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B. Abbott et al.
The D0 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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B. Abbott,[30] M. Abolins,[27] B.S. Acharya,[45] I. Adam,[12] D.L. Adams,[39] M. Adams,[17]
S. Ahn,[14] H. Aihara,[23] G.A. Alves,[10] N. Amos,[26] E.W. Anderson,[19] R. Astur,[44]
M.M. Baarmand,[44] A. Baden,[25] V. Balamurali,[34] J. Balderston,[16] B. Baldin,[14]
S. Banerjee,[45] J. Bantly,[5] E. Barberis,[23] J.F. Bartlett,[14] K. Bazizi,[41] A. Belyaev,[28]
S.B. Beri,[36] I. Bertram,[33] V.A. Bezzubov,[37] P.C. Bhat,[14] V. Bhatnagar,[36]
M. Bhattacharjee,[44] N. Biswas,[34] G. Blazey,[32] S. Blessing,[15] P. Bloom,[7] A. Boehnlein,[14]
N.I. Bojko,[37] F. Borcherding,[14] C. Boswell,[9] A. Brandt,[14] R. Brock,[27] A. Bross,[14]
D. Buchholz,[33] V.S. Burtovoi,[37] J.M. Butler,[3] W. Carvalho,[10] D. Casey,[41] Z. Casilum,[44]
H. Castilla-Valdez,[11] D. Chakraborty,[44] S.-M. Chang,[31] S.V. Chekulaev,[37] L.-P. Chen,[23]
W. Chen,[44] S. Choi,[43] S. Chopra,[26] B.C. Choudhary,[9] J.H. Christenson,[14] M. Chung,[17]
D. Claes,[29] A.R. Clark,[23] W.G. Cobau,[25] J. Cochran,[9] L. Coney,[34] W.E. Cooper,[14]
C. Cretsinger,[41] D. Cullen-Vidal,[5] M.A.C. Cummings,[32] D. Cutts,[5] O.I. Dahl,[23] K. Davis,[2]
K. De,[46] K. Del Signore,[26] M. Demarteau,[14] D. Denisov,[14] S.P. Denisov,[37] H.T. Diehl,[14]
M. Diesburg,[14] G. Di Loreto,[27] P. Draper,[46] Y. Ducros,[42] L.V. Dudko,[28] S.R. Dugad,[45]
D. Edmunds,[27] J. Ellison,[9] V.D. Elvira,[44] R. Engelmann,[44] S. Eno,[25] G. Eppley,[39]
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D. Fein,[2] T. Ferbel,[41] G. Finocchiaro,[44] H.E. Fisk,[14] Y. Fisyak,[7] E. Flattum,[14]
G.E. Forden,[2] M. Fortner,[32] K.C. Frame,[27] S. Fuess,[14] E. Gallas,[46] A.N. Galyaev,[37]
P. Gartung,[9] T.L. Geld,[27] R.J. Genik II,[27] K. Genser,[14] C.E. Gerber,[14] B. Gibbard,[4]
S. Glenn,[7] B. Gobbi,[33] A. Goldschmidt,[23] B. Gómez,[1] G. Gómez,[25] P.I. Goncharov,[37]
J.L. González Solís,[11] H. Gordon,[4] L.T. Goss,[47] K. Gounder,[9] A. Goussiou,[44] N. Graf,[4]
P.D. Grannis,[44] D.R. Green,[14] H. Greenlee,[14] G. Grim,[7] S. Grinstein,[6] N. Grossman,[14]
P. Grudberg,[23] S. Grünendahl,[14] G. Guglielmo,[35] J.A. Guida,[2] J.M. Guida,[5] A. Gupta,[45]
S.N. Gurzhiev,[37] P. Gutierrez,[35] Y.E. Gutnikov,[37] N.J. Hadley,[25] H. Haggerty,[14]
S. Hagopian,[15] V. Hagopian,[15] K.S. Hahn,[41] R.E. Hall,[8] P. Hanlet,[31] S. Hansen,[14]
J.M. Hauptman,[19] D. Hedin,[32] A.P. Heinson,[9] U. Heintz,[14] R. Hernández-Montoya,[11]

