Evidence for the Rare Decay $B \rightarrow K^{*}\ell^{+}\ell^{-}$ and Measurement of the $B \rightarrow K\ell^{+}\ell^{-}$ Branching Fraction

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We present evidence for the flavor-changing neutral current decay \( B \to K^{*} \ell^+ \ell^- \) and a measurement of the branching fraction for the related process \( B \to K \ell^+ \ell^- \), where \( \ell^+ \ell^- \) is either an \( e^+e^- \) or \( \mu^+\mu^- \) pair. These decays are highly suppressed in the Standard Model, and they are...
Rare decays of $B$ mesons that involve loop diagrams in the Standard Model (SM) provide a promising means to search for effects beyond the SM. The decays $B \to K\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$, where $\ell^\pm$ are charged leptons and $K^*$ is the $K^*(892)$ meson, result from one-loop processes that transform the $b$-quark in the initial-state $B$ meson into an $s$-quark in the final-state $K^*$ meson.

Because of their loop structure, these decays are highly suppressed, with SM branching fractions expected to be roughly $0.5 \times 10^{-6}$ for $B \to K^*\ell^+\ell^-$ and about three times that for the $B \to K^*\ell^+\ell^-$ modes. Due to the complexity of strong interaction effects, however, theoretical uncertainties on the rates are currently at least 35% (Ali et al. [1]). Both $B \to K^*\ell^+\ell^-$ and $B \to K^*\mu^+\mu^-$ receive a contribution from the pole in the EM penguin amplitude at $q^2 = m^2_{\ell^+\ell^-} = 0$, but the enhancement in the electron mode is larger. An important consequence of the loop structure of these decays is that their branching fractions and kinematic distributions can be significantly more complex than $B \to K^*\gamma$, which proceeds solely through an EM penguin.

We select events that include two oppositely charged leptons ($e^+e^-$, $\mu^+\mu^-$), a kaon (either $K^\pm$ or $K_S^0$), and, for the $B \to K^*\ell^+\ell^-$ modes, a $\pi^\pm$ that combines with a kaon to form a $K^*$ candidate. Electrons are identified primarily in the CsI(Tl) electromagnetic calorimeter, while muons are identified by their penetration through iron plates of the magnet flux return. Electron (muon) candidates are required to satisfy $p > 0.5 (1.0)$ GeV/$c$.

We perform a three-dimensional fit to the distribution of two kinematic variables, which can be fit to extract the signal and background yields. For a candidate system of $B$ daughter particles with masses $m_1$ and three-momenta $p_1^*$ in the $\Upsilon(4S)$ center-of-mass (CM) frame, we define $m_{ES} = \sqrt{E_b^2 - |\sum_i p_i^*|^2}$ and $\Delta E = \sum_i \sqrt{m_i^2 + p_i^*|^2} - E_b$, where $E_b$ is the beam energy in the CM frame. For signal events, the $m_{ES}$ distribution peaks at the $B$ meson mass with resolution $\sigma \approx 2.5$ MeV/$c^2$, and the $\Delta E$ distribution peaks near zero, with a typical width $\sigma \approx 20$ MeV. In $B \to K\ell^+\ell^-$ channels, we perform a two-dimensional unbinned maximum-likelihood fit to the distribution of $m_{ES}$ and $\Delta E$ in the region $m_{ES} > 5.2$ GeV/$c^2$ and $|\Delta E| < 0.25$ GeV. In $B \to K^*\ell^+\ell^-$ decays, we perform a three-dimensional fit to $m_{ES}$, $\Delta E$, and the kaon-pion invariant mass in the region $0.7 < m_{K\pi} < 1.1$ GeV/$c^2$.

Backgrounds arise from three main sources: random combinations of particles from $q\bar{q}$ events produced in the continuum, random combinations of particles from $\Upsilon(4S) \to B\bar{B}$ decays, and $B$ decays to topologies similar to the signal modes. The first two ("combinatorial") backgrounds typically arise from pairs of semileptonic decays and produce broad distributions in $m_{ES}$ and $\Delta E$. We select events that include two oppositely charged leptons ($e^+e^-$, $\mu^+\mu^-$), a kaon (either $K^\pm$ or $K_S^0$), and, for the $B \to K^*\ell^+\ell^-$ modes, a $\pi^\pm$ that combines with a kaon to form a $K^*$ candidate. Electrons are identified primarily in the CsI(Tl) electromagnetic calorimeter, while muons are identified by their penetration through iron plates of the magnet flux return. Electron (muon) candidates are required to satisfy $p > 0.5 (1.0)$ GeV/$c$.
compared to the signal. The third source arises from modes such as $B \to J/\psi K^{(*)}$ (with $J/\psi \to \ell^+\ell^-$) or $B \to K^{(*)}\pi\pi$ (with pions misidentified as muons), which have shapes similar to the signal. All selection criteria are optimized with GEANT4 simulated data or with data samples outside the full fit region.

