally, for $m_{X_s} > 1.1$ GeV/c$^2$, the fraction of modes with more than one $\pi^0$ is varied around the generator value of 0.20 by ±50%; the fraction of modes with either no $\pi^0$ and more than two charged pions, or one $\pi^0$ and more than one charged pion, is varied by ±50% around the $q^2$-dependent generator value; and the fraction of modes with more than one neutral or charged kaon is varied around the generator value of 0.034 by ±50%. Contributions from final states with photons that do not come from $\pi^0$ decays but rather from $\eta, \eta', \omega, \ldots$ are expected to be insignificant, and we do not vary the fractions of these decays. Each of the above variations is added in quadrature to obtain the final model-dependent systematic. Table I lists both the experimental and model-dependent systematics.

We calculate the total inclusive rate by summing the $q^2_i$ through $q^2_5$ results taking into account correlations in the systematic uncertainties and estimating signal contributions in the vetoed charmonium $q^2$ regions. The lepton-flavor-averaged $B \rightarrow X_s e^+ e^-$ results are weighted averages of the individual $B \rightarrow X_s e^+ e^-$ and $B \rightarrow X_s \mu^+ \mu^-$ results that take into account correlations in the systematic uncertainties. Figure 1 shows the differential BF results as a function of $q^2$ and $m_{X_s}$ overlaid with the SM expectation. The results in these bins, as well as in the $q^2_5$ region, are generally in good agreement with SM predictions. Given our experimental uncertainties, we are insensitive to the relatively small differences in the $e^+ e^-$ and $\mu^+ \mu^-$ rates expected in the SM, and observe no significant differences between $e^+ e^-$ and $\mu^+ \mu^-$ final states.

Several model-independent analyses of the form-factor-independent angular observables reported in a recent $B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ LHCb analysis [35] explain the anomaly reported there in terms of a nonvanishing beyond-SM contribution $C_{BSM}^{\psi}$ [59-68]. These phenomenological studies all present generally similar results, yielding a $3\sigma$ range for $C_{BSM}^{\psi}$ of $\sim[-2,0]$, implying a corresponding suppression in the fully inclusive BF of up to $\sim25\%$ in the $1 < q^2 < 6$ GeV$^2/c^4$ and $q^2 > 14.4$ GeV$^2/c^4$ ranges. Although our results in the $q^2_5$ range are consistent with both the SM expectation and a possible suppression in the decay rate, our results in the $q^2_5$ range show an excess, rather than a deficit, of $\sim2\sigma$ in both the $B \rightarrow X_s e^+ e^-$ and $B \rightarrow X_s \mu^+ \mu^-$ rates with respect to the SM expectation [22].

We search for $C_{CP}$ violation in each $q^2_i$ bin by dividing our data set into four disjoint samples according to lepton identity ($e^+ e^-$ or $\mu^+ \mu^-$) and the $B$ or $\bar{B}$ flavor as determined by the kaon and pion charges of the $X_s$ system. Modes with $X_s = K_s^0, K_s^0\pi^0, \text{or } K_s^0\pi^-\pi^+$ are not used, and, because we perform no model-dependent extrapolation of signal rates, we measure $A_{CP}$ only for the particular combination of final
states used here. We simultaneously fit all four data sets, sharing a single value of \(A_{CP}\) as a free parameter, using the \(B\)’s fit model described above. Our \(A_{CP}\) results are shown in Table I, and a plot of the results as a function of \(q^2\) is included as part of the Supplemental Material [56].

We analyze the vetoed \(J/\gamma\) data set, where \(CP\) violation is expected to be trivially small [69,70], with the same fitting methodology used for the signal \(q^2\) bins; we find 
\[ A_{CP}^{\gamma} = 0.0046 \pm 0.0057 \text{(stat)}. \]

Observing no significant bias, we assign the statistical uncertainty here as the systematic uncertainty for the \(A_{CP}\) results. To extract \(A_{CP}\) for the full dilepton mass range, we sum the \(A_{CP}\) BF across the four disjoint \(A_{CP} q^2\) bins; excluding the charmion vetom veto windows, we find 
\[ A_{CP} = 0.04 \pm 0.11 \text{(stat)} \pm 0.01 \text{(syst)}. \]

We observe no significant asymmetry in any \(q^2\) region for the full dilepton mass range.

