

Direct CP , Lepton Flavor, and Isospin Asymmetries in the Decays $B \rightarrow K^{(*)}l^+l^-$

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We measure branching fractions and integrated rate asymmetries for the rare decays $B \rightarrow K^{(*)}l^+l^-$, where l^+l^- is either e^+e^- or $\mu^+\mu^-$, using a sample of $384 \times 10^6 B\bar{B}$ events collected with the BABAR detector at the PEP-II e^+e^- collider. We find no evidence for direct CP or lepton-flavor asymmetries. However, for dilepton masses below the J/ψ resonance, we find evidence for unexpectedly large isospin asymmetries in both $B \rightarrow Kl^+l^-$ and $B \rightarrow K^*l^+l^-$ which differ, respectively, by 3.2σ and 2.7σ , including systematic uncertainties, from the standard model expectations.

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The decays $B \rightarrow K^{(*)}l^+l^-$, where l^+l^- is either e^+e^- or $\mu^+\mu^-$, arise from flavor-changing neutral current processes that are forbidden at the tree level in the standard model (SM). The lowest-order SM processes contributing to these decays are a W^+W^- box diagram, and the radiative photon and electroweak Z penguin diagrams [1]. Their amplitudes are expressed in terms of hadronic form factors and effective Wilson coefficients C_7^{eff} , C_9^{eff} , and C_{10}^{eff} , representing the electromagnetic penguin diagram, and the vector part and the axial-vector part of the Z penguin and W^+W^- box diagrams, respectively [2]. New physics contributions may enter the penguin and box diagrams at the same order as the SM diagrams, modifying the Wilson coefficients from their SM expectations [3].

We report results herein on exclusive branching fractions, direct CP asymmetries, the ratio of rates to dimuon and dielectron final states, and isospin asymmetries, measured in two regions of dilepton mass squared chosen to exclude the region of the J/ψ resonance: a low q^2 region $0.1 < q^2 \equiv m_{ll}^2 < 7.02 \text{ GeV}^2/c^4$ and a high q^2 region $q^2 > 10.24 \text{ GeV}^2/c^4$. We also present results for the two regions combined. The $\psi(2S)$ resonance is removed from the high q^2 region by vetoing events with $12.96 < q^2 < 14.06 \text{ GeV}^2/c^4$. For $K^*e^+e^-$ final states, we also report results in extended low and extended combined q^2 regions including events $q^2 < 0.1 \text{ GeV}^2/c^4$, where there is an enhanced coupling to the photonic penguin amplitude unique to this mode. Recent BABAR results on angular observables using the same data set and similar event selection as is used here are reported in [1].

The $B \rightarrow Kl^+l^-$ branching fraction is predicted to be $(0.35 \pm 0.12) \times 10^{-6}$, while $B \rightarrow K^*l^+l^-$ for $q^2 > 0.1 \text{ GeV}^2/c^4$ is expected to be roughly 3 times larger at $(1.19 \pm 0.39) \times 10^{-6}$ [3]. The $\sim 30\%$ uncertainties are due to lack of knowledge about the form factors that model the hadronic effects in the $B \rightarrow K$ and $B \rightarrow K^*$ transitions. Thus, measurements of decay rates to exclusive final states are less suited to searches for new physics than rate asymmetries, where many theory uncertainties cancel [4].

The direct CP asymmetry

$$A_{CP}^{K^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \rightarrow \bar{K}^{(*)}l^+l^-) - \mathcal{B}(B \rightarrow K^{(*)}l^+l^-)}{\mathcal{B}(\bar{B} \rightarrow \bar{K}^{(*)}l^+l^-) + \mathcal{B}(B \rightarrow K^{(*)}l^+l^-)} \quad (1)$$

is expected to be $O(10^{-3})$ in the SM, but new physics at the

electroweak scale could produce a significant enhancement [5].

The ratio of rates to dimuon and dielectron final states

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \rightarrow K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \rightarrow K^{(*)}e^+e^-)} \quad (2)$$

is unity in the SM to within a few percent [6]. In two-Higgs-doublet models, including supersymmetry, these ratios are sensitive to the presence of a neutral Higgs boson, which might, at large $\tan\beta$, increase $R_{K^{(*)}}$ by $\sim 10\%$ [7]. In the region $q^2 < (2m_\mu)^2$, where only the e^+e^- modes are allowed, there is a large enhancement of $B \rightarrow K^*e^+e^-$ due to a $1/q^2$ scaling of the photon penguin contribution. The expected SM value of R_{K^*} including this region is 0.75 [6], and we fit the K^* data set over the extended combined and extended low q^2 regions in order to test this prediction.

