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Search for the Flavor-Changing Neutral Current Decays $B^+ \rightarrow \mu^+ \mu^- K^+$ and $B^0 \rightarrow \mu^+ \mu^- K^{*0}$

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We report on a search for the flavor-changing neutral current decays $B^+ \rightarrow \mu^+ \mu^- K^+$ and $B^0 \rightarrow \mu^+ \mu^- K^{*0}$ using 88 pb^{-1} of data from $\bar{p}p$ collisions at $\sqrt{s} = 1.8 \text{ TeV}$, collected with the Collider Detector at Fermilab. Finding no evidence for these decays, we set upper limits on the branching fractions $\mathcal{B}(B^+ \rightarrow \mu^+ \mu^- K^+) < 5.2 \times 10^{-6}$ and $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^- K^{*0}) < 4.0 \times 10^{-6}$ at the 90% confidence level.

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In the standard model of electroweak interactions, the flavor-changing neutral current (FCNC) processes $B^+ \rightarrow \mu^+ \mu^- K^+$ and $B^0 \rightarrow \mu^+ \mu^- K^{*0}$ [1] are forbidden at tree level. At higher order, these decays occur through penguin and box diagrams with predicted branching fractions $(0.3\text{--}0.5) \times 10^{-6}$ for $B^+ \rightarrow \mu^+ \mu^- K^+$ and $(1.0\text{--}1.5) \times 10^{-6}$ for $B^0 \rightarrow \mu^+ \mu^- K^{*0}$ [2]. Many deviations from standard model physics can increase these rates significantly [3–6]. For example, an anomalous weak gauge boson coupling at the WWZ vertex $\Delta g_1^Z = -0.2$, well within the current bounds from LEP [7] and the Tevatron [8], can result in a branching fraction 2.5 times larger than the standard model value [4]. Similar enhancements are allowed by existing experimental data in multi-Higgs boson models [5] and models with two Higgs doublets and flavor changing neutral currents [6]. Because the spread in standard model predictions, due mainly to uncertainties in hadronic form factors, is well bounded, the observation of much larger branching fractions would be a signal for physics outside the standard model.

To date, no observation of these decays has been reported. The CLEO Collaboration [9] has set the limits $\mathcal{B}(B^+ \rightarrow \mu^+ \mu^- K^+) < 0.97 \times 10^{-5}$ and $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^- K^{*0}) < 0.95 \times 10^{-5}$ at the 90% confidence level (C.L.). The CDF Collaboration [10] has previously searched for these decays in an 18 pb^{-1} data sample recorded in 1992–1993 and set the 90% C.L. limits $\mathcal{B}(B^+ \rightarrow \mu^+ \mu^- K^+) < 1.0 \times 10^{-5}$ and $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^- K^{*0}) < 2.5 \times 10^{-5}$. The result presented in this Letter is based on an 88 pb^{-1} combined data sample from the 1992–1993 and 1994–1995 running periods and supersedes the earlier CDF result.

Briefly, the method used in this search is as follows. The CDF trigger selects events containing two muon candidates, which we combine off-line with K^+ and K^{*0} candidates to form B^+ and B^0 candidates. Using the topologically identical resonant processes $B^+ \rightarrow J/\psi K^+ \rightarrow (\mu^+ \mu^-) K^+$ and $B^0 \rightarrow J/\psi K^{*0} \rightarrow (\mu^+ \mu^-) K^{*0}$ for normalization, we measure ratios of branching fractions, thus canceling most uncertainties due to B meson production and detection efficiency. Small acceptance and trigger efficiency differences due to the different decay kinematics are corrected with a Monte Carlo calculation.

The CDF detector has been described in detail elsewhere [11]. Detector components most relevant to this search are the muon chambers and charged particle tracking system. The muon system is composed of drift chambers outside the hadron calorimeter, allowing the reconstruction of track segments for penetrating particles

in the pseudorapidity [12] range $|\eta| < 1$. The minimum transverse momentum (p_T) of detectable muons varies between 1.4 and 2.2 GeV/c as a function of η , depending on the amount of material between the interaction point and the muon chambers. Charged particles are reconstructed in the central tracking chamber (CTC) and the silicon vertex detector (SVX) [13], both located inside a 1.4 T solenoidal magnetic field. The CTC, covering $|\eta| < 1.1$, is a cylindrical drift chamber containing 84 layers grouped into nine alternating superlayers of axial and stereo wires. The SVX consists of four layers of single-sided silicon microstrip detectors mounted at radii between 2.9 and 7.9 cm from the beam. It provides track measurements in the r - ϕ plane with impact parameter resolution $(13 + 40/p_T) \mu\text{m}$, where p_T is in GeV/c. The impact parameter of a track is defined as the distance of closest approach to the beam in a plane transverse to the beam.