In summary, we have measured the total and partial BFs, as well as \(A_{CP}\), for the inclusive radiative electroweak process \(B \rightarrow X_c \ell^+\ell^-\). Our results are in general agreement with SM expectations with the exception of our partial BF results in the high-\(q^2\) region, which show a \(\sim 2\sigma\) excess compared to both the SM expectation and the most favored value of the beyond-SM contribution \(C_{B}^{\text{eff}}\) advanced to explain recent observations by LHCb [35].

We are grateful to Enrico Lunghi, Tobias Hurch, and Tobias Huber for useful discussions, as well as providing dilepton mass-squared theory distributions derived using the most up-to-date corrections. We are additionally grateful for the excellent luminosity and machine conditions provided by our PEP-II2 colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (U.S.), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (Netherlands), NFR (Norway), MES (Russia), MINECO (Spain), and STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A.P. Sloan Foundation (U.S.).

---

1 Deceased.

2 Now at: University of Tabuk, Tabuk 71491, Saudi Arabia.

3 Also at: Università di Perugia, Dipartimento di Fisica, I-06123 Perugia, Italy.

4 Now at: Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, F-75252 Paris, France.

5 Now at: University of Huddersfield, Huddersfield HD1 3DH, United Kingdom.

6 Now at: University of South Alabama, Mobile, Alabama 36688, USA.

7 Also at: Università di Sassari, I-07100 Sassari, Italy.

8 Also at: INFN Sezione di Roma, I-00185 Roma, Italy.

9 Now at: Universidad Técnica Federico Santa Maria, 2390123 Valparaíso, Chile.

10 K. S. M. Lee and F. J. Tackmann, Phys. Rev. D 83, 114021 (2011).

11 A. Soni, A. K. Alok, R. Mohanta, and S. Nandi, Phys. Rev. D 82, 033009 (2010).

12 J. Beringer et al. (Particle Data Group), Phys. Rev. D 85, 010001 (2012).

13 H. H. Asatryan, H. M. Asatryan, G. Greub, and M. Walker, Phys. Rev. D 65, 074004 (2002).

14 H. H. Asatryan, H. M. Asatryan, G. Greub, and M. Walker, Phys. Rev. D 66, 034009 (2002).

15 A. Ghinculov, T. Hurth, G. Isidori, and Y. P. Yao, Nucl. Phys. B648, 254 (2003).

16 H. M. Asatryan, K. Bieri, C. Greub, and A. Hovhannisyan, Phys. Rev. D 66, 094013 (2002).

17 P. Gambino, M. Gorbahn, and U. Haisch, Nucl. Phys. B673, 238 (2003).

18 A. Ghinculov, T. Hurth, G. Isidori, and Y. P. Yao, Eur. Phys. J. C 33, S288 (2004).

19 C. Bobeth, P. Gambino, M. Gorbahn, and U. Haisch, J. High Energy Phys. 04 (2004) 071.

20 A. Ghinculov, T. Hurth, G. Isidori, and Y. P. Yao, Nucl. Phys. B685, 351 (2004).

21 C. Greub, V. Plipp, and C. Schupbach, J. High Energy Phys. 12 (2008) 040.

22 T. Huber, T. Hurth, and E. Lunghi, Nucl. Phys. B802, 40 (2008).

23 T. Huber, E. Lunghi, M. Misiak, and D. Wyler, Nucl. Phys. B740, 105 (2006).

24 M. Beneke, G. Buchalla, M. Neubert, and C. T. Sachrajda, Eur. Phys. J. C 61, 439 (2009).

25 D. S. Du and M. Z. Yang, Phys. Rev. D 54, 882 (1996).

26 A. Ali and G. Hiller, Eur. Phys. J. C 8, 619 (1999).

27 C. Bobeth, G. Hiller, and G. Piranishvili, J. High Energy Phys. 07 (2008) 106.

28 W. Altmannshofer et al., J. High Energy Phys. 01 (2009) 019.

29 B. Aubert et al. (BABAR Collaboration), Phys. Rev. Lett. 93, 081802 (2004).

