Search for the Decays $B^0_{(s)} \to e^+\mu^-$ and $B^0_{(s)} \to e^+e^-$ in CDF Run II

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We report results from a search for the lepton flavor violating decays $B_s^0 \to e^+\mu^-$ and $B^0 \to e^+\mu^-$, and the flavor-changing neutral-current decays $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$. The analysis uses data corresponding to 2 fb^{-1} of integrated luminosity of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the upgraded Collider Detector (CDF II) at the Fermilab Tevatron. The observed number of B^0 and B_s^0 candidates is consistent with background expectations. The resulting Bayesian upper limits on the branching ratios at 90% credibility level are $\mathcal{B}(B_s^0 \to e^+\mu^-) < 2.0 \times 10^{-7}$, $\mathcal{B}(B^0 \to e^+\mu^-) < 6.4 \times 10^{-8}$,

$\mathcal{B}(B_s^0 \to e^+e^-) < 2.8 \times 10^{-7}$, and $\mathcal{B}(B^0 \to e^+e^-) < 8.3 \times 10^{-8}$. From the limits on $\mathcal{B}(B_{(s)}^0 \to e^+\mu^-)$, the following lower bounds on the Pati-Salam leptoquark masses are also derived: $M_{LQ}(B_s^0 \to e^+\mu^-) > 47.8\ \text{TeV}/c^2$, and $M_{LQ}(B^0 \to e^+\mu^-) > 59.3\ \text{TeV}/c^2$, at 90% credibility level.

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Rare particle decays that are either forbidden within the standard model (SM) of particle physics or are expected to have very small branching ratios provide excellent signatures with which to look for new physics and allow us to probe subatomic processes that are beyond the reach of direct searches. The decays $B_s^0 \to e^+\mu^-$ and $B^0 \to e^+\mu^-$ [1] are forbidden within the SM, in which lepton number and lepton flavor are conserved. However, the observation of neutrino oscillations indicates that lepton flavor is not conserved. To date, no lepton flavor violating (LFV) decays in the charged sector such as $B_s^0 \to e^+\mu^-$ and $B^0 \to e^+\mu^-$ have been observed. These decays are allowed in models where the SM has been extended by heavy singlet Dirac neutrinos [2]. The LFV decays are also allowed in some physics scenarios beyond the SM, such as the Pati-Salam model [3] and supersymmetry models [4]. The grand-unification theory by Pati and Salam predicts a new interaction to mediate transitions between leptons and quarks via exchange of spin-1 gauge bosons, which are called Pati-Salam leptoquarks (LQ), that carry both color and lepton quantum numbers [3]. The lepton and quark components of the leptoquarks are not necessarily from the same generation [5,6], and the decays $B_s^0 \to e^+\mu^-$ and $B^0 \to e^+\mu^-$ can be mediated by different types of leptoquarks. Processes involving flavor-changing neutral currents (FCNCs) can occur in the SM only through higher-order Feynman diagrams where new physics contributions can provide a significant enhancement. Compared to $B_{(s)}^0 \to \mu^+\mu^-$ [7], the FCNC decays of $B_{(s)}^0 \to e^+e^-$ are further suppressed by the square of the ratio of the electron and muon masses $(m_e/m_\mu)^2$. The SM expectations for branching ratios of $B_{(s)}^0 \to e^+e^-$ are of the order of 10^{-15} [8].

In this Letter we report on a search for the LFV decays $B_s^0 \to e^+\mu^-$ and $B^0 \to e^+\mu^-$ and the FCNC decays $B_{(s)}^0 \to e^+e^-$, using a data sample corresponding to 2 fb^{-1} of integrated luminosity collected in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. With no evidence for either the LFV or FCNC decays, we set upper limits on their branching ratios using the common reference decay $B^0 \to K^+\pi^-$, which has a precisely known branching ratio.

A detailed description of the CDF II detector can be found in Ref. [9]. Here we give a brief description of the detector elements most relevant to this analysis. Charged particle tracking is provided by a silicon microstrip detector together with the surrounding open-cell wire drift chamber (COT), both immersed in a 1.4 T axial magnetic field. The tracking system provides precise vertex and momentum measurement for charged particles in the pseudorapidity range $|\eta| < 1.0$ [10]. Surrounding the tracking system are electromagnetic (CEM) and hadronic sampling calorimeters, arranged in a projective geometry. Drift chambers and scintillation counters are located behind the calorimeters to detect muons within $|\eta| < 0.6$ (CMU) and $0.6 < |\eta| < 1.0$ (CMX).

