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

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We measure rate asymmetries for the rare decays $B \to K^{(*)}\ell^+\ell^-$, where $\ell^+\ell^-$ is either e^+e^- or $\mu^+\mu^-$, using a sample of 384 million $B\overline{B}$ events collected with the *BABAR* detector at the PEP-II e^+e^- collider. We find no evidence for direct CP or lepton-flavor asymmetries. For dilepton masses below the J/ψ resonance, we find evidence for unexpectedly large isospin asymmetries in both $B \to K\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$ which differ respectively by 3.2σ and 2.7σ, including systematic uncertainties, from the Standard Model expectations.

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The decays $B \to K^{(*)}\ell^+\ell^-$, where $\ell^+\ell^-$ is either e^+e^- or $\mu^+\mu^-$, arise from flavor-changing neutral current processes that are forbidden at tree level in the Standard Model (SM). The lowest-order SM processes contributing to these decays are the photon penguin, the Z penguin and the W^+W^- box diagrams shown in Fig. 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 [1]. 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 [2].

The calculation of hadronic form factors has significant uncertainties, so decay rates to exclusive final states are less suited to searches for new physics than rate asymmetries, where many of the uncertainties cancel [3]. Previous *BABAR* results on branching fractions, direct *CP* violation and ratios of rates to di-muon and di-electron final states can be found in [4]. More recent results on angular asymmetries using the same dataset as is used here are reported in [5]. We study herein direct *CP* asymmetries, the ratio of rates to di-muon and di-electron 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 $0.1 < q^2 \equiv m^2_{\ell\ell} < 7.02\,\mathrm{GeV}^2/c^4$ and a high q^2 region $q^2 > 10.24\,\mathrm{GeV}^2/c^4$. 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 $12.96 < q^2 < 14.06\,\mathrm{GeV}^2/c^4$. For $K^*e^+e^-$ final states, we also report results in extended low and extended combined q^2 regions including events $q^2 < 0.1\,\mathrm{GeV}^2/c^4$, where there is an enhanced coupling to the photonic penguin amplitude unique to this mode.

The direct *CP* asymmetry

$$A_{CP}^{K^{(*)}} \equiv \frac{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-) - \mathcal{B}(B \to K^{(*)}\ell^+\ell^-)}{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\ell^+\ell^-) + \mathcal{B}(B \to K^{(*)}\ell^+\ell^-)} \quad (1)$$

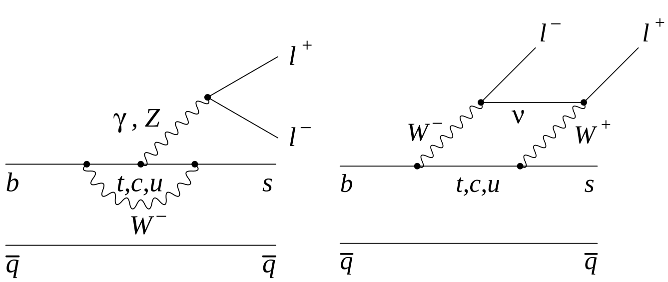

FIG. 1: Lowest-order SM Feynman diagrams for $b \to s\ell^+\ell^-$.

is expected to be $O(10^{-3})$ in the SM, but new physics at the electroweak scale could produce a significant enhancement [6].

The ratio of rates to di-muon and di-electron final states

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

is unity in the SM to within a few percent [7]. 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 $\sim 10\%$ [8]. In the region $q^2 < (2m_\mu)^2$, where only the e^+e^- modes are allowed, there is a large enhancement of $B \to K^*e^+e^-$ due to a $1/q^2$ scaling of the photon penguin. The expected SM value of R_{K^*} including this region is 0.75 [7], and we fit the K^* dataset over the extended combined and extended low q^2 regions in order to test this prediction.

The *CP*-averaged isospin asymmetry

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

where $r = \tau_0/\tau_+ = 1/(1.07 \pm 0.01)$ is the ratio of the B^0 and B^+ lifetimes [9], has a SM expectation of $+6-13\%$ as $q^2 \to 0\,\mathrm{GeV}^2/c^4$ [10]. This is consistent with the measured asymmetry of $3\pm3\%$ in $B \to K^*\gamma$ [9]. A calculation of the predicted K^{*+} and K^{*0} rates integrated over the low q^2 region gives $A_I^{K^*} = -0.005 \pm 0.020$ [11, 12]. 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 [9].