CDF uses a three-level trigger system. The muon pair trigger requires the presence of two track segments in the muon chambers at the first level and matching CTC track candidates found by the central fast track (CFT) processor [14] for one or both muon segments at the second level. The third-level trigger tightens the matching criteria using fully reconstructed CTC tracks.

Muons inside the acceptance of the muon chambers are found by the first-level trigger with an efficiency that rises from about 40% at $p_T = 1.5 \text{ GeV}/c$ to a plateau value of 93% for muon transverse momenta exceeding 3 GeV/c. The efficiency for finding the corresponding tracks with the CFT at level two rises from about 50% at $p_T = 2 \text{ GeV}/c$ to about 96% for $p_T > 2.3 \text{ GeV}/c$. If one muon does not have a matching CFT track a higher p_T threshold is imposed for the other muon, leading to an efficiency that rises from about 50% at $p_T = 2.6 \text{ GeV}/c$ and reaches the same plateau value for $p_T > 3.1 \text{ GeV}/c$. The first type of trigger, requiring two CFT tracks, was not implemented during the 1992–1993 running period. A muon pair is called resonant when its invariant mass is close to the $c\bar{c}$ resonances J/ψ or ψ' . Event selection is identical for resonant and nonresonant muon pairs.

To reconstruct $\mu^+ \mu^- K^+$ candidates, we combine the two muon candidates selected by the trigger with an additional charged track, assumed to be a kaon. The kaon track must satisfy $p_T > 2 \text{ GeV}/c$, and the B candidate must satisfy $p_T > 6 \text{ GeV}/c$.

The reconstruction of the K^{*0} in the $B^0 \rightarrow \mu^+ \mu^- K^{*0}$ process is via the $K^{*0} \rightarrow K^+ \pi^-$ decay. We require

$p_T > 0.5$ GeV/ c for each track, and to reduce random combinations, we require $p_T > 2$ GeV/ c for the K^{*0} candidate. To allow for the $K^*(892)^0$ width, we require the K^{*0} candidate mass to be between 796 and 996 MeV/ c^2 . No particle identification is used, and each pair of tracks is considered as $K^+\pi^-$ and π^+K^- , respectively. We choose the K^{*0}/\bar{K}^{*0} -daughter mass assignment with invariant mass closer to the world-average K^{*0} mass.

An isolation requirement is a well established means of improving the signal to background ratio in reconstructing B decays [15]. We require isolation $I > 0.6$, where I is the transverse momentum of the B candidate divided by the scalar sum of the transverse momenta of the B and all other tracks in a cone $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.0$ around the B momentum. The measured efficiency from our data for the requirement $I > 0.6$ is $(92 \pm 6)\%$ for B mesons with $p_T > 6$ GeV/ c and $|\eta| < 1$.

A possible background for the rare decay search comes from $B \rightarrow J/\psi K$ decays in which the kaon is misidentified as a muon and the muon is taken as the kaon instead. We apply a cut to remove candidates that are compatible with this hypothesis. In fact, no nonresonant candidate showed this ambiguity after all other selection cuts were applied.

We require B daughters to be consistent with originating at a displaced decay vertex and inconsistent with originating at the beam line. All tracks forming the B candidate must include hits on at least three SVX layers, to ensure a good impact parameter measurement, and must miss the beam line with at least 2σ significance, where σ is the estimated impact parameter resolution. The tracks are fit to a common decay vertex. The fit assumes that the B meson is produced at the beam line and constrains the B momentum to be parallel to its line of flight in the r - ϕ plane. The fit quality must be acceptable ($\chi^2 < 20$ with 4 degrees of freedom for $\mu^+\mu^-K^+$ and 6 for $\mu^+\mu^-K^{*0}$) and the transverse decay length must exceed 400 μm . The transverse decay length is the distance between the beam line and the B decay vertex measured in the r - ϕ plane. The beam spot of the Tevatron has a transverse size of approximately 25 μm (rms) and a mean that is measured with negligible uncertainty [16]. The impact-parameter and decay-length criteria are chosen to minimize the expected upper limit using the signal efficiency from a Monte Carlo calculation and a background estimate from the B sideband mass region 5.38–5.88 GeV/ c^2 .