30 M. Iwasaki et al. (Belle Collaboration), Phys. Rev. D 72, 092005 (2005).

31 J. P. Lees et al. (BABAR Collaboration), Phys. Rev. D 86, 032012 (2012).

32 J.-T. Wei et al. (Belle Collaboration), Phys. Rev. Lett. 103, 171801 (2009).
[33] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. 107, 201802 (2011).
[34] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 108, 181806 (2012).
[35] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 111, 191801 (2013).
[36] B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 79, 031102 (2009).
[37] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 110, 031801 (2013).
[38] J. P. Lees et al. (BABAR Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 726, 203 (2013).
[39] B. Aubert et al. (BABAR Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 479, 1 (2002).
[40] B. Aubert et al. (BABAR Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 729, 615 (2013).
[41] The use of charge conjugate reactions is implied unless otherwise indicated.
[42] F. Kruger and L. M. Sehgal, Phys. Lett. B 380, 199 (1996).
[43] A. Ali, G. Hiller, L. T. Handoko, and T. Morozumi, Phys. Rev. D 55, 4105 (1997).
[44] C. Bobeth, M. Misiak, and J. Urban, Nucl. Phys. B574, 291 (2000).
[45] T. Sjöstrand, Comput. Phys. Commun. 82, 74 (1994).
[46] P. Ball and R. Zwicky, Phys. Rev. D 71, 014029 (2005).
[47] P. Ball and R. Zwicky, Phys. Rev. D 71, 014015 (2005).
[48] L. Breiman, Mach. Learn. 24, 123 (1996).
[49] I. Narsky, arXiv:physics/0507157.
[50] M. J. Oreglia, Ph.D. thesis, Stanford University (Report No. SLAC-236, 1980).
[51] J. E. Gaiser, Ph.D. thesis, Stanford University (Report No. SLAC-255, 1982).
[52] T. Skwarnicki, Report No. DESY-F31-86-02.
[53] E. Parzen, Ann. Math. Stat. 33, 1065 (1962).
[54] V. A. Epanechnikov, Theory Probab. Appl. 14, 153 (1969).
[55] B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 73, 092001 (2006).
[56] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.112.211802 for plots of our results as a function of $q^2$ and $m_x$, as well as tables of systematics and raw fitted numerical yields, and projections of each of our branching fraction fits onto their respective data sets.
[57] Y. Amhis et al. (Heavy Flavor Averaging Group), arXiv:1207.1158.
[58] B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 69, 071101 (2004).
[59] S. Descotes-Genon, J. Matias, and J. Virto, Phys. Rev. D 88, 074002 (2013).
[60] S. Jäger and J. Martin Camalich, J. High Energy Phys. 05 (2013) 043.
[61] A. J. Buras and J. Girrbach, J. High Energy Phys. 12 (2013) 009.
[62] W. Altmannshofer and D. M. Straub, Eur. Phys. J. C 73, 2646 (2013).
[63] R. Gauld, F. Goertz, and U. Haisch, Phys. Rev. D 89, 015005 (2014).
[64] R. Gauld, F. Goertz, and U. Haisch, J. High Energy Phys. 01 (2014) 069.
[65] F. Beaujean, C. Bobeth, and D. van Dyk, arXiv:1310.2478.
[66] R. R. Horgan, Z. Liu, S. Meinel, and M. Wingate, arXiv:1310.3887 [Phys. Rev. Lett. (to be published)].
[67] A. J. Buras, F. De Fazio, and J. Girrbach, J. High Energy Phys. 02 (2014) 112.
[68] T. Hurth and F. Mahmoudi, J. High Energy Phys. 04 (2014) 097.
[69] G.-H. Wu and A. Soni, Phys. Rev. D 62, 056005 (2000).
[70] W.-S. Hou, M. Nagashima, and A. Soddu, arXiv:hep-ph/0605080.