We use a data sample enriched in two-body B decays selected by a three-level trigger system using the extremely fast tracker [11] at level 1, and the silicon vertex trigger [12] at level 2. The trigger requires two oppositely charged tracks, each with a transverse momentum $p_T > 2\ \text{GeV}/c$, and an impact parameter [13] $0.1 < d_0 < 1$ mm. It also requires the scalar sum of the transverse momenta of the two tracks to be greater than 5.5 GeV/c, the difference in the azimuthal angles of the tracks $20° < \Delta\varphi < 135°$, and a transverse decay length [14] $L_{xy} > 200\ \mu\text{m}$. At the level-3 trigger stage, and in the off-line analysis, the trigger selections are enforced with a more accurate determination of the same quantities. In the off-line analysis, additionally we require the B-meson isolation $I > 0.675$ [15], the pointing angle $\Delta\phi < 6.3°$ [16], and a tighter selection of $L_{xy} > 375\ \mu\text{m}$. These three thresholds were optimized in an unbiased way to obtain the best sensitivity for the searches using the procedure described in Ref. [17].

Electron and muon identification is applied in the selection of $B_s^0(B^0) \to e^+\mu^-$ and $B_s^0(B^0) \to e^+e^-$ decay modes. The electron identification [18] requires that both the specific ionization (dE/dx) measured in the COT and the transverse and longitudinal shower shape as measured in the CEM be consistent with the hypothesis that the particle is an electron. The performance of electron identification is optimized using pure electron samples reconstructed from $\gamma \to e^+e^-$ conversions and hadron and muon samples from $D^0 \to K^-\pi^+$, $\Lambda \to p\pi^-$, and $J/\psi \to \mu^+\mu^-$ decays. We find the identification efficiency to be around 70% for electrons passing through the fiducial regions of the detectors used for electron identification. The muon identification starts from tracks in the COT that are extrapolated into the muon detectors and are required to match hits in the muon systems. The muon selection efficiency for muons with $p_T > 2\ \text{GeV}/c$ in CMU or CMX has been measured to be greater than 99% using muons from J/ψ decays.

The mass resolution σ_m of fully reconstructed B-meson decays to two charged particles is about 28 MeV/c^2. Energy loss due to bremsstrahlung by electrons generates a tail on the low side of the mass distribution. This tail is more prominent for the $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$ channels, where two electrons are involved. We define search windows of (5.262–5.477) GeV$/c^2$ for $B_s^0 \to e^+\mu^-$ and (5.171–5.387) GeV$/c^2$ for $B^0 \to e^+\mu^-$. These correspond to a window around the nominal values of the B_s^0 and B^0 masses [19] of approximately $\pm 3\sigma_m$. To recover some of the acceptance loss due to electron bremsstrahlung for the $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$ channels, we choose wider and asymmetric search windows ranging from $6\sigma_m$ below to $3\sigma_m$ above the nominal values of the B_s^0 and B^0 masses. The search windows are (5.154–5.477) GeV$/c^2$ for the B_s^0 and (5.064–5.387) GeV$/c^2$ for the B^0. The sideband regions (4.800–5.028) GeV$/c^2$ and (5.549–5.800) GeV$/c^2$ are used to estimate the combinatorial backgrounds.

The background contributions considered include combinations of random track pairs and partial B decays that accidentally meet the selection requirement (combinatorial), and hadronic two-body B decays in which both final particles are misidentified as leptons. The combinatorial background is evaluated by extrapolating the normalized number of events found in the sidebands to the signal region. The double-lepton misidentification rate is determined by applying electron and muon misidentification probabilities to the number of two-body decays found in the search window.