Figures 1 and 2 show scatter plots of the $\mu^+\mu^-K^+$ and $\mu^+\mu^-K^{*0}$ mass versus the $\mu^+\mu^-$ mass for candidates passing all requirements. The signal region for B mesons, whose half-width is chosen to be twice the invariant mass resolution, includes reconstructed B meson masses between 5.23 and 5.33 GeV/ c^2 .

The decays $B^+ \rightarrow J/\psi(\psi')K^+$ and $B^0 \rightarrow J/\psi(\psi')K^{*0}$ followed by $J/\psi(\psi') \rightarrow \mu^+\mu^-$ have product branching fractions 2 orders of magnitude larger than the standard model predictions for the nonresonant $B^+ \rightarrow \mu^+\mu^-K^+$ and $B^0 \rightarrow \mu^+\mu^-K^{*0}$ decays. Candidates with an invari-

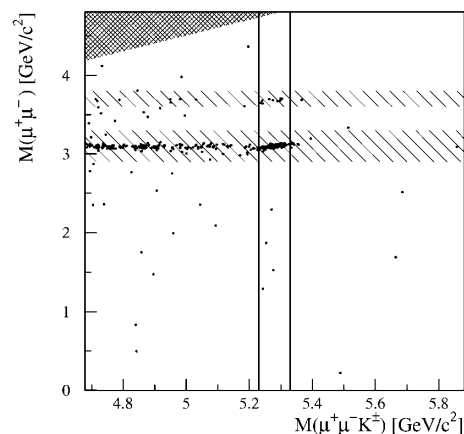


FIG. 1. Scatter plot showing the $B^+ \rightarrow \mu^+\mu^-K^+$ candidates. The hatched horizontal bands are the excluded regions around the J/ψ and ψ' resonances. The signal region is between the vertical lines. The cross-hatched area in the upper left corner is kinematically forbidden. Entries with $M(\mu^+\mu^-K^+) < 5.23$ GeV/ c^2 and dimuon masses in the J/ψ region can be attributed to incompletely reconstructed $B \rightarrow J/\psi X$ decays.

ant mass of the muon pair in the regions 2.9–3.3 GeV/ c^2 or 3.6–3.8 GeV/ c^2 are therefore excluded from the rare decay search. This removes resonant events and the remaining contribution arising from the interference of resonant and nonresonant amplitudes amounts to 10%. Events that have dimuon masses within 100 MeV/ c^2 of the J/ψ mass are used as the normalization sample.

In the B mass region for $\mu^+\mu^-K^+$ final states, we count 4 nonresonant candidates and count 122 J/ψ candidates. In case of the $\mu^+\mu^-K^{*0}$ final state, no nonresonant candidate is found in the B -mass region, while we count 76 J/ψ candidates. The background for the resonant decays is estimated by counting events in the B mass sideband 5.38–5.88 GeV/ c^2 and scaling for the relative sizes of the B signal region and sideband

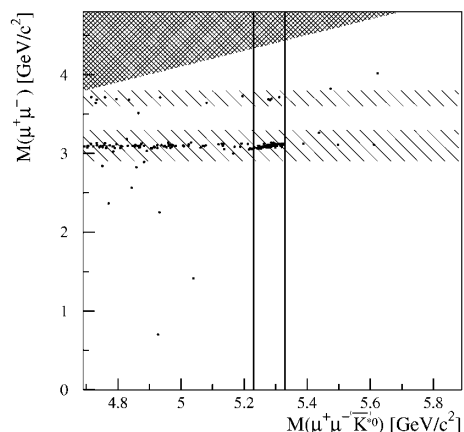


FIG. 2. Scatter plot showing the $B^0 \rightarrow \mu^+\mu^-K^{*0}$ and $\bar{B}^0 \rightarrow \mu^+\mu^-K^{*0}$ candidates. The hatched horizontal bands are the excluded regions around the J/ψ and ψ' resonances.

regions. The estimates obtained this way are 0.4 events for $B^+ \rightarrow J/\psi K^+ \mu^- K^+$ and 0.6 events for $B^0 \rightarrow J/\psi K^{*0} \mu^- K^+$.