The CP -averaged isospin asymmetry

$$A_I^{K^{(*)}} \equiv \frac{\mathcal{B}(B^0 \rightarrow K^{(*)0}l^+l^-) - r\mathcal{B}(B^\pm \rightarrow K^{(*)\pm}l^+l^-)}{\mathcal{B}(B^0 \rightarrow K^{(*)0}l^+l^-) + r\mathcal{B}(B^\pm \rightarrow K^{(*)\pm}l^+l^-)}, \quad (3)$$

where $r = \tau_0/\tau_+ = 1/(1.07 \pm 0.01)$ is the ratio of the B^0 and B^+ lifetimes [8], has a SM expectation of $+6\%$ – 13% as $q^2 \rightarrow 0 \text{ GeV}^2/c^4$ [9]. This is consistent with the measured asymmetry of $3\% \pm 3\%$ in $B \rightarrow K^*\gamma$ [8]. A calculation of the predicted $K^{*+}l^+l^-$ and $K^{*0}l^+l^-$ rates integrated over the low q^2 region gives $A_I^{K^*} = -0.005 \pm 0.020$ [10,11]. In the high q^2 region, contributions from charmonium states may provide an additional source of isospin asymmetry, although the measured asymmetry in $J/\psi K^{(*)}$ is at most a few percent [8].

We use a data sample of $384 \times 10^6 B\bar{B}$ pairs collected at the $Y(4S)$ resonance with the BABAR detector [12] at the PEP-II asymmetric-energy e^+e^- collider at SLAC. Our selection of charged and neutral particle candidates, as well as reconstruction of π^0 , K_S^0 , and K^* candidates, are described at [1]. We reconstruct signal events in ten separate final states containing an e^+e^- or $\mu^+\mu^-$ pair, and a K_S^0 ($\rightarrow \pi^+\pi^-$), K^+ , or $K^*(892)$ candidate with an invariant mass $0.82 < M(K\pi) < 0.97 \text{ GeV}/c^2$. We reconstruct K^{*0} candidates in the final state $K^+\pi^-$, and K^{*+} candidates in the final states $K^+\pi^0$ and $K_S^0\pi^+$ (charge conjugation is implied throughout except as explicitly noted). We also

TABLE I. $A_{CP}^{K^{(*)}}$ results in each relevant q^2 region. The uncertainties are statistical and systematic, respectively.

Mode	Combined q^2	Low q^2	High q^2
$K^+ l^+ l^-$	$-0.18^{+0.18}_{-0.18} \pm 0.01$	$-0.18^{+0.19}_{-0.19} \pm 0.01$	$-0.09^{+0.36}_{-0.39} \pm 0.02$
$K^{*0} l^+ l^-$	$0.02^{+0.20}_{-0.20} \pm 0.02$	$-0.23^{+0.38}_{-0.38} \pm 0.02$	$0.17^{+0.24}_{-0.24} \pm 0.02$
$K^{*+} l^+ l^-$	$0.01^{+0.26}_{-0.24} \pm 0.02$	$0.10^{+0.25}_{-0.24} \pm 0.02$	$-0.18^{+0.45}_{-0.55} \pm 0.04$
$K^{*+} l^+ l^-$	$0.01^{+0.16}_{-0.15} \pm 0.01$	$0.01^{+0.21}_{-0.20} \pm 0.01$	$0.09^{+0.21}_{-0.21} \pm 0.02$

study final states $K^{(*)} h^\pm \mu^\mp$, where h is a track with no particle identification requirement applied, to characterize backgrounds from hadrons misidentified as muons.

$B \rightarrow K^{(*)} l^+ l^-$ decays are reconstructed using the kinematic variables $m_{ES} = \sqrt{s/4 - p_B^{*2}}$ and $\Delta E = E_B^* - \sqrt{s}/2$, where p_B^* and E_B^* are the B momentum and energy in the $\Upsilon(4S)$ center-of-mass (c.m.) frame, and \sqrt{s} is the total c.m. energy. We define a fit region $m_{ES} > 5.2 \text{ GeV}/c^2$, with $-0.07 < \Delta E < 0.04$ ($-0.04 < \Delta E < 0.04$) GeV for $e^+ e^-$ ($\mu^+ \mu^-$) final states in the low and extended low q^2 region, and $-0.08 < \Delta E < 0.05$ ($-0.05 < \Delta E < 0.05$) GeV for high q^2 .