T. Heuring,[15] R. Hirosky,[17] J.D. Hobbs,[14] B. Hoeneisen,[1,*] J.S. Hoftun,[5] F. Hsieh,[26]
Ting Hu,[44] Tong Hu,[18] T. Huehn,[9] A.S. Ito,[14] E. James,[2] J. Jaques,[34] S.A. Jerger,[27]
R. Jesik,[18] J.Z.-Y. Jiang,[44] T. Joffe-Minor,[33] K. Johns,[2] M. Johnson,[14] A. Jonckheere,[14]
M. Jones,[16] H. Jöstlein,[14] S.Y. Jun,[33] C.K. Jung,[44] S. Kahn,[4] G. Kalbfleisch,[35] J.S. Kang,[20]
D. Karmanov,[28] D. Karmgard,[15] R. Kehoe,[34] M.L. Kelly,[34] C.L. Kim,[20] S.K. Kim,[43]
A. Klatchko,[15] B. Klima,[14] C. Klopfenstein,[7] V.I. Klyukhin,[37] V.I. Kochetkov,[37]
J.M. Kohli,[36] D. Koltick,[38] A.V. Kostritskiy,[37] J. Kotcher,[4] A.V. Kotwal,[12] J. Kourlas,[30]
A.V. Kozelov,[37] E.A. Kozlovski,[37] J. Krane,[29] M.R. Krishnaswamy,[45] S. Krzywdzinski,[14]
S. Kunori,[25] S. Lami,[44] R. Lander,[7] F. Landry,[27] G. Landsberg,[14] B. Lauer,[19] A. Leflat,[28]
H. Li,[44] J. Li,[46] Q.Z. Li-Demarteau,[14] J.G.R. Lima,[40] D. Lincoln,[26] S.L. Linn,[15]
J. Linnemann,[27] R. Lipton,[14] Y.C. Liu,[33] F. Lobkowicz,[41] S.C. Loken,[23] S. Lökös,[44]
L. Lueking,[14] A.L. Lyon,[25] A.K.A. Maciel,[10] R.J. Madaras,[23] R. Madden,[15]
L. Magaña-Mendoza,[11] V. Manankov,[28] S. Mani,[7] H.S. Mao,[14,†] R. Markeloff,[32]
T. Marshall,[18] M.I. Martin,[14] K.M. Mauritz,[19] B. May,[33] A.A. Mayorov,[37] R. McCarthy,[44]
J. McDonald,[15] T. McKibben,[17] J. McKinley,[27] T. McMahon,[35] H.L. Melanson,[14]
M. Merkin,[28] K.W. Merritt,[14] H. Miettinen,[39] A. Mincer,[30] C.S. Mishra,[14] N. Mokhov,[14]
N.K. Mondal,[45] H.E. Montgomery,[14] P. Mooney,[1] H. da Motta,[10] C. Murphy,[17] F. Nang,[2]
M. Narain,[14] V.S. Narasimham,[45] A. Narayanan,[2] H.A. Neal,[26] J.P. Negret,[1] P. Nemethy,[30]
D. Norman,[47] L. Oesch,[26] V. Oguri,[40] E. Oliveira,[10] E. Oltman,[23] N. Oshima,[14] D. Owen,[27]
P. Padley,[39] A. Para,[14] Y.M. Park,[21] R. Partridge,[5] N. Parua,[45] M. Paterno,[41] B. Pawlik,[22]
J. Perkins,[46] M. Peters,[16] R. Piegaia,[6] H. Piekarz,[15] Y. Pischalnikov,[38] V.M. Podstavkov,[37]
B.G. Pope,[27] H.B. Prosper,[15] S. Protopopescu,[4] J. Qian,[26] P.Z. Quintas,[14] R. Raja,[14]
S. Rajagopalan,[4] O. Ramirez,[17] L. Rasmussen,[44] S. Reucroft,[31] M. Rijssenbeek,[44]
T. Rockwell,[27] M. Roco,[14] N.A. Roe,[23] P. Rubinov,[33] R. Ruchti,[34] J. Rutherfoord,[2]
A. Sánchez-Hernández,[11] A. Santoro,[10] L. Sawyer,[24] R.D. Schamberger,[44] H. Schellman,[33]
J. Sculli,[30] E. Shabalina,[28] C. Shaffer,[15] H.C. Shankar,[45] R.K. Shivpuri,[13] M. Shupe,[2]
H. Singh,[9] J.B. Singh,[36] V. Sirotenko,[32] W. Smart,[14] E. Smith,[35] R.P. Smith,[14] R. Snihur,[33]
G.R. Snow,[29] J. Snow,[35] S. Snyder,[4] J. Solomon,[17] P.M. Sood,[36] M. Sosebee,[46]

