Search for $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$ Decays in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report on a search for $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$ decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using 171 pb^{-1} of data collected by the CDF II experiment at the Fermilab Tevatron Collider. The decay rates of these rare processes are sensitive to contributions from physics beyond the standard model. One event survives all our selection requirements, consistent with the background expectation. We derive branching ratio limits of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 5.8 \times 10^{-7}$ and $\mathcal{B}(B_d^0 \to \mu^+\mu^-) < 1.5 \times 10^{-7}$ at 90% confidence level.

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The rare flavor-changing neutral current decay $B_s^0 \to \mu^+\mu^-$ [1] is one of the most sensitive probes to physics beyond the standard model (SM) [2–6]. The decay has not been observed and is currently limited to $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 2.0 \times 10^{-6}$ at 90% confidence level (C.L.) [7], while the SM prediction is $(3.5 \pm 0.9) \times 10^{-9}$ [8]. The limit on the related branching ratio, $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.6 \times 10^{-7}$ [9], is approximately 1000 times larger than its SM expectation. The $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ can be significantly enhanced in various supersymmetric (SUSY) extensions of the SM. Minimal supergravity models at large $\tan\beta$ [3–5] predict $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < \mathcal{O}(10^{-7})$ in regions of parameter space consistent with the observed muon $g - 2$ [10] and also with the observed relic density of cold dark matter [11]. SO(10) models [6], which naturally accommodate neutrino masses, predict a branching ratio as large as 10^{-6} in regions of parameter space consistent with these same experimental constraints. R-parity violating SUSY models can also accommodate $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ up to 10^{-6} [4]. Correspondingly, the $\mathcal{B}(B_d^0 \to \mu^+\mu^-)$ can be enhanced by the same models. Even modest improvements to the experimental limits can significantly restrict the available parameter space of these models.

We report on a search for $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$ decays using the upgraded Collider Detector at

Fermilab (CDF II) at the Tevatron $p\bar{p}$ collider. The CDF II detector consists of a magnetic spectrometer surrounded by calorimeters and muon chambers and is described in detail in Ref. [12]. A cylindrical drift chamber (COT) provides 96 measurement layers, organized into alternating axial and $\pm 2°$ stereo superlayers [13], and a five-layer silicon microstrip detector (SVX II) provides precise tracking information near the beam line [14]. These are immersed in a 1.4 T magnetic field and measure charged particle momenta in the plane transverse to the beam line, p_T. Four layers of planar drift chambers (CMU) detect muons which penetrate the five absorption lengths of calorimeter steel [15]. Another four layers of planar drift chambers (CMP) instrument 0.6 m of steel outside the magnet return yoke [16]. The CMU and CMP chambers each provide coverage in the pseudorapidity range $|\eta| < 0.6$, where $\eta = -\ln(\tan\frac{\theta}{2})$ and θ is the angle of the track with respect to the beam line. The data set reported here corresponds to an integrated luminosity of $\mathcal{L} = 171 \pm 10\ \text{pb}^{-1}$ [17].

The data used in this analysis are selected by dimuon triggers. Muons are reconstructed as track stubs in the CMU chambers. Two well-separated stubs are required and each is matched to a track reconstructed online using COT axial information [18]. The matched tracks must have $p_T > 1.5$ GeV/c. A complete event reconstruction performed online confirms the p_T and track-stub matching requirements. If the overlapping CMP chambers contain a confirming muon stub, the track is required to have $p_T > 3$ GeV/c. The two tracks must originate from the same vertex, be oppositely charged, and have an opening angle inconsistent with a cosmic ray event. The invariant mass of the muon pair must satisfy $M_{\mu^+\mu^-} < 6$ GeV/c^2. Events in which neither muon is reconstructed with a CMP stub must additionally satisfy $p_T^{\mu^+} + p_T^{\mu^-} > 5$ GeV/c and $M_{\mu^+\mu^-} > 2.7$ GeV/c^2. This set of triggers is used for all the data included here and events passing these requirements are recorded for further analysis.