Figure 1 shows the invariant mass distribution for $e^+\mu^-$ candidates. We observe one event in the B_s^0 mass window, and two events in the B^0 mass window, consistent with the estimated total background of 0.8 ± 0.6 events in the B_s^0 search window, and 0.9 ± 0.6 in the B^0 window. The total background consists of two components: the combinatorial background in both channels is estimated to be 0.7 ± 0.6 events, the number of events where two tracks are misidentified as electron and muon is estimated to be 0.09 ± 0.02 for the B_s^0 case and 0.22 ± 0.04 for the B^0 case.

Figure 2 shows the invariant mass distributions for e^+e^- candidate pairs where both tracks were identified as electrons. We observe one event in the B_s^0 mass window, and two events in the B^0 mass window. We estimate the total background contributions to be 2.7 ± 1.8 events in both the B_s^0 and B^0 mass windows. The dominant contribution comes from combinatorial background, 2.7 ± 1.8, compared to the contribution where both tracks are misidentified as electrons, 0.038 ± 0.008, for both B_s^0 or B^0.

We use the reference decay $B^0 \to K^+\pi^-$ to set a limit on $\mathcal{B}(B_s^0 \to e^+\ell^-)$ (where ℓ is either e or μ), using the following expression:

$$\mathcal{B}(B_s^0 \to e^+\ell^-) = \frac{N(B_s^0 \to e^+\ell^-)\mathcal{B}(B^0 \to K^+\pi^-) f_d/f_s}{\epsilon^{\rm rel}_{B_s^0 \to e^+\ell^-} N(B^0 \to K^+\pi^-)}.$$

The expression for the B^0 channels is identical, except that the ratio of b-quark fragmentation probabilities, f_d/f_s, is not present. In the expression, $N(B_s^0 \to e^+\ell^-)$ is the calculated upper limit on the number of $B_s^0 \to e^+\ell^-$ events, $N(B^0 \to K^+\pi^-)$ is the observed number of events from

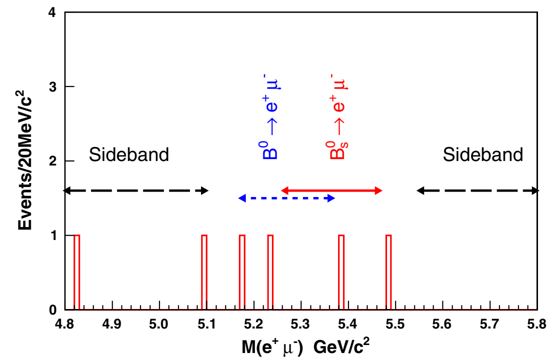

FIG. 1 (color online). Invariant mass distribution of $e^+\mu^-$ pairs for events where one track passed the electron identification and the other track the muon identification. The B_s^0 (B^0) search window is indicated by the solid line (short dashed line). The sideband regions are indicated by the dashed lines.

the reference channel $B^0 \to K^+\pi^-$, $\mathcal{B}(B^0 \to K^+\pi^-) = (19.4 \pm 0.6) \times 10^{-6}$ [19] is the branching ratio for the $B^0 \to K^+\pi^-$ decay, and $\epsilon^{\rm rel}_{B_s^0 \to e^+\ell^-}$ is the detector acceptance and event selection efficiency for reconstructing $B_s^0 \to e^+\ell^-$ decays relative to that for $B^0 \to K^+\pi^-$. The value of f_d/f_s is 3.86 ± 0.59, where the (anti)correlation between the uncertainties has been accounted for [20]. To account for the differences in detector fiducial coverage and event selection efficiencies between the search and reference channel we use Monte Carlo events with a detailed simulation of the CDF detector response. Collision data are used to measure electron and muon identification efficiencies. We obtain $\epsilon^{\rm rel}_{B_s^0 \to e^+\mu^-} = 0.207 \pm 0.016$, $\epsilon^{\rm rel}_{B^0 \to e^+\mu^-} = 0.210 \pm 0.012$, $\epsilon^{\rm rel}_{B_s^0 \to e^+e^-} = 0.129 \pm 0.011$, and $\epsilon^{\rm rel}_{B^0 \to e^+e^-} = 0.128 \pm 0.011$. These results of relative detector acceptance and efficiency also include effects of the different search windows for the $e^+\mu^-$ and e^+e^- channels. The uncertainties listed above are the combined

