Search for the rare decay $B^0_s \rightarrow \mu^+ \mu^-$


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We present the results of a search for the flavor changing neutral current decay $B^0 \rightarrow \mu^+\mu^-$ using 6.1 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 1.96$ TeV collected by the D0 experiment at the Fermilab Tevatron Collider. The observed number of $B^0$ candidates is consistent with background expectations. The resulting upper limit on the branching fraction is $B(B^0 \rightarrow \mu^+\mu^-) < 5.1 \times 10^{-8}$ at the 95% C.L. This limit is a factor of 2.4 better than that of the previous D0 analysis and the best limit to date.

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The standard model (SM) provides an accurate description of current observations in high energy physics experiments, in particular precision electroweak measurements and flavor physics observables. A flavor changing neutral current (FCNC) process is an apparent transition between quarks of different flavor but equal charge. In the SM, the FCNC processes are forbidden at first order. They can occur at second order only through Glashow-Iliopoulos-Maiani (GIM) suppressed box and penguin diagrams. The decay $B^0_s \rightarrow \mu^+\mu^-$ is an example of such a process, as shown in Fig. 1. Unlike other FCNC decays this decay rate is further suppressed by helicity factors in the final state [3].

The SM expectation for the branching fraction of this decay is $(3.6 \pm 0.3) \times 10^{-9}$ [4]. The decay amplitude for $B^0_s \rightarrow \mu^+\mu^-$ can be enhanced by several orders of magnitude in some extensions of the SM. For example, in some supersymmetric models such as the minimal supersymmetric standard model this decay can occur through the mediation of superpartners of the SM intermediate par-
particles as well as particles from the extended Higgs sector. This extended contribution becomes larger if the value of $\tan \beta$, the ratio of the vacuum expectation values of the two neutral Higgs fields, is large [5-10]. Similarly, in some supersymmetric models with $R$-parity violating couplings [11], this enhancement can be present even in the regime of low $\tan \beta$. Improved limits on the branching fraction of this decay can be used to set limits on the parameter space of supersymmetric models and other new theories. Since the predicted rate for this process in the SM is beyond the current experimental sensitivity at the Tevatron, the observation of this decay would necessarily imply physics beyond the SM. Similar annihilation topologies have also been studied for new theories. Since the predicted rate for this process in the SM is beyond the current experimental sensitiv-

All data collected up to June 2009 are included in this analysis. The integrated luminosities for the Run Ila and Run Iib data sets are 1.3 fb$^{-1}$ and 4.8 fb$^{-1}$, respectively. Events are recorded using a set of single muon triggers, dimuon triggers, and triggers that select $pp$ interactions based on energy depositions in the calorimeter. $B^0 \rightarrow \mu^+\mu^-$ candidates are formed from pairs of oppositely charged muons identified by extrapolating tracks reconstructed in the central tracking detectors to the muon detectors, and matching them with information from the muon system. The muon selection has been updated with respect to the previous analysis [17], yielding 10% higher acceptance while keeping the fraction of misidentified muons below 0.5%. Each muon is required to have a transverse momentum $p_T^\mu \geq 1.5$ GeV, and to have hits in at least two layers of both the CFT and the SMT. The $B^0$ candidate is required to have a reconstructed three-dimensional (3D) decay vertex displaced from the interaction point with a transverse decay length significance $L_T/\sigma_{L_T} \geq 3$ to reduce prompt dimuon background, where $L_T = \delta T \cdot \frac{p_T^\mu}{|p_T^\mu|}$. The vectors $\delta T$ and $p_T^\mu$ are, respectively, the vector from the interaction point to the decay point and the transverse momentum vector of the $B^0$ meson in the transverse plane. The $pp$ interaction vertex is found for each event using a beam-spot constrained fit as described in [22]. Events are selected if the reconstructed invariant dimuon mass, $m_{\mu\mu}$, is between 4.0 GeV and 7.0 GeV.