We suppress combinatorial background from continuum processes using a Fisher discriminant, which is a linear combination of variables with coefficients optimized to distinguish between signal and background. The variables (defined in the CM frame) are (1) the ratio of second- to zeroth-order Fox-Wolfram moments for the event, computed using all charged tracks and neutral energy clusters; (2) the angle between the thrust axis of the $B$ candidate and that of the remaining particles in the event; (3) the production angle $\theta_B$ of the $B$ candidate with respect to the beam axis; and (4) the masses of $K\ell$ pairs with charge correlation consistent with $D$ decay.

We suppress combinatorial backgrounds from $B\bar{B}$ events using a likelihood function constructed from (1) the missing energy of the event, computed from all charged tracks and neutral energy clusters; (2) the vertex fit probability of all tracks from the $B$ candidate; (3) the vertex fit probability of the two leptons; and (4) the angle $\theta_B$. Missing energy provides the strongest suppression of combinatorial $B\bar{B}$ background events, which typically contain neutrinos from two semileptonic decays.

The most prominent backgrounds that peak in $m_{ES}$ and $\Delta E$ are $B$ decays to charmonium: $B \to J/\psi K^{(*)}$ (with $J/\psi \to \ell^+\ell^-$) and analogous $B$ decays to $\psi(2S)$. We exclude dilepton pairs consistent with the $J/\psi$ ($2.90 < m_{\ell^+\ell^-} < 3.20$ GeV/c$^2$) and 3.00 $< m_{\mu^+\mu^-} < 3.20$ GeV/c$^2$) or with the $\psi(2S)$ (3.60 $< m_{\ell^+\ell^-} < 3.75$ GeV/c$^2$). This veto is also applied to $m_{\ell^+\ell^-}$ computed without bremsstrahlung photon recovery. When a lepton radiates or is mismeasured, $m_{\ell^+\ell^-}$ can shift away from the charmonium mass, while $\Delta E$ shifts in a correlated manner. The veto region is extended in the ($m_{\ell^+\ell^-}, \Delta E$) plane to account for this correlation, removing nearly all charmonium events and simplifying the description of the background in the fit. Because the charmonium events removed by these vetoes are so similar to signal events, these modes provide extensive control samples (about 5200 events in all) for studying signal shapes, selection efficiencies, and systematic errors. Outside the charmonium veto regions, the signal efficiency is similar over the full $q^2$ range of each mode.

In muon modes, where the probability for a hadron to be misidentified as a muon can be as high as a few percent, background from the decay $B^- \to D^0\pi^-$ with $D^0 \to K^-\pi^+$ or $D^0 \to K^+\pi^-$, or from $B^0 \to D^+\pi^-$ with $D^+ \to K^{*+}\pi^+$, is significant. These events are suppressed by vetoing events where the $K^{(*)}\mu$ kinematics are consistent with those of a hadronic $D$ decay.

We estimate the residual peaking background from measurements in the data, supplemented in some cases by simulation studies. Events from $B \to K^{(*)}\pi\pi$, $B \to K^{(*)}K\pi$, and $B \to K^{(*)}K\bar{K}$ are highly suppressed by the particle identification criteria. These backgrounds are estimated from control samples to be $0.19 \pm 0.11$ events per channel averaged over muon modes and less than 0.01 events per channel in electron modes. After the vetoes on $B \to J/\psi K^{(*)}$ and $B \to \psi(2S)K^{(*)}$ decays, the remaining peaking background is estimated from simulation to be $0.17 \pm 0.07$ events per channel averaged over $B \to K^{*}\ell^+\ell^-$ modes, and it is negligible in $B \to K\ell^+\ell^-$ modes. The background from $B \to K^{*}\gamma$ (with photon conversion in the detector) is determined from simulation to be $0.48 \pm 0.16$ events in $B^0 \to K^{(*)}\ell^+\ell^-$ and $0.09 \pm 0.04$ events in $B^+ \to K^{*+}\ell^+\ell^-$. The signal shapes are parameterized with a Gaussian core for $m_{ES}$ and a double Gaussian core for $\Delta E$. Both the $m_{ES}$ and $\Delta E$ shapes include a radiative tail, which accounts for the effects of bremsstrahlung. The $m_{ES}$ shape parameters are assumed to have $\Delta E$ dependence $c_0 + c_2(\Delta E)^2$. All signal shape parameters are fixed from signal simulation, except for the mean and width parameters in $m_{ES}$ ($c_0$ only) and $\Delta E$, which are fixed to values from charmonium data control samples.