N. Sotnikova,[28] M. Souza,[10] A.L. Spadafora,[23] G. Steinbrück,[35] R.W. Stephens,[46]
M.L. Stevenson,[23] D. Stewart,[26] F. Stichelbaut,[44] D.A. Stoianova,[37] D. Stoker,[8]
M. Strauss,[35] K. Streets,[30] M. Strovink,[23] A. Sznajder,[10] P. Tamburello,[25] J. Tarazi,[8]
M. Tartaglia,[14] T.L.T. Thomas,[33] J. Thompson,[25] T.G. Trippe,[23] P.M. Tuts,[12]
N. Varelas,[17] E.W. Varnes,[23] D. Vititoe,[2] A.A. Volkov,[37] A.P. Vorobiev,[37] H.D. Wahl,[15]
G. Wang,[15] J. Warchol,[34] G. Watts,[5] M. Wayne,[34] H. Weerts,[27] A. White,[46] J.T. White,[47]
J.A. Wightman,[19] S. Willis,[32] S.J. Wimpenny,[9] J.V.D. Wirjawan,[47] J. Womersley,[14]
E. Won,[41] D.R. Wood,[31] H. Xu,[5] R. Yamada,[14] P. Yamin,[4] J. Yang,[30] T. Yasuda,[31]
P. Yepes,[39] C. Yoshikawa,[16] S. Youssef,[15] J. Yu,[14] Y. Yu,[43] Z.H. Zhu,[41] D. Zieminska,[18]
A. Zieminski,[18] E.G. Zverev,[28] and A. Zylberstejn[42]

(DØ Collaboration)

[1] *Universidad de los Andes, Bogotá, Colombia*

[2] *University of Arizona, Tucson, Arizona 85721*

[3] *Boston University, Boston, Massachusetts 02215*

[4] *Brookhaven National Laboratory, Upton, New York 11973*

[5] *Brown University, Providence, Rhode Island 02912*

[6] *Universidad de Buenos Aires, Buenos Aires, Argentina*

[7] *University of California, Davis, California 95616*

[8] *University of California, Irvine, California 92697*

[9] *University of California, Riverside, California 92521*

[10] *LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

[11] *CINVESTAV, Mexico City, Mexico*

[12] *Columbia University, New York, New York 10027*

[13] *Delhi University, Delhi, India 110007*

[14] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[15] *Florida State University, Tallahassee, Florida 32306*