Our offline analysis begins by identifying the muon candidates and matching them to the trigger tracks using COT hit information. To avoid regions of rapidly changing trigger efficiency, we omit muons with $p_T < 2$ GeV/c. To reduce backgrounds from fake muons, stricter track-stub matching requirements are made and the vector sum of the muon momenta must satisfy $|\vec{p}_T^{\,\mu^+\mu^-}| > 6$ GeV/c. To ensure good vertex resolution, stringent requirements are made on the number of SVX II hits associated with each track. Surviving events have the two muon tracks constrained to a common 3D vertex satisfying vertex quality requirements. The two-dimensional decay length, $|\vec{L}_T|$, is calculated as the transverse distance from the beam line to the dimuon vertex and is signed relative to $\vec{p}_T^{\,\mu^+\mu^-}$. For each B candidate we estimate the proper decay length using $\lambda = cM_{\mu^+\mu^-}|\vec{L}_T|/|\vec{p}_T^{\,\mu^+\mu^-}|$. In the data, 2981 events survive all the above trigger and offline reconstruction requirements. This forms a background-dominated sample with contributions from two principal sources: combinatoric background events with a fake muon and events from generic B-hadron decays (e.g., sequential semileptonic decays $b \to c\mu^- X \to \mu^+\mu^- X$ or double semileptonic decay in gluon splitting events $g \to b\bar{b} \to \mu^+\mu^- X$).

We model the signal decays using the PYTHIA Monte Carlo (MC) program [19] tuned to inclusive B-hadron data [20]. The PYTHIA events are passed through a full detector simulation and satisfy the same requirements as the data. To normalize to experimentally determined cross sections, we require $p_T(B^0_{s(d)}) > 6$ GeV/c and rapidity $|y| < 1$.

To discriminate $B^0_{s(d)} \to \mu^+\mu^-$ decays from background events we use these four variables: the invariant mass of the muon pair ($M_{\mu^+\mu^-}$), the B-candidate proper decay length (λ), the opening angle ($\Delta\Phi$) between the B-hadron flight direction (estimated as the vector $\vec{p}_T^{\,\mu^+\mu^-}$) and the vector $\vec{L}_T$, and the B-candidate track isolation (I) [21]. Figure 1 shows the distributions of these variables for background-dominated data and MC signal events.

A "blind" analysis technique is used to determine the optimal selection criteria for these four variables. The data in the search window $5.169 < M_{\mu^+\mu^-} < 5.469$ GeV/c^2 are hidden, and the optimization is performed using only data in the sideband regions, $4.669 < M_{\mu^+\mu^-} < 5.169$ GeV/c^2 and $5.469 < M_{\mu^+\mu^-} < 5.969$ GeV/c^2. The search region corresponds to approximately ± 4 times the two-track invariant mass resolution centered on the B^0_s and B^0_d masses [22]. We use the set of ($M_{\mu^+\mu^-}$, λ, $\Delta\Phi$, I) criteria which minimizes the *a priori*

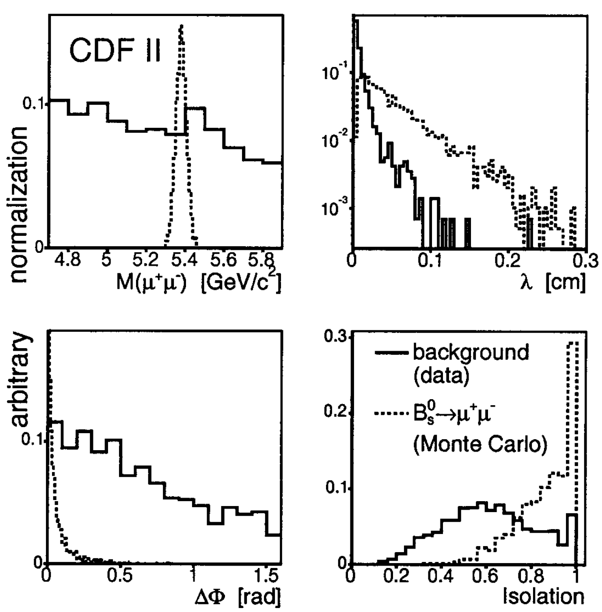

FIG. 1. Arbitrarily normalized distributions of the discriminating variables for events in our background-dominated data sample (solid line) compared to Monte Carlo $B^0_s \to \mu^+\mu^-$ events (dashed line).