| Mode                   | Signal yield | $\epsilon$ (%) | $\Delta B_1 / B$ (10^{-6}) | $B$ (10^{-6}) |
|------------------------|--------------|-----------------|-----------------------------|---------------|
| $K^+e^+e^-$            |              | 19.2            | +6.3                        | +0.02         | 1.05 \text{+0.25} \text{-0.07} |
| $K^\mu^+\mu^-$        | 0.71 \text{+0.6} | 8.5             | +7.6                        | +0.02         | 0.07 \text{+0.19} \text{-0.02} |
| $K^\mu^+\mu^-$        | 1.81 \text{+0.7} | 8.0             | +8.4                        | +0.08         | -0.21 \text{+0.23} \text{-0.08} |
| $K^0\mu^+\mu^-$       | 5.91 \text{+0.9} | 8.6             | +8.8                        | +0.02         | 1.63 \text{+0.22} \text{-0.14} |
| $K^0\ell^+\ell^-$     | 12.44 \text{+6.3} | 13.6            | +7.6                        | +0.08         | 1.11 \text{+0.56} \text{-0.11} |
| $K^0\ell^+\ell^-$     | 4.54 \text{+4.1} | 6.4             | +10.1                       | +0.07         | 0.86 \text{+0.79} \text{-0.11} |
| $K^\ell^+\ell^-$      | 0.63 \text{+3.8} | 10.2            | +10.7                       | +0.28         | 0.20 \text{+0.24} \text{-0.28} |
| $K^{*+}\ell^+\ell^-$  | 4.23 \text{+3.5} | 4.8             | +12.7                       | +0.15         | 3.07 \text{+0.58} \text{-0.42} |
| $K^0e^+e^-$            | 91.7 \text{+22} |                | +6.5                        | +0.02         | 0.74 \text{+0.18} \text{-0.05} |
| $K^\mu^+\mu^-$        | 55.2 \text{+20} | 7.4             | +7.6                        | +0.01         | 0.45 \text{+0.16} \text{-0.04} |
| $K^\ell^+\ell^-$      | 80.7 \text{+23} | 6.4             | +6.4                        | +0.01         | 0.65 \text{+0.14} \text{-0.04} |
| $K^0\ell^+\ell^-$     | 121.5 \text{+21} | 7.8             | +7.8                        | +0.08         | 0.98 \text{+0.50} \text{-0.11} |
| $K^\ell^+\ell^-$      | 156.5 \text{+34} | 10.1            | +10.1                       | +0.09         | 1.27 \text{+0.76} \text{-0.16} |
| $K^{*+}\ell^+\ell^-$  | 108.7 \text{+36} | 8.1             | +12.7                       | +0.07         | 0.88 \text{+0.32} \text{-0.10} |
The background is modeled as the sum of three terms: (1) a combinatorial background shape with floating normalization, written as the product of an ARGUS function [12] in $m_{ES}$, an exponential in $\Delta E$, and the product of $\sqrt{m_{K\pi}-m_K-m_{\pi}}$ and a quadratic function of $m_{K\pi}$ for the $K^*$ modes; (2) a peaking background contribution, with the same shape as the signal, but with normalization fixed to measured peaking backgrounds; and (3) terms with floating normalization to describe (a) background in $B \to K^\pm \ell^{-} \ell^{+}$ ($B \to K^*\ell^{-}\ell^{+}$) from $B \to K^*\ell^{-}\ell^{-}$ ($B \to K^*\pi\ell^{-}\ell^{+}$) events with a lost pion, and (b) background in $B \to K^*\ell^{-}\ell^{-}$ from $B \to K\ell^{-}\ell^{-}$ events with a randomly added pion. In the $K^*$ modes, we allow an additional background (4) that uses our combinatorial shape in $m_{ES}$ and $\Delta E$, but peaks in $m_{K\pi}$ at the $K^*$ mass. Because the normalizations for terms (1), (3), and (4) are floating, as are the combinatorial background shape parameters, much of the uncertainty in the background is propagated into the statistical uncertainty on the signal yield obtained from the fit.

Table I lists signal yields and branching fractions for each mode. The relative systematic uncertainties on the efficiency, $\Delta B_{ES}/B$, arise from charged-particle tracking (1.0% per lepton, 1.7% per charged hadron), particle identification (1.1% per electron, 1.6% per muon, 0.9% per pion, 0.9% per kaon), the continuum suppression cut [(0.8–2.8)%], the $B\overline{B}$ suppression cut [(1.4–5.0)%], $K_{S}^{0}$ selection (3.8%), signal simulation statistics [(0.7–1.4)%], theoretical model dependence of the efficiency [(4–7)%], depending on the mode], and the number of $B\overline{B}$ events (1.1%). Uncertainties on efficiencies due to model dependence of form factors are taken to be the full range of variation from a set of models [2].