We use a data sample of 384 million $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector [13] at the PEP-II asymmetric-energy e^+e^- collider at SLAC. Tracking is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) in a 1.5-T magnetic field. We identify electrons with a CsI(Tl) electromagnetic calorimeter, and muons using an instrumented magnetic flux return. Electrons (muons) are required to have momenta $p > 0.3(0.7)\,\mathrm{GeV}/c$ in the laboratory frame. We combine photons with electrons when they are consistent with bremsstrahlung, and do not use electrons that are associated with a photon converting to a low-mass e^+e^- pair. We identify K^+ using a detector of internally reflected Cherenkov light, as well as ionization energy loss measurements from the DCH and SVT. Charged tracks other than identified e, μ and K candidates are treated as pions. Neutral pion candidates are formed from two photons with laboratory energies $E_\gamma > 50\,\mathrm{MeV}$ and an invariant mass between 115 and $155\,\mathrm{MeV}/c^2$.

We reconstruct signal events in ten separate final states containing an e^+e^- or $\mu^+\mu^-$ pair, and a $K^0_S(\to \pi^+\pi^-)$, K^+, or $K^*(892)$ candidate with an invariant mass $0.82 < M(K\pi) < 0.97\,\mathrm{GeV}/c^2$. We reconstruct K^{*0} candidates in the final state $K^+\pi^-$, and K^{*+} candidates in the final states $K^+\pi^0$ and $K^0_S\pi^+$ (charge conjugation is implied throughout except as explicitly noted). Neutral $K^0_S \to \pi^+\pi^-$ candidates are required to have an invariant mass consistent with the nominal K^0 mass [14], and a flight distance from the primary interaction point which is more than three times its uncertainty. We also 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.

$B \to K^{(*)}\ell^+\ell^-$ decays are reconstructed using the kinematic variables $m_{\rm ES} = \sqrt{s/4 - p^{*2}_B}$ 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 (CM) frame, and $\sqrt{s}$ is the total CM energy. We define a fit region $m_{\rm ES} > 5.2\,\mathrm{GeV}/c^2$, 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 combinations of leptons from semileptonic B and D decays. We suppress these combinatorial backgrounds through the use of neural networks (NN). For each of the ten final states we use separate NN optimized to suppress either continuum or $B\overline{B}$ backgrounds in the low, extended low or high q^2 regions. Inputs to these NN include event shape variables, vertexing information and missing energy. We separately optimize the NN selections for each of the final states in each relevant q^2 region to give the best signal statistical significance. We use simulated samples of signal and background events in the construction of the NN, and assume rates consistent with accepted values [9].

There is a further background contribution from $B \to D(\to K^{(*)}\pi)\pi$ 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 $m_{\rm ES}$ distributions to obtain signal and background yields. We use an ARGUS shape [15] 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 $m_{\rm ES}$ 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 $A^{K^{(*)}}_{CP}$, $R_{K^{(*)}}$ and $A^{K^{(*)}}_I$ 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 datasets for each of the ten final states in each q^2 region of interest, and fitting each dataset with the full fit model described above. These tests also confirm the unbiased nature and proper error scaling of our fit methodology.

Table I summarizes the results for $A^{K^{(*)}}_{CP}$. In the fits to the separate B and $\overline{B}$ datasets 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 results for R_K and R_{K^*}, which are also consistent with the SM expectations.

Table III shows the results for the isospin asymmetry $A^{K^{(*)}}_I$. We directly fit the data for $A^{K^{(*)}}_I$ taking into account the differing lifetimes of B^0 and B^+. Figure 2 shows the charged and neutral low q^2 datasets 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

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

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

TABLE II: $R_{K^{(*)}}$ results in each q^2 region. The extended ("ext.") regions are relevant only for R_{K^*}. The errors 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 errors 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
$K\mu^+\mu^-$	$0.13^{+0.29}_{-0.37} \pm 0.04$	$-0.91^{+1.2}_{-\infty} \pm 0.18$	$0.39^{+0.35}_{-0.46} \pm 0.04$
Ke^+e^-	$-0.73^{+0.39}_{-0.50} \pm 0.04$	$-1.41^{+0.49}_{-0.69} \pm 0.04$	$0.21^{+0.32}_{-0.41} \pm 0.03$
$K\ell^+\ell^-$	$-0.37^{+0.27}_{-0.34} \pm 0.04$	$-1.43^{+0.56}_{-0.85} \pm 0.05$	$0.28^{+0.24}_{-0.30} \pm 0.03$
$K^*\mu^+\mu^-$	$-0.00^{+0.36}_{-0.26} \pm 0.05$	$-0.26^{+0.50}_{-0.34} \pm 0.05$	$-0.08^{+0.37}_{-0.27} \pm 0.05$
$K^*e^+e^-$	$-0.20^{+0.22}_{-0.20} \pm 0.03$	$-0.66^{+0.19}_{-0.17} \pm 0.02$	$0.32^{+0.75}_{-0.45} \pm 0.03$
$K^*\ell^+\ell^-$	$-0.12^{+0.18}_{-0.16} \pm 0.04$	$-0.56^{+0.17}_{-0.15} \pm 0.03$	$0.18^{+0.36}_{-0.28} \pm 0.04$
$K^*e^+e^-$	$-0.27^{+0.21}_{-0.18} \pm 0.03$	$-0.25^{+0.20}_{-0.18} \pm 0.03$	—