[16]*University of Hawaii, Honolulu, Hawaii 96822*

[17]*University of Illinois at Chicago, Chicago, Illinois 60607*

[18]*Indiana University, Bloomington, Indiana 47405*

[19]*Iowa State University, Ames, Iowa 50011*

[20]*Korea University, Seoul, Korea*

[21]*Kyungsung University, Pusan, Korea*

[22]*Institute of Nuclear Physics, Kraków, Poland*

[23]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720*

[24]*Louisiana Tech University, Ruston, Louisiana 71272*

[25]*University of Maryland, College Park, Maryland 20742*

[26]*University of Michigan, Ann Arbor, Michigan 48109*

[27]*Michigan State University, East Lansing, Michigan 48824*

[28]*Moscow State University, Moscow, Russia*

[29]*University of Nebraska, Lincoln, Nebraska 68588*

[30]*New York University, New York, New York 10003*

[31]*Northeastern University, Boston, Massachusetts 02115*

[32]*Northern Illinois University, DeKalb, Illinois 60115*

[33]*Northwestern University, Evanston, Illinois 60208*

[34]*University of Notre Dame, Notre Dame, Indiana 46556*

[35]*University of Oklahoma, Norman, Oklahoma 73019*

[36]*University of Panjab, Chandigarh 16-00-14, India*

[37]*Institute for High Energy Physics, 142-284 Protvino, Russia*

[38]*Purdue University, West Lafayette, Indiana 47907*

[39]*Rice University, Houston, Texas 77005*

[40]*Universidade do Estado do Rio de Janeiro, Brazil*

[41]*University of Rochester, Rochester, New York 14627*

[42]*CEA, DAPNIA/Service de Physique des Particules, CE-SACLAY, Gif-sur-Yvette, France*

[43]*Seoul National University, Seoul, Korea*

[44] *State University of New York, Stony Brook, New York 11794*

[45] *Tata Institute of Fundamental Research, Colaba, Mumbai 400005, India*

[46] *University of Texas, Arlington, Texas 76019*

[47] *Texas A&M University, College Station, Texas 77843*

We have searched for the flavor-changing neutral current decay $b \to X_s\mu^+\mu^-$ in $p\bar{p}$ collisions at $\sqrt{s}$ =1.8 TeV with the DØ detector at Fermilab. We determine the 90% confidence level limit for the branching fraction to be $B(b \to X_s\mu^+\mu^-) < 3.2\times10^{-4}$. We argue that this limit is more stringent than the best published limit on this decay rate.

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In the Standard Model of electroweak interactions (SM) the decay processes $b \to X_s\mu^+\mu^-$ (where X_s stands for a hadronic state containing a strange quark) and $B^0 \to \mu^+\mu^-$ are forbidden at tree level and are possible only through loop diagrams. The largest contributions to the branching fraction for these processes come from diagrams involving the top quark and therefore the predicted branching fractions depend on the top quark mass. The "rare" flavor-changing neutral current (FCNC) decays are expected to be more frequent for b quarks than for strange quarks. The $b \to c$ transition is suppressed by $|V_{bc}| = \mathcal{O}(10^{-1})$ while loop corrections are large due to $|V_{tb}| \approx 1$ and the large top quark mass, m_t. At m_t= 170 GeV/c^2, the SM expected branching fraction [1,2] for the semi-inclusive decay $b \to X_s\mu^+\mu^-$ is 6×10^{-6}.

Extensions to the minimal Standard Model which allow new particles contributing to the higher order corrections, such as fourth generation quarks, charged Higgs bosons or supersymmetric particles, provide additional possible sources of FCNC. Precision measurements of rare b decay rates thus extend the new physics discovery potential beyond direct searches. We describe a search for such decays in the data collected with the DØ detector [3] during the 1994–1995 Fermilab Tevatron run. The data correspond to a total integrated luminosity of $\mathcal{L} = 50.0 \pm 2.7$ pb^{-1}.

Dimuon events are selected by requiring two muons in the central muon system, at both hardware and software trigger levels [4]. We select events containing an oppositely charged muon pair with the invariant mass $M_{\mu\mu} < 7$ GeV/c^2, transverse momentum $p_T^{\mu\mu} > 5$ GeV/c, and pseudorapidity $|\eta_{\mu\mu}| < 0.6$. The muons are required to have a transverse momentum p_T^{μ} > 3.5 GeV/c and pseudorapidity $|\eta_{\mu}| < 1.0$.