The systematic uncertainties on the fit yields, $\Delta B_{ES}$, arise from three sources: uncertainties in the parameters describing the signal shapes, possible correlation between $m_{ES}$ and $\Delta E$ in the combinatorial background shape, and uncertainties in the peaking backgrounds. The uncertainties in the means and widths of the signal shapes are obtained by comparing data and simulation for the charmonium control samples. For modes with electrons, we also vary the fraction of signal events in the tail of the $\Delta E$ distribution. To evaluate sensitivity to the background parameterization, we allow additional parameters and a correlation between $m_{ES}$ and $\Delta E$.

Table I also lists results from simultaneous fits to combinations of $B \to K^\pm \ell^{-}$ modes and combinations of $B \to K^*\ell^{-}\ell^{-}$ modes, where the relative branching fractions for the contributing modes are constrained. $B^0$ and $B^+\mu$ production rates are constrained to be equal, and the ratio of their total widths is constrained to be $1.085 \pm 0.017$ [13]. All branching fractions from simultaneous fits are expressed in terms of the $B^0$ total width. The projections of the fit on $m_{ES}$ and $\Delta E$ are shown in Fig. 4 for the simultaneous fit to $B \to K^\pm \ell^{-}$ channels. We assume that all four $B \to K^\pm \ell^{-}$ modes have equal partial widths. A signal is evident at the $B$ mass in $m_{ES}$ and at $\Delta E = 0$. Figure 5 shows projections of the simultaneous fit to all $B \to K^*\ell^{-}\ell^{-}$ modes. Here, the partial width ratio of electron and muon modes is constrained to be $\Gamma(B \to K^*\ell^{-}\ell^{-})/\Gamma(B \to K^*\mu^{+}\mu^{-}) = 1.33$ from the model of Ali et al. [1]. Our simultaneous fit result is expressed as a $B^0 \to K^{0}\mu^{+}\mu^{-}$ branching fraction.

The significance of the $B \to K^\pm \ell^{-}$ signal from the simultaneous fit is $\sim 8 \sigma$, computed as $\sqrt{\Delta \log L}$, where $\Delta \log L$ is the likelihood difference between the best fit and the null-signal hypothesis. We account for systematic uncertainties in the significance by simultaneously including all effects that individually lower the fit yields prior to computing the change in likelihood. The significance of the $B \to K^*\ell^{-}\ell^{-}$ signal, including all systematic uncertainties, is $3.3 \sigma$ ($3.8 \sigma$ not including them).

In summary, we have observed signals for $B \to K^\pm \ell^{-}$, averaged over lepton type ($e^+e^-$ and $\mu^+\mu^-$) and $B$ charge, and we have obtained the first evidence for $B \to K^*\ell^{-}\ell^{-}$, similarly averaged. We obtain

$$B(B \to K^\pm \ell^{-}) = (0.65^{+0.14}_{-0.13} \pm 0.04) \times 10^{-6},$$

$$B(B \to K^*\ell^{-}\ell^{-}) = (0.88^{+0.33}_{-0.29} \pm 0.10) \times 10^{-6},$$

where the first error is statistical and the second is systematic. Our branching fraction for $B \to K^*\ell^{-}\ell^{-}$ is slightly higher than our previous limit $0.51 \times 10^{-6}$ (90% confidence level) [4] and is in agreement with the Belle result $(0.75^{+0.25}_{-0.21} \pm 0.09) \times 10^{-6}$ [6]. Our $B \to K^*\ell^{-}\ell^{-}$ branching fraction is consistent with previous 90% confidence level limits from $B\overline{B}$ (without $K^* \ell^{-}\ell^{-}$) [3] and Belle $(< 3.1 \times 10^{-6}$ for $K^*\ell^{-}\ell^{-})$ [7]. These results are consistent with the range of predictions based on the Standard Model [14, 15, 16, 17].

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![FIG. 2: Distributions of the fit variables in $K^*\ell^+\ell^-$ data (points), compared with projections of the simultaneous fit (curves): (a) $m_{ES}$ after requiring $-0.11 < \Delta E < 0.05$ GeV and $0.817 < m_{K\ell} < 0.967$ GeV/$c^2$, (b) $\Delta E$ after requiring $|m_{ES} - m_{B}| < 6.6$ MeV/$c^2$ (2.6$\sigma$), $0.817 < m_{K\ell} < 0.967$ GeV/$c^2$, and (c) $m_{K\ell}$ after requiring $|m_{ES} - m_{B}| < 6.6$ MeV/$c^2$ and $-0.11 < \Delta E < 0.05$ GeV. The solid curve is the sum of all fit components, including signal; the dashed curve is the sum of all background components.]

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