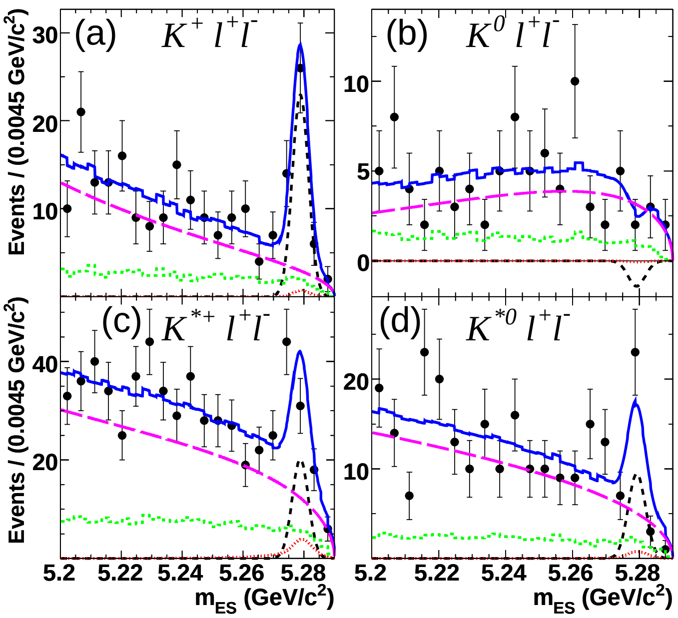

FIG. 2: Charged and neutral fit projections in the low q^2 region. Total fit [solid], combinatoric background [long dash], signal [medium dash], hadronic background [short dash], peaking background [dots].

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 3 shows the likelihood curves obtained from the $K\ell^+\ell^-$ and $K^*\ell^+\ell^-$ 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 Figure 3 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

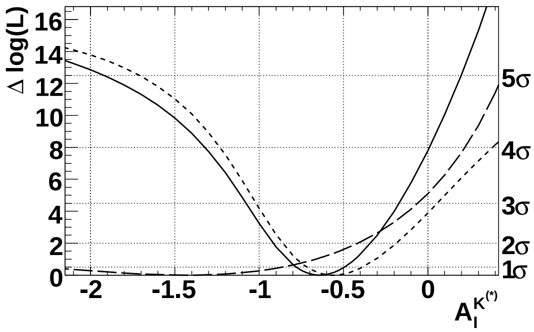

FIG. 3: Low q^2 region $A_I^{K^{(*)}}$ fit likelihood curves. $K\ell^+\ell^-$ [long dash], $K^*\ell^+\ell^-$ [short dash], $(K, K^*)\ell^+\ell^-$ [solid].

for $K\ell^+\ell^-$ and 2.7σ for $K^*\ell^+\ell^-$. We have verified these confidence intervals by performing fits to ensembles of simulated datasets 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 $K\ell^+\ell^-$ and $K^*\ell^+\ell^-$ 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 Figure 3 and obtain $A_I^{K^{(*)}} = -0.64^{+0.15}_{-0.14} \pm 0.03$. 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 parameterization in di-muon 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 errors on the rates are particle identification, the characterization of the hadronic background and the signal $m_{\rm ES}$ pdf shape. All of these cancel at least partially in the rate asymmetries, and the final systematic errors are small compared to the statistical errors.

We perform several additional checks of effects that might cause a bias in our final results. We vary the parameterization 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 present in the combinatorial background, we compare data and simulated background events within a larger region $|\Delta E| < 0.25\,\mathrm{GeV}$ outside our ΔE selection window and in the $5.2 < m_{\rm ES} < 5.27\,\mathrm{GeV}/c^2$ region. We find that the number of simulated events and the observed number of events in data agree well, and observe no background isospin asymmetry.

In summary, we have studied direct *CP* violation, ratios of rates to di-muon and di-electron final states, and isospin asymmetries in the rare decays $B \to K^{(*)}\ell^+\ell^-$. 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 $B \to K\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$ we measure large negative asymmetries that are each about 3σ different from zero, including systematic uncertainties. Combining these results, we obtain $A_I^{K^{(*)}} = -0.64^{+0.15}_{-0.14} \pm 0.03$, 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 $q^2 \to 0$, an asymmetry of $\sim +10\%$, opposite in sign to our observation in the low q^2 region.

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