expected 90% C.L. upper limit on the branching ratio. For a given number of observed events n and an expected background of $n_{\rm bg}$, the branching ratio is determined using

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \le \frac{N(n, n_{\rm bg})}{2\sigma_{B_s^0}\mathcal{L}\alpha\epsilon_{\rm total}},$$

where $N(n, n_{\rm bg})$ is the number of candidate $B_s^0 \to \mu^+\mu^-$ decays at 90% C.L., estimated using the Bayesian approach of Ref. [23] and incorporating the uncertainties into the limit. The *a priori* expected limit is given by the sum over all possible observations, n, weighted by the corresponding Poisson probability when expecting $n_{\rm bg}$. The B_s^0 production cross section is estimated as $\sigma_{B_s^0} = \frac{f_s}{f_u} = \frac{0.100}{0.391}$ [24] and σ_{B^+} is taken from Ref. [25]. For the $B_d^0 \to \mu^+\mu^-$ limit we substitute $\sigma_{B_d^0}$ for $\sigma_{B_s^0}$, f_d for f_s, and assume $f_d = f_u$. The factor of 2 in the denominator accounts for the charge-conjugate B-hadron final states. The expected background $n_{\rm bg}$ and the total acceptance times efficiency $\alpha\epsilon_{\rm total}$ are estimated separately for each combination of requirements.

For both signal and background, the variables λ and $\Delta\Phi$ are the only correlated variables with a linear correlation of -0.3. Thus we estimate the number of background events as $n_{\rm bg} = n_{\rm sb}(\lambda, \Delta\Phi)f_I f_M$, where $n_{\rm sb}(\lambda, \Delta\Phi)$ is the number of sideband events passing a particular set of λ and $\Delta\Phi$ cuts, f_I is the fraction of background events that survive a given I requirement, and f_M is the ratio of the number of events in the search window to the number of events in the sideband regions. Since $M_{\mu^+\mu^-}$ and I are uncorrelated with the rest of the variables, we evaluate f_M and f_I on samples with no λ or $\Delta\Phi$ requirement, thus reducing their associated uncertainty.

We estimate f_I from the background-dominated sample for a variety of thresholds. We investigate sources of systematic bias by calculating f_I in bins of $M_{\mu^+\mu^-}$ and λ and conservatively assign a relative systematic uncertainty of $\pm5\%$. Since the $M_{\mu^+\mu^-}$ distribution of the background-dominated sample is well described by a first-order polynomial, f_M is given by the ratio of widths of the search to sideband regions.

MC studies demonstrate that our estimate of $n_{\rm bg}$ accurately accounts for generic $b\bar{b}$ contributions, while two-body decays of B mesons ($B_{s(d)}^0 \to h^+h^-$, where $h^\pm = \pi^\pm$ or $K^\pm$) are estimated to contribute to the search region at levels at least 100 times smaller than our expected sensitivity.

Using these background-dominated control samples, $\mu^\pm\mu^\pm$ events and $\mu^+\mu^-$ events with $\lambda < 0$, we compare our background predictions to the number of events in the search window for a wide range of $(\lambda, \Delta\Phi, I)$ requirements. No statistically significant discrepancies are observed. For example, using the optimized set of selection criteria described below and summing over these control samples, we get a total prediction of 3 ± 1 events and observe five. Another cross-check is performed using a fake muon enhanced $\mu^+\mu^-$ sample. By requiring at least one of the muon legs to fail the muon identification requirements, we reduce the signal efficiency by a factor of 50 while increasing the background acceptance by a factor of 3. In this sample, using the optimized requirements, we predict 6 ± 1 and observe seven events.