The excess of resonant events in the sideband below the B signal region over the sideband above the B mass is understood to come from incompletely reconstructed $B \rightarrow J/\psi X$ decays. The nonresonant excess below the B signal region is not understood. The high-mass sideband, 5 times as wide as the signal region, contains 4 nonresonant $\mu^+ \mu^- K^+$ and 2 nonresonant $\mu^+ \mu^- K^{*0}$ candidates. Note that simply extrapolating these sideband rates may underestimate the background in the signal region, because the high-mass sideband is used to optimize the selection criteria.

Assuming all observed candidates in the signal region are signal events, we set upper limits on the numbers of observable FCNC decays using Poisson statistics and conclude that $\bar{N}(\mu^+ \mu^- K^+) < 8.0$ and $\bar{N}(\mu^+ \mu^- K^{*0}) < 2.3$ at the 90% confidence level.

We use a Monte Carlo simulation to calculate R_ϵ , the ratio of the total trigger and reconstruction efficiency for the nonresonant mode to that of the J/ψ mode, including the effect of the restricted dimuon mass range in the case of nonresonant decays. In the Monte Carlo simulation, B decays are sampled from a phase space distribution and weighted according to the decay amplitude, using form factors and Wilson coefficients taken from Ref. [17]. We find $R_\epsilon(\mu^+ \mu^- K^+) = 0.79$ and $R_\epsilon(\mu^+ \mu^- K^{*0}) = 0.65$. For observable numbers $\bar{N}(\mu^+ \mu^- K^{(*)})$ and $\bar{N}(J/\psi K^{(*)})$ of nonresonant and J/ψ decays, one obtains the branching fractions for the FCNC decays,

$$\begin{aligned} \mathcal{B}(B \rightarrow \mu^+ \mu^- K^{(*)}) &= \frac{\bar{N}(\mu^+ \mu^- K^{(*)})}{\bar{N}(J/\psi K^{(*)}) \times R_\epsilon} \\ &\times \mathcal{B}(B \rightarrow J/\psi K^{(*)}) \\ &\times \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-). \end{aligned}$$

Whereas the central values of R_ϵ assume standard model couplings, distributions of kinematic variables in the decays $B \rightarrow \mu^+ \mu^- K^{(*)}$ can be sensitive to nonstandard short-distance interactions [17,18]. This affects the trigger efficiency, the acceptance of the event selection, and the extrapolation over excluded dimuon mass regions. To study such model dependence, we varied the signs of the relevant Wilson coefficients at M_W , as suggested in Ref. [17], and found the change in efficiency to be much less than the change in the predicted branching fraction. No variation in R_ϵ larger than 4% (12%) was found for $\mu^+ \mu^- K^+ (\mu^+ \mu^- K^{*0})$.

While this procedure does not cover the most general set of models, we conclude that the limits reported in this Letter, which are determined assuming standard model couplings, will change little when applied to many extended models. We do not treat model dependence as a source of error.

The impact of hadronic form factor uncertainties on R_ϵ was studied by replacing the form factors from Ref. [17]

by the two sets given in Ref. [19]. We use the observed change in R_ϵ , less than 4% (8%) for the $K (K^*)$ mode, as an estimate of the systematic error due to form factors.

Dominant systematic errors are the 11% (14%) uncertainty on the product of world-average values for the branching fractions $B \rightarrow J/\psi K^+ (K^{*0})$ and $J/\psi \rightarrow \mu^+ \mu^-$ [20], and the statistical uncertainty on the number of resonant events. All other sources of error are found to make much smaller contributions. We estimate the total systematic error, including hadronic uncertainties, to be 15% (20%) for $\mu^+ \mu^- K(K^*)$, and include it in the determination of an upper limit on the branching fraction, using the method of Ref. [21].

Assuming all observed candidates to be signal events we find

$$\mathcal{B}(B^+ \rightarrow \mu^+ \mu^- K^+) < 5.2 \times 10^{-6}$$

and

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^- K^{*0}) < 4.0 \times 10^{-6}$$

at 90% confidence level. These are the strictest limits on these decay branching fractions to date. Assuming standard model predictions, the expectation is to observe approximately 0.5 signal events in each channel.

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