Both muon trajectories are required to be consistent with the reconstructed vertex position and to have a matching track in the central detector. There must be appropriate energy deposition along the muons' path in the calorimeter. The total number of events satisfying the above criteria is 1564.

The dimuon mass spectrum of these events is shown in Fig. 1. In addition to the J/ψ resonance, the major known sources [5] of dimuons for $M_{\mu\mu} < 7$ GeV/c^2 are: (1) $b\bar{b}$ and $c\bar{c}$ events with both heavy quarks decaying semileptonically or with a sequential semileptonic decay $b \to c + \mu$, $c \to s + \mu$; (2) the case where one muon comes from a b or c decay and the other from the decay of a π or K meson, and (3) virtual photon decays (the Drell-Yan process).

The curve in Fig. 1(a) shows the results of a maximum likelihood fit of a sum of the J/ψ signal and processes (1)–(3) to the dimuon mass spectrum in the range $1 < M_{\mu\mu} <$ 7 GeV/c^2. By J/ψ signal we mean the J/ψ plus an admixture of ψ'. We use the ratio $N(\psi')/N(J/\psi)$ = (6$\pm$2)%, based on the recent results from the CDF collaboration [6,7], corrected for the mass dependence of the kinematic acceptance for dimuons at DØ. The ψ' mass is assumed to be higher than the J/ψ mass by 0.59 GeV/c^2 [8], and its width is assumed to be 20% larger than the J/ψ width. The normalized $M_{\mu\mu}$ distributions for processes (1)–(3) were obtained by fitting the corresponding Monte Carlo (MC) simulated spectra. We use a dimuon mass resolution function parametrized by a superposition of two Gaussians, with the shape determined by fitting MC simulated events of the decay $J/\psi \to \mu^+\mu^-$ and the mass scale allowed to vary. For a five parameter fit to 60 bins in Fig. 1(a), we obtain $\chi^2(55)$=56. The overall quality of the fit gives us confidence in the simulation of the dimuon mass resolution and the contributing physics processes.

The search for the decay $b \to X_s\mu^+\mu^-$ is performed in the mass window $3.9 < M_{\mu\mu} < 4.9$ GeV/c^2. This mass range is above most of the known sources of dimuons and hence constitutes the region of maximum sensitivity to the $b \to X_s\mu^+\mu^-$ decay. Although we do not identify the strange particle among the hadrons originating from the b decay, we assume that the decay $b \to X_s\mu^+\mu^-$ dominates over the corresponding CKM-suppressed decay $b \to X_d\mu^+\mu^-$.

We observe 56 events in our search window, where 68±2(stat.)±4(syst.) are expected from the fit. We thus find no evidence for an excess of events to be attributed to the decay $b \to X_s\mu^+\mu^-$. To estimate the systematic error, we have performed alternative fits, changing within their uncertainties the width and skewness of the dimuon mass resolution function and mass scale, as well as the mix of backgrounds. MC studies of 10,000 simulated experiments, with the background composition as obtained in the fit to the data, indicate that the probability of obtaining 56 events in a given experiment where 68±5 events are expected is 12%. The contribution to the χ^2 from the 10 bins within the search window is 7.3.

We follow two independent ways of relating the observed number of events in the search window to the expected b quark yield. First, we use the absolute normalization to the inclusive b quark production cross section. The result depends on the assumed b cross section, on the b production model and on the estimates for the trigger and offline reconstruction efficiencies. A similar method has been employed previously by the UA1 Collaboration [9]. In the alternative approach, we normalize to the observed J/ψ signal, where the uncertainties in the variables used in the denominator of Equation (1) largely cancel. The result of the latter method depends on the knowledge of the fraction of J/ψ events that originate from b decays, and on the branching fraction for the decay sequence $b \to X_sJ/\psi$, $J/\psi \to \mu\mu$.