The main backgrounds arise from random combinations of leptons from semileptonic B and D decays, which are suppressed through the use of neural networks (NN) whose construction is described in detail in [1]. For each of the ten final states we use separate NN optimized to suppress either continuum or $B\bar{B}$ backgrounds in the low, extended low or high q^2 regions. We use simulated samples of signal and background events in the construction of the NN, and assume rates consistent with accepted values [8].

There is a further background contribution from $B \rightarrow D(\rightarrow K^{(*)} \pi) \pi$ decays, where both pions are misidentified as leptons. The pion misidentification rates are 2%–3% for muons and <0.1% for electrons, so this background is only significant in the $\mu^+ \mu^-$ final states. We veto these events by assigning the pion mass to a muon candidate, and requiring the invariant mass of the hypothetical $K^{(*)} \pi$ system to be outside the range 1.84–1.90 GeV/ c^2 . After all the above selections have been applied, the final reconstruction efficiency for signal events varies from 3.5% for $K^+ \pi^0 \mu^+ \mu^-$ for the combined q^2 region, to 22% for $K^+ \pi^- e^+ e^-$ in the high q^2 region.

We perform unbinned maximum likelihood fits to m_{ES} distributions to obtain signal and background yields. We use an ARGUS shape [13] to describe the combinatorial background, allowing the shape parameter to float in the fits. For the signal, we use a fixed Gaussian shape unique to each final state, with mean and width determined from fits to the analogous final states in the vetoed $J/\psi K^{(*)}$ events. We account for a small residual contribution from misidentified hadrons by constructing a probability density function (PDF) using $K^{(*)} h^\pm \mu^\mp$ events weighted by the probability for the h^\pm to be misidentified as a muon. We

also account for background events that peak in the m_{ES} signal region, arising from charmonium events that escape the veto, and for contributions from misreconstructed signal events. We test our fits in each final state using the large samples of vetoed $J/\psi K^{(*)}$ and $\psi(2S) K^{(*)}$ events, and find that all the branching fractions are in good agreement with accepted values [14]. We perform simultaneous fits for $A_{CP}^{K^{(*)}}$, $R_{K^{(*)}}$ and $A_I^{K^{(*)}}$ summed over all the signal modes that contribute to the particular measurement.

We estimate the statistical significance of our fits by generating ensembles of 1000 data sets for each of the ten final states in each q^2 region of interest, and fitting each data set with the full fit model described above. These tests also confirm the unbiased nature and proper error scaling of our fit methodology.

For the total $B \rightarrow K l^+ l^-$ and $B \rightarrow K^* l^+ l^-$ branching fractions averaged assuming isospin and lepton-flavor symmetry, we measure $(0.394^{+0.073}_{-0.069} \pm 0.020) \times 10^{-6}$ and $(1.11^{+0.19}_{-0.18} \pm 0.07) \times 10^{-6}$, respectively, where the first uncertainty is statistical and the second is systematic. Complete branching fraction results in all final states and q^2 regions, along with the statistical significance of each measurement and frequentist upper limits for measurements with $<4\sigma$ statistical significance, are available online [15]. All results are in good agreement with previous measurements [8].

Table I summarizes the results for $A_{CP}^{K^{(*)}}$. In the fits to the separate B and \bar{B} data sets in charge-conjugate final states, we assume a common background ARGUS shape parameter. Our final results are consistent with the SM expectation of negligible direct CP asymmetry. Table II shows the

TABLE II. $R_{K^{(*)}}$ results in each q^2 region. The extended (“ext.”) regions are relevant only for R_{K^*} . The uncertainties are statistical and systematic, respectively.

q^2 Region	R_{K^*}	R_K
Combined	$1.37^{+0.53}_{-0.40} \pm 0.09$	$0.96^{+0.44}_{-0.34} \pm 0.05$
Ext. combined	$1.10^{+0.42}_{-0.32} \pm 0.07$...
Low	$1.01^{+0.58}_{-0.44} \pm 0.08$	$0.40^{+0.30}_{-0.23} \pm 0.02$
Ext. low	$0.56^{+0.29}_{-0.23} \pm 0.04$...
High	$2.15^{+1.42}_{-0.78} \pm 0.15$	$1.06^{+0.81}_{-0.51} \pm 0.06$

TABLE III. $A_I^{K^{(*)}}$ results in each q^2 region. The uncertainties are statistical and systematic, respectively. The last table row shows $K^*e^+e^-$ results for the extended regions.