To further suppress the background we use the following discriminating variables: the transverse momentum of the $B^0$ candidate $p_T^B$, the pointing angle, $L_T/\sigma_{L_T}$, the decay vertex fit $\chi^2$, the smaller impact parameter significance $\frac{\|\delta/\sigma_3\|$ of the two muons, $\text{min}(\delta/\sigma_3)$, and the smaller $p_T^\mu$ of the two muons, $\text{min}(p_T^\mu)$. The pointing angle is defined to be the 3D opening angle between the $B^0$ meson momentum vector and the displacement vector from the interaction to the dimuon vertex. The impact parameter $\delta$ is defined to be the distance of closest approach of the track to the interaction point in the transverse plane, and $\sigma_3$ is its uncertainty. We use a Bayesian Neural Network (BNN) [23, 24] multivariate classifier with the above variables to distinguish signal events from background. The BNN is trained using background events sampled from the sideband regions (4.5 GeV $\leq m_{\mu\mu} \leq 5.0$ GeV and 5.8 GeV $\leq m_{\mu\mu} \leq 6.1$ GeV). Improved limits on the branching fraction of this decay can be used to set limits on the parameter space of supersymmetric models and other new theories. Since the predicted rate for this process in the SM is beyond the current experimental sensitivity at the Tevatron, the observation of this decay would necessarily imply physics beyond the SM.
In the context of dimuon production, the DØ collaboration has investigated inclusive dimuon events to study background contributions. To isolate these, sideband events were utilized. The dimuon signal region is defined as $5.0 \text{ GeV} < m_{\mu\mu} < 5.8 \text{ GeV}$, where $m_{\mu\mu}$ is the dimuon invariant mass. The background estimate is dominated by statistical uncertainty of the sideband sample (10-35%).

The branching fraction $B(B_0^0 \rightarrow \mu^+\mu^-)$ is computed by normalizing the number of events, $N(B_0^0)$, to the number of reconstructed $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ events, $N(B^+)$:

$$B(B_0^0 \rightarrow \mu^+\mu^-) = \frac{N(B_0^0)}{N(B^+)} \cdot \frac{\epsilon_{B^+}}{\epsilon_{B_0^0}} \cdot f_9 \cdot f_9^* \cdot B(B^+)$$

where the efficiencies $\epsilon_{B^+}$ and $\epsilon_{B_0^0}$ are the reconstruction efficiencies for $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ and $B_0^0 \rightarrow \mu^+\mu^-$, respectively. They are estimated from simulations. We use $B(B^+) = B(B^+ \rightarrow J/\psi K^+) \times B(J/\psi \rightarrow \mu^+\mu^-) = (5.97 \pm 0.22) \times 10^{-5}$ [30] and the ratio of $B$-hadron production fractions $f_9/f_9^* = 3.86 \pm 0.59$ [29].

A sample of $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ events is selected using all but the $\beta$ selection requirements, with an additional requirement of $p_T^\mu \geq 1 \text{ GeV}$ for the kaon candidate. By performing a binned likelihood fit with the $J/\psi K^+$ invariant mass distribution in data, we observe $N(B^+) = 14340 \pm 665$ events for Run IIa and $32463 \pm 875$ events for Run IIb, where the uncertainty is only statistical. The statistical significance of the $B^+$ signal yield in Run IIb is higher than that in Run IIa although the lower yield per the integrated luminosity. The $J/\psi K^+$ invariant mass distribution is shown in Fig. 3. A systematic uncertainty of 2% on the $B^+$ yield is found by varying the fit parametrization. The efficiency for additional kaon tracks in $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ is calibrated using the ratio of $B^0 \rightarrow J/\psi(\mu^+\mu^-)K^{*0}(K^+\pi^-)$ to $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ data with an uncertainty of 7.5%. The trigger efficiency depends on the muon transverse momentum $p_T^\mu$. This is modeled by comparing the parametrized using an exponential function to estimate the number of background events in the signal region after fitting the dimuon mass in the data sideband regions, $4.0 \text{ GeV} \leq m_{\mu\mu} \leq 5.0 \text{ GeV}$ and $6.0 \text{ GeV} \leq m_{\mu\mu} \leq 7.0 \text{ GeV}$, in each $\beta$ bin. The uncertainty on this background estimate is dominated by the statistical uncertainty of the sideband sample (10-35%).