In the first approach, the branching fraction for the decay $b \to X_s\mu^+\mu^-$ is given by

$$B(b \to X_s\mu^+\mu^-) = \frac{N}{2 \cdot \sigma(b) \cdot \mathcal{L} \cdot \epsilon} , \qquad (1)$$

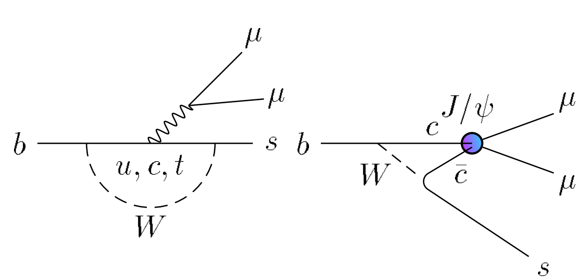
where N is the number of events due to this decay, $\sigma(b)$ denotes the inclusive b quark production cross section for $p_T(b) > 6$ GeV/c and rapidity $|y(b)| < 1$, and ϵ is the combined kinematic acceptance and trigger and offline reconstruction efficiency.

The inclusive b quark production cross section for $p_T(b) > 6$ GeV/c and $|y(b)| < 1$ is $\sigma(b) = 7.2 \pm 1.8$ μb. This estimate results from a fit to a compilation of DØ measurements [10] of the integrated, inclusive b production cross section at $p_T(b) > p_T^{\min}$.

The calculation of ϵ proceeds by multiplying the theoretical mass spectrum [2], normalized to unity, by the mass-dependent detection efficiency, convoluting the detector resolution, and integrating the resulting distribution over the search window. The simulated mass spectrum including the detector response is compared to the input distribution from Ref. [2] in Fig. 2.

The mass-dependent dimuon detection efficiency is determined from events with b quarks generated with the ISAJET program [11] in the lowest order QCD approximation. Quarks that satisfy the above kinematic requirements are fragmented according to the Peterson fragmentation model [12]. We adjust the value of the fragmentation parameter ϵ_b to obtain the dimuon transverse momentum spectrum that matches the p_T spectrum of J/ψ coming from b quark decay, measured by the CDF Collaboration [6].

To expedite the simulation procedure, preselection cuts (called $\mathcal{K}$) of $p_T^{\mu} > 3$ GeV/c and $|\eta_\mu| < 1.0$ are applied to both muons. The acceptance $A(M_{\mu\mu})$ for this preselection increases with $M_{\mu\mu}$. It is determined by studying MC samples of the decay $b \to X_s\mu^+\mu^-$ generated at various values of $M_{\mu\mu}$. At the parton level, the decay $b \to X_s\mu^+\mu^-$ has the same final state as the b decay to J/ψ, as illustrated in the diagrams below:



Therefore, we use "$J/\psi + X_s$", simulated according to Ref. [11], as a model for the final state of the decay $b \to X_s\mu^+\mu^-$ by substituting various discrete values for the J/ψ mass. At $M_{\mu\mu}$ = 4.1 GeV/c^2 we remove multibody channels, keeping the channels $J/\psi K$ and $J/\psi K^*$ with the relative rate 1:2. We find the resulting acceptance insensitive to the number of channels included and their relative rates. We also calculate the acceptance for the exclusive B meson decay to a muon pair. The results are fitted with the form $A(M_{\mu\mu}) = 2.9\times10^{-3}\times {M_{\mu\mu}}^{2.64}$. The uncertainty on $A(4.1)$, taken from the difference between its values at ϵ_b=0.02 and at ϵ_b=0.006, is 20%. The uncertainty of the ratio of $A(4.1)$ to $A(3.1)$ is 5%.