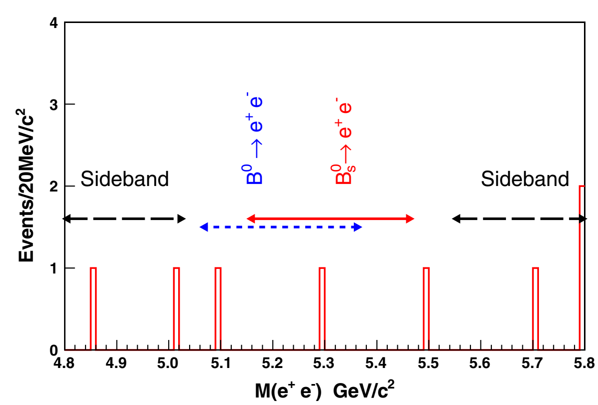

FIG. 2 (color online). Invariant mass distributions of e^+e^- pairs for events where both tracks passed the electron identification. The B_s^0 (B^0) search window is indicated by the solid line (short dashed line). The sideband regions are indicated by dashed lines.

TABLE I. Values used to calculate the limits on $\mathcal{B}(B^0_{(s)} \to e^+\mu^-)$ and $\mathcal{B}(B^0_{(s)} \to e^+e^-)$ and their uncertainties.

Source	Values	$\mathcal{B}(B^0_s \to e^+\mu^-)$	$\mathcal{B}(B^0 \to e^+\mu^-)$	$\mathcal{B}(B^0_s \to e^+e^-)$	$\mathcal{B}(B^0 \to e^+e^-)$
$N(B^0 \to K^+\pi^-)$	6387 ± 214	3.4%	3.4%	3.4%	3.4%
$\mathcal{B}(B^0 \to K^+\pi^-)$	$(19.4 \pm 0.6) \times 10^{-6}$	3.1%	3.1%	3.1%	3.1%
f_d/f_s	3.86 ± 0.59	15.3%	$\cdots$	15.3%	$\cdots$
$\epsilon^{\text{rel}}_{B^0_s \to e^+\mu^-}$	0.207 ± 0.016	7.6%	$\cdots$	$\cdots$	$\cdots$
$\epsilon^{\text{rel}}_{B^0 \to e^+\mu^-}$	0.210 ± 0.012	$\cdots$	5.9%	$\cdots$	$\cdots$
$\epsilon^{\text{rel}}_{B^0_s \to e^+e^-}$	0.129 ± 0.011	$\cdots$	$\cdots$	8.9%	$\cdots$
$\epsilon^{\text{rel}}_{B^0 \to e^+e^-}$	0.128 ± 0.011	$\cdots$	$\cdots$	$\cdots$	8.9%
Total		17.7%	7.5%	18.3%	10.0%

statistical and systematic uncertainties. The latter include uncertainties from detector fiducial coverage, electron and muon identification efficiencies, detector material determination, B^0_s and B^0 p_T spectrum, and B^0_s and B^0 lifetimes. The reference channel $B^0 \to K^+\pi^-$ has been reconstructed using the same selection criteria except lepton identification. We find 6387 ± 214 $B^0 \to K^+\pi^-$ events, using a fitting procedure similar to that described in Ref. [21]. The uncertainty as returned by the fit is a combination of the mass fitting uncertainty and the sample composition uncertainties.

The upper limit on the branching ratio in each search window is obtained using the Bayesian approach [19], assuming a flat prior, and incorporating Gaussian uncertainties into the limit. The total systematic uncertainties, listed in Table I, are used as input for the limit calculation. Table II lists the upper limits we obtain on the branching ratios at 90% (95%) credibility level (C.L.).