Additional background contributions from $B^0$ and $B^0_s$ decays $B \rightarrow h^+h^-$, where $h^+$ and $h^-$ represent a charged kaon or pion, are evaluated using the $J/\psi \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow K^+\pi^-$ decays. The dimuon identification efficiency and fractions of pions and kaons misidentified as muons are estimated using simulations. The muon identification efficiency and the fractions of pions and kaons misidentified as muons are estimated using simulations.
$p_T^\mu$ distribution in the selected data events with a control sample requiring a $p_T^\mu$ independent trigger and then applying the ratio to the simulated events as a $p_T^\mu$ dependent weight factor. A possible dependence of this weight factor on the dimuon kinematics is evaluated by choosing another sample at higher dimuon masses; this effect is found to be less than 1%. The $p_T^\mu$ spectra in the $B_0^0$ and $B^+$ simulations are corrected following comparisons of the $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ in data and simulation. A similar correction is obtained from $B_0^0 \rightarrow J/\psi\phi$ decays, and the difference between the two is assigned as an uncertainty of 6.5%. The product of the factors multiplying $N(B_0^0)$ on the right-hand side of Eq. 1 is called the single event sensitivity. We find a single event sensitivity $(4.9 \pm 1.0) \times 10^{-9}$ for Run IIa and $(1.84 \pm 0.36) \times 10^{-9}$ for Run IIb in the signal region. Using the SM prediction of $B(B_0^0 \rightarrow \mu^+\mu^-)$ [4], there are $0.74 \pm 0.17$ events in Run IIa and $1.95 \pm 0.42$ events in Run IIb expected in the signal region. Aside from the background uncertainty, the largest uncertainty of 15% common to Run IIa and Run IIb comes from the fragmentation ratio, $f_\mu/f_\pi$.

We compute the final sensitivity using 2D histograms of $m_{\mu\mu}$ vs. $\beta$ of the signal and the backgrounds by combining the sensitivity of each bin taking into account the correlated uncertainties. In addition to the uncertainty on the signal normalization, we add uncertainties on the expected $B_0^0$ mass and its resolution in the calculation. Additional uncertainties on the dimuon background distributions are assigned to allow for possible variation in the background $m_{\mu\mu}$ distribution as a function of $\beta$. The resulting median expected limits are $B(B_0^0 \rightarrow \mu^+\mu^-) < 8.5 \times 10^{-8}(6.8 \times 10^{-8})$ for Run IIa, and $4.6 \times 10^{-8}(3.7 \times 10^{-8})$ for Run IIb at the 95% (90%) C.L. and the combined median expected limit is $B(B_0^0 \rightarrow \mu^+\mu^-) < 4.0 \times 10^{-8}(3.2 \times 10^{-8})$. The limits are calculated from Eq. 1 using the semi-Frequentist confidence level approach (CL$_{sb}$) [32–34] with a Poisson log-likelihood ratio test statistic. The limit incorporates Gaussian uncertainties on the signal efficiency and the background. This expected limit is a factor of 2.4 better than the expected limit of $9.7 \times 10^{-8}$ at the 95% C.L. of the previous DØ result [17], where 10% of this improvement results from changes in the analysis technique.

After finalizing the selection criteria and all systematic uncertainties, we study events in the signal region. There are 256 events for Run IIa, and 823 events for Run IIb observed in the signal region where the expected number of background events is $264 \pm 13$ events for Run IIa and $827 \pm 23$ events for Run IIb. The observed distributions of dimuon events in the highest sensitivity region are shown in Fig. 4. The observed number of events is consistent with the background expectations. We extract 95% (90%) C.L. limits of $B(B_0^0 \rightarrow \mu^+\mu^-) < 8.2 \times 10^{-8}(6.5 \times 10^{-8})$ for Run IIa and $6.5 \times 10^{-8}(5.3 \times 10^{-8})$ for Run IIb. The resulting combined limit is $B(B_0^0 \rightarrow \mu^+\mu^-) < 5.1 \times 10^{-8}(4.2 \times 10^{-8})$ at the 95% (90%) C.L. The probability for the expected background distributions to fluctuate to the observed data distributions is 31%.

In conclusion, we have reported a search for the rare decay $B_0^0 \rightarrow \mu^+\mu^-$ using 6.1 fb$^{-1}$ of $pp$ collisions collected.
by the D0 experiment at Fermilab Tevatron Collider. We observe no evidence for physics beyond the SM and set a limit of $B(B^0_d \to \mu^+\mu^-) < 5.1 \times 10^{-8} (4.2 \times 10^{-8})$ at the 95% (90%) C.L. This result is more stringent than the previous results [16, 17] and the best limit to date.

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[2] Charge conjugate states are assumed implicitly throughout this paper.
[29] W.-M. Yao et al., Journal of Physics G 33, 1 (2006). We use this version of the reference for the $B$ hadron fragmentation ratio in order to compare the result with those of the previous analyses.