Events that satisfy the muon pseudorapidity and momentum cuts ($\mathcal{K}$) are passed through a detector simulation, trigger simulation, and offline reconstruction programs. We find the effect of the trigger and reconstruction efficiency for those events to be independent of $M_{\mu\mu}$. The trigger efficiency, corrected for effects not included in the simulation, is 0.052 ± 0.005. The efficiency of the offline selection cuts, 0.19 ± 0.03, has been obtained by comparing the total number of J/ψ events passing the dimuon trigger, 3310 ± 500, to the number of triggered J/ψ events that satisfy our offline selection cuts, 633 ± 45. The product of the trigger and offline selection efficiencies is $\epsilon_{\rm det}$ =(1.0 ± 0.2)$\times10^{-2}$.

The integral of the spectrum in Fig. 2(b) over the search window is $\epsilon = (7.0 \pm 2.0)\times10^{-5}$. The acceptance of the kinematic selection alone, including the selection ($\mathcal{K}$) and the mass cut, is (7.0 ± 1.4)$\times10^{-3}$.

The J/ψ signal allows an alternative normalization, to the J/ψ yield due to the b quark decay, $N_{b\to J/\psi}$. The ratio of the kinematic acceptance $A(M_{\mu\mu})$ integrated over the search window to $A(3.1)$ is $\alpha = 0.123 \pm 0.006$. From the total number of J/ψ events in our dimuon sample, 633 ± 45, and the fraction of J/ψ events originating from b decay, f_b = 0.31 ± 0.03 [6,13], the number of J/ψ events coming from b decays is $N_{b\to J/\psi}$=196 ± 23. With the branching fraction for the decay sequence $b \to X_s J/\psi, J/\psi \to \mu\mu$, $B(b \to J/\psi \to \mu\mu)$ = (7.0±0.6) $\times$ 10^{-4} [8], we have:

$$B(b \to X_s\mu^+\mu^-) = \frac{N}{N_{b\to J/\psi}/B(b \to J/\psi \to \mu\mu)\cdot\alpha}. \quad (2)$$

The respective results for the denominators in Eqs. (1) and (2), (5.0 ± 1.9)$\times10^4$ and

$(3.4\pm 0.5)\times 10^4$, are consistent. Using the latter by virtue of its smaller systematic error, we obtain a 90% confidence level limit of $B(b \to X_s\mu^+\mu^-) < 3.2 \times 10^{-4}$. To derive the limit, we apply a Bayesian approach in which the observed number of events is compared to the number of background events in the region of interest. We assume Poisson statistics for the signal and background and account for uncertainty in the background and in the estimates of the total cross section and of the dimuon detection efficiency. We have found the results to be stable with respect to the choice of the search window by varying the lower and upper limits of the window within $\pm$ 50 MeV/c^2 and $\pm$ 200 MeV/c^2, repsectively.

The best published limit for this decay (5×10^{-5}) was set by the UA1 Collaboration [9]. We have attempted to reproduce the UA1 limit and to make the cross-check between their quoted efficiency and their J/ψ signal [14]. We have failed to reconcile the two. Instead of the quoted efficiency of 0.011 we obtain [15] $\epsilon_{\rm UA1} \approx 5.8\times 10^{-4}$ – lower by a factor $\approx$ 20. Differences between the theoretical dimuon mass distributions for the decay $b \to X_s\mu^+\mu^-$, or in the versions of the ISAJET program that were used here and in Ref. [9], cannot account for such a large disparity in the results. Using our estimates of their efficiency we obtain $\approx 1\times 10^{-3}$ as the upper limit on $B(b \to X_s\mu^+\mu^-)$ from their experiment.