We estimate the total acceptance times efficiency as $\alpha\epsilon_{\rm total} = \alpha\epsilon_{\rm trig}\epsilon_{\rm reco}\epsilon_{\rm final}$, where α is the geometric and kinematic acceptance of the trigger, $\epsilon_{\rm trig}$ is the trigger efficiency for events in the acceptance, $\epsilon_{\rm reco}$ is the offline reconstruction efficiency for events passing the trigger, and $\epsilon_{\rm final}$ is the efficiency for passing the final cuts on the discriminating variables for events satisfying the trigger and reconstruction requirements. For the optimization, only $\epsilon_{\rm final}$ changes as we vary the requirements on $M_{\mu^+\mu^-}$, λ, $\Delta\Phi$, and I.

The acceptance is estimated as the fraction of $B_{s(d)}^0 \to \mu^+\mu^-$ MC events which fall within the geometric acceptance and satisfy the kinematic requirements of at least one of the analysis triggers. We find $\alpha = (6.6 \pm 0.5)\%$. The uncertainty includes roughly equal contributions from systematic variations of the modeling of the B-hadron p_T spectrum and longitudinal beam profile, and from the statistics of the sample. It also includes negligible contributions from variations of the beam line offsets and of the detector material description used in the simulation.

The trigger efficiency, including the effects of the offline-to-trigger track matching, is estimated from samples of $J/\psi \to \mu^+\mu^-$ decays selected with a trigger requiring only one identified muon. The data are used to parametrize the trigger efficiency as a function of p_T and η for the unbiased muon. The efficiency for $B_{s(d)}^0 \to \mu^+\mu^-$ decays is determined by the convolution of this parametrization with the $(p_T^{\mu^+}, \eta^{\mu^+}, p_T^{\mu^-}, \eta^{\mu^-})$ spectra of signal MC events within the acceptance. Including the online reconstruction requirements, the trigger efficiency is $\epsilon_{\rm trig} = (85 \pm 3)\%$. The uncertainty is dominated by the systematic uncertainty accounting for kinematic differences between $J/\psi \to \mu^+\mu^-$ and $B_{s(d)}^0 \to \mu^+\mu^-$ decays and also includes contributions from variations in the functional form used in the parametrization, the effects of two-track correlations, and sample statistics.

The offline reconstruction efficiency is given by the product $\epsilon_{\rm reco} = \epsilon_{\rm COT}\epsilon_\mu\epsilon_{\rm SVX}$, where $\epsilon_{\rm COT}$ is the absolute reconstruction efficiency of the COT, ϵ_μ is the muon reconstruction efficiency given a COT track, and $\epsilon_{\rm SVX}$ is the fraction of reconstructed muons which satisfy the SVX II requirements. Each term is a two-track efficiency. A hybrid data-MC method is used to determine $\epsilon_{\rm COT}$. Occupancy effects are accounted for by embedding COT hits from MC tracks in data events. The MC simulation is tuned at the hit level to reproduce residuals, hit width, and hit usage in the data. For embedded muons with $p_T > 2$ GeV/c, we measure $\epsilon_{\rm COT} = 99\%$. Using the unbiased $J/\psi \rightarrow \mu^+\mu^-$ samples, we estimate the muon reconstruction efficiency, including the track-stub matching requirements, to be 96%. A sample of $J/\psi \rightarrow \mu^+\mu^-$ events satisfying our COT and muon reconstruction requirements is used to determine $\epsilon_{\rm SVX} = 75\%$. The total reconstruction efficiency is given by the above product, $\epsilon_{\rm reco} = (71 \pm 3)\%$. The uncertainty is dominated by the systematic uncertainty accounting for kinematic differences between $J/\psi \rightarrow \mu^+\mu^-$ and $B^0_{s(d)} \rightarrow \mu^+\mu^-$ decays and also includes contributions from the variation of the COT simulation parameters and sample statistics.