Within the Pati-Salam leptoquark model, the following relationship between the $\mathcal{B}(B^0_{(s)} \to e^+\mu^-)$ and the leptoquark mass (M_{LQ}) can be derived [5]:

$$\mathcal{B}(B^0_{(s)} \to e^+\mu^-) = \pi\alpha_s^2(M_{\text{LQ}})\frac{1}{M_{\text{LQ}}^4}F^2_{B^0_{(s)}}m^3_{B^0_{(s)}}R^2\frac{\tau_{B^0_{(s)}}}{\hbar},$$

where $R = \frac{m_{B^0_{(s)}}}{m_b}\left(\frac{\alpha_s(M_{\text{LQ}})}{\alpha_s(m_t)}\right)^{-4/7}\left(\frac{\alpha_s(m_t)}{\alpha_s(m_b)}\right)^{-12/23}$. The values and uncertainties of the quantities used in the calculation of M_{LQ} are the following [19]: the top-quark mass m_t (171.2 ± 2.1 GeV$/c^2$), the bottom-quark mass m_b (4.20 ± 0.17 GeV$/c^2$), the charm quark mass m_c (1.27 ± 0.11 GeV$/c^2$), the B^0-meson mass m_{B^0} ($5.279\,53 \pm 0.000\,33$ GeV$/c^2$), the B^0_s-meson mass $m_{B^0_s}$ (5.3663 ± 0.0006 GeV$/c^2$), the B^0-meson lifetime τ_{B^0} (1.530 ± 0.009 ps), the B^0_s-meson lifetime $\tau_{B^0_s}$ (1.470 ± 0.027 ps), the coupling strength F_{B^0} (0.178 ± 0.014 GeV), and $F_{B^0_s}$ (0.200 ± 0.014 GeV) [22]. For the strong coupling constant we use $\alpha_s(M_{Z^0}) = 0.115$, which is evolved to M_{LQ} using the Marciano approximation [23] assuming no colored particles exist with masses between m_t and M_{LQ}. Using the limits on the branching ratios listed in Table II, we calculate limits on the masses of the corresponding Pati-Salam leptoquarks of $M_{\text{LQ}}(B^0_s \to e^+\mu^-) > 47.8(44.9)$ TeV$/c^2$ and $M_{\text{LQ}}(B^0 \to e^+\mu^-) > 59.3(56.3)$ TeV$/c^2$ at 90% (95)% C.L. Figure 3 shows the limit and the relation between the leptoquark mass and the branching ratio for the B^0_s meson.

TABLE II. Branching ratio limits at 90% (95)% C.L.

$\mathcal{B}(B^0_s \to e^+\mu^-) < 2.0(2.6) \times 10^{-7}$
$\mathcal{B}(B^0 \to e^+\mu^-) < 6.4(7.9) \times 10^{-8}$
$\mathcal{B}(B^0_s \to e^+e^-) < 2.8(3.7) \times 10^{-7}$
$\mathcal{B}(B^0 \to e^+e^-) < 8.3(10.6) \times 10^{-8}$

In summary, we report on a search for the lepton flavor violating decays $B^0_s \to e^+\mu^-$ and $B^0 \to e^+\mu^-$ and the flavor-changing neutral-current decays $B^0_s \to e^+e^-$ and $B^0 \to e^+e^-$ using data corresponding to 2 fb^{-1} of integrated luminosity collected in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. This is the first search for $B^0_s \to e^+e^-$ and $B^0 \to e^+e^-$ decays at the Tevatron. We observe no evidence for

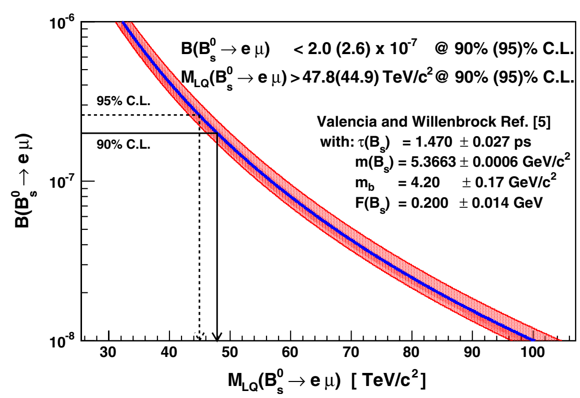

FIG. 3 (color online). Leptoquark mass limit corresponding to the 90(95)% C.L. on $\mathcal{B}(B^0_s \to e^+\mu^-)$. The error band is obtained by varying the values entering the theoretical calculation within their uncertainties. The uncertainties stemming from approximating α_s are not included.

these decays and set limits that are the most stringent to date. These results represent a significant improvement compared to the previous measurement [24] by CDF and the best results from B Factories [25–27] and LEP [28].

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