Mode	Combined q^2	Low q^2	High q^2
$K\mu^+\mu^-$	$0.13_{-0.37}^{+0.29} \pm 0.04$	$-0.91_{-\infty}^{+1.2} \pm 0.18$	$0.39_{-0.46}^{+0.35} \pm 0.04$
Ke^+e^-	$-0.73_{-0.50}^{+0.39} \pm 0.04$	$-1.41_{-0.69}^{+0.49} \pm 0.04$	$0.21_{-0.41}^{+0.32} \pm 0.03$
Kl^+l^-	$-0.37_{-0.34}^{+0.27} \pm 0.04$	$-1.43_{-0.85}^{+0.56} \pm 0.05$	$0.28_{-0.30}^{+0.24} \pm 0.03$
$K^*\mu^+\mu^-$	$-0.00_{-0.26}^{+0.36} \pm 0.05$	$-0.26_{-0.34}^{+0.50} \pm 0.05$	$-0.08_{-0.27}^{+0.37} \pm 0.05$
$K^*e^+e^-$	$-0.20_{-0.20}^{+0.22} \pm 0.03$	$-0.66_{-0.17}^{+0.19} \pm 0.02$	$0.32_{-0.45}^{+0.75} \pm 0.03$
$K^*l^+l^-$	$-0.12_{-0.16}^{+0.18} \pm 0.04$	$-0.56_{-0.15}^{+0.17} \pm 0.03$	$0.18_{-0.28}^{+0.36} \pm 0.04$
$K^*e^+e^-$ (ext.)	$-0.27_{-0.18}^{+0.21} \pm 0.03$	$-0.25_{-0.18}^{+0.20} \pm 0.03$...

results for R_K and R_{K^*} , which are also consistent with the SM expectations.

Table III shows the results for the isospin asymmetry $A_I^{K^{(*)}}$. We directly fit the data for $A_I^{K^{(*)}}$ taking into account the differing lifetimes of B^0 and B^+ . Figure 1 shows the charged and neutral low q^2 data sets with overlaid fit projections. We find no significant isospin asymmetries in the high and combined q^2 regions, or for $K^*e^+e^-$ fits in the extended regions. However, we find evidence for large negative asymmetries in the low q^2 region.

We calculate the statistical significance with which a null isospin asymmetry hypothesis is rejected using the change in log likelihood $\sqrt{2\Delta \ln \mathcal{L}}$ between the nominal fit to the data and a fit with $A_I^{K^{(*)}} = 0$ fixed. Figure 2 shows the likelihood curves obtained from the Kl^+l^- and $K^*l^+l^-$ fits. The parabolic nature of the curves in the $A_I^{K^{(*)}} > -1$ region demonstrates the essentially Gaussian nature of our

fit results in the physical region, and the right-side axis of Fig. 2 shows purely statistical significances based on Gaussian coverage. Incorporating the relatively small systematic uncertainties as a scaling factor on the change in log likelihood, the significance in the low q^2 region that $A_I^{K^{(*)}}$ is different from zero is 3.2σ for Kl^+l^- and 2.7σ for $K^*l^+l^-$. We have verified these confidence intervals by performing fits to ensembles of simulated data sets generated with $A_I^{K^{(*)}} = 0$ fixed, and we find frequentist coverage consistent with the $\Delta \ln \mathcal{L}$ calculations. The highly negative $A_I^{K^{(*)}}$ values for both Kl^+l^- and $K^*l^+l^-$ at low q^2 suggest that this asymmetry may be insensitive to the hadronic final state, and so we sum the likelihood curves as shown in Fig. 2 and obtain $A_I^{K^{(*)}} = -0.64_{-0.14}^{+0.15} \pm 0.03$. Including systematics, this is a 3.9σ difference from a null $A_I^{K^{(*)}}$ hypothesis.