The efficiency $\epsilon_{\rm final}$ is determined from the $B^0_{s(d)} \rightarrow \mu^+\mu^-$ MC sample and varies from 28%–78% over the range ($M_{\mu^+\mu^-}$, λ, $\Delta\Phi$, I) requirements considered in the optimization. The MC modeling is checked by comparing the mass resolution and λ, $\Delta\Phi$, and I efficiency as a function of selection threshold for $B^+ \rightarrow J/\psi K^+ (J/\psi \rightarrow \mu^+\mu^-)$ events. The $B^+ \rightarrow J/\psi K^+$ MC sample is produced in the same manner as the $B^0_s \rightarrow \mu^+\mu^-$ sample. The $B^+ \rightarrow J/\psi K^+$ data sample is collected using dimuon triggers very similar to those used in the analysis, but with a larger acceptance for $B^+ \rightarrow J/\psi K^+$ decays. We make the same requirements on the dimuon tracks and vertex as employed in the analysis. The MC efficiency is consistent with the sideband-subtracted data efficiency for a range of cut thresholds within 5% (relative), which is assigned as a systematic uncertainty on $\epsilon_{\rm final}$. In both the data and the MC sample, the mean of the three-track invariant mass distribution is within 3 MeV/c^2 of the world average B^+ mass. The two-track invariant mass resolution is well described by the MC sample.

The optimal set of selection criteria uses a ± 80 MeV/c^2 search window around the B^0_s mass, $\lambda > 200$ μm, $\Delta\Phi < 0.10$ rad, and $I > 0.65$. The mass resolution, estimated from the MC for the events surviving all requirements, is 27 MeV/c^2 so that the B^0_d and B^0_s masses are resolved. We define a separate search window centered on the world average B^0_d mass and use the same set of selection criteria for the $B^0_d \rightarrow \mu^+\mu^-$ search. The total acceptance times efficiency is $\alpha\epsilon_{\rm total} = (2.0 \pm 0.2)\%$ for both decays.

Using these criteria one event survives all requirements and has an invariant mass of $M_{\mu^+\mu^-} = 5.295$ GeV/c^2, thus falling into both the B^0_s and B^0_d search windows as shown in Fig. 2. This is consistent with the 1.1 ± 0.3 background events expected in each of the B^0_s and B^0_d mass windows. We derive 90% (95%) C.L. limits of $\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-7}$ (7.5×10^{-7}) and $\mathcal{B}(B^0_d \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-7}$ (1.9×10^{-7}). The new $B^0_s \rightarrow \mu^+\mu^-$ limit improves the previous limit [7] by a factor of 3 and significantly reduces the allowed parameter space of R-parity violating and SO(10) SUSY models [4,6]. The $B^0_d \rightarrow \mu^+\mu^-$ limit is slightly better than the recent limit from the Belle Collaboration [9].

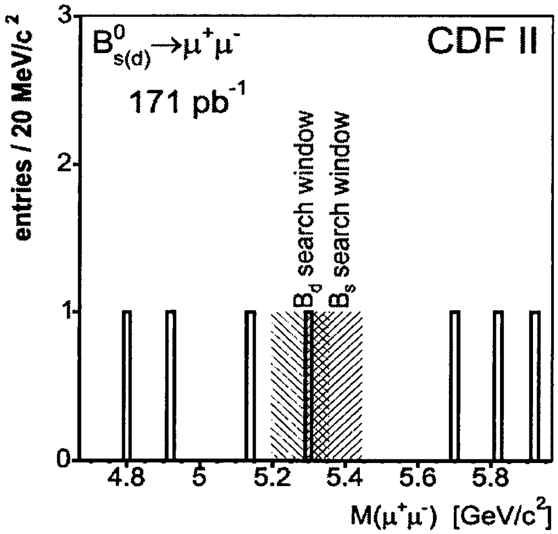

FIG. 2. The $\mu^+\mu^-$ invariant mass distribution of the events in the sideband and search regions satisfying all requirements.

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