We consider systematic uncertainties associated with reconstruction efficiencies; hadronic background parametrization in dimuon final states; peaking background contributions obtained from simulated events; and possible CP , lepton flavor, and isospin asymmetries in the background PDFs. We quantify the efficiency systematics using the vetoed $J/\psi K^{(*)}$ samples. These include charged track, π^0 , and K_S^0 reconstruction, particle identification, NN selection, and the ΔE and K^* mass selections. The largest contributions to the systematic uncertainties on the rates are particle identification, the characterization of the had-

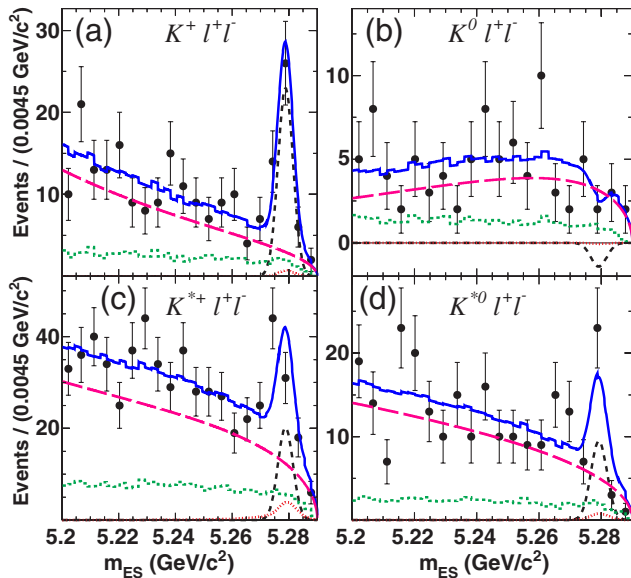


FIG. 1 (color online). Charged and neutral fit projections in the low q^2 region. Total fit (solid), combinatoric background (long dash), signal (medium dash), hadronic background (short dash), peaking background (dots).

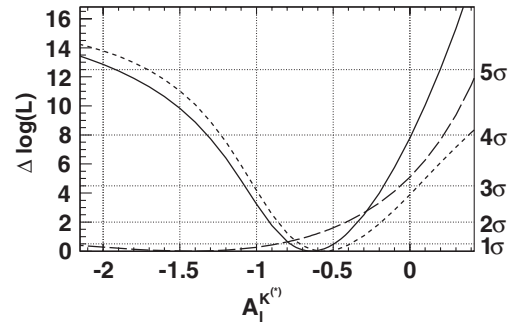


FIG. 2. Low q^2 region $A_I^{K^{(*)}}$ fit likelihood curves. Kl^+l^- (long dash), $K^*l^+l^-$ (short dash), $(K, K^*)l^+l^-$ (solid).

ronic background and the signal m_{ES} PDF shape. All of these cancel at least partially in the rate asymmetries, and the final systematic uncertainties are small compared to the statistical ones.

We perform several additional checks of effects that might cause a bias in our final results. We vary the parametrization of the hadronic background PDFs, and of the random combinatorial background ARGUS shapes in the low q^2 region, to test the robustness of the large $A_I^{K^{(*)}}$ asymmetries. We remove all the NN selections, and perform separate fits to the two K^{*+} final states, and observe no significant variation in the $A_I^{K^{(*)}}$ results. To understand if an isospin asymmetry might be induced by the combinatorial background, we compare data and simulated background events within a larger region $|\Delta E| < 0.25$ GeV outside our ΔE selection window and in the $5.2 < m_{ES} < 5.27$ GeV/ c^2 region. We find that the numbers of simulated and data events in this larger region agree well. No signal isospin asymmetry is found using simulated events within the fit region.

In summary, we have measured branching fractions, and studied direct CP violation, ratios of rates to dimuon and dielectron final states, and isospin asymmetries in the rare decays $B \rightarrow K^{(*)}l^+l^-$. Our branching fraction results agree with both SM predictions and previous measurements. Our results for the direct CP asymmetries and lepton-flavor rate ratios are in good agreement with their respective SM predictions of zero and one. The isospin asymmetries in the high and combined q^2 regions are consistent with zero, but in the low q^2 region in both $B \rightarrow Kl^+l^-$ and $B \rightarrow K^*l^+l^-$ we measure large negative asymmetries that are each about 3σ different from zero, including systematic uncertainties. Combining these results, we obtain $A_I^{K^{(*)}} = -0.64_{-0.14}^{+0.15} \pm 0.03$, with a 3.9σ difference (including systematics) from $A_I^{K^{(*)}} = 0$. Such large negative asymmetries are unexpected in the SM, which predicts essentially no isospin asymmetry integrated over our low q^2 region and, as $q^2 \rightarrow 0$, an asymmetry of $\sim +10\%$, opposite in sign to our observation in the low q^2 region.

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