For the exclusive decay $B^0 \to \mu^+\mu^-$ (an unseparated mixture of B_d and B_s decays) we define the search window as $4.8 < M_{\mu\mu} < 5.8$ GeV/c^2, resulting in the maximum sensitivity to the signal. The acceptance for this mass window is 0.60 ± 0.03. In this process, the two muons are expected to carry a large fraction of the energy in a cone around the direction of the parent b quark. To reduce background, we select events whose energy deposition in the calorimeter in a cone around each muon of radius $\Delta\mathcal{R}= 0.4$ in the pseudorapidity – azimuthal angle space is less than 8 GeV. The acceptance of the isolation requirement is 0.80 ± 0.03.

The mass spectrum for isolated dimuons is shown in Fig. 3(a). We find 15 events in the search region. From a fit to the sum of the J/ψ signal and processes (1)–(3), the background in the search window is estimated to be 15 ± 2 events.

The B^0 production cross section at $p_T(B) > 6$ GeV and $|y(B)| < 1$, measured by the

CDF collaboration [16], is 2.39 ± 0.54 μb. The product of the acceptance for kinematic and geometric restrictions on the two muons coming from the decay of a B^0 meson, the trigger and offline reconstruction efficiency, and the mass and isolation cuts is $\epsilon = (1.4 \pm 0.35)\times10^{-3}$. We obtain a 90% confidence level limit of $B(B^0 \rightarrow \mu^+\mu^-) < 4.0 \times 10^{-5}$. The best published limit for this decay is 1.6×10^{-6}, set by the CDF Collaboration in Ref. [16]. The SM prediction is 1.5×10^{-10}. We estimate [17] that the limit published by the UA1 collaboration in Ref. [9] should be shifted upward by about a factor of four.

In conclusion, we have conducted a search for the FCNC decays $b \rightarrow X_s\mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$. We find no evidence for either decay. For the semi-inclusive decay $b \rightarrow X_s\mu^+\mu^-$ we set a 90% confidence level limit of $B(b \rightarrow X_s\mu^+\mu^-) < 3.2 \times 10^{-4}$. In view of our observations we conclude [18] that this limit is more stringent than the best published limit on this decay rate. The SM prediction is 6×10^{-6}.

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* Visitor from Universidad San Francisco de Quito, Quito, Ecuador.

† Visitor from IHEP, Beijing, China.

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[7] CDF has measured the ratio of cross section times branching fraction for J/ψ and ψ' as a function of p_T. Taking the CDF measurement at our mean dimuon p_T and accounting for the $M_{\mu\mu}$ dependence of the dimuon detection efficiency at DØ, we obtain the expected ratio of the number of events of ψ' and J/ψ in our sample to be $\approx 0.06\pm0.02$.

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[13] The value of f_b used in this analysis is an interpolation of CDF measurements at $p_T^{\mu\mu}$ = 12 GeV/c.

[14] With $\sigma(b) = 2.5\ \mu$b and $\mathcal{L} = 5.3$ pb^{-1}, the number of J/ψ events from b decays in the dimuon channel at $\sqrt{s} = 630$ GeV is ≈19,000. UA1 observes ≈250 J/ψ events, ≈78 of them originating from b decays. Thus, the apparent efficiency is ≈0.0041. This is inconsistent with the value 0.073 (=14713/200000) quoted by UA1 for the efficiency averaged over a spectrum that peaks below 3 GeV/c^2.

[15] We use the leading order QCD ISAJET simulation at $\sqrt{s} = 630$ GeV, with $\epsilon_b = 0.02$, that

reproduces the shape of the p_T spectrum of J/ψ mesons observed by UA1 in C. Albajar *et al.*, Phys. Lett. B **256**, 112 (1991). For the kinematic cuts of Ref.[9], $p_T^{\mu} > 3$ GeV/c and $p_T^{\mu\mu} > 7$ GeV/c, we obtain the acceptance $A(3.1) = 0.041$. With the apparent overall efficiency at the J/ψ mass of 0.0041, the detection efficiency for accepted events is thus ≈0.1. For the dimuon mass spectrum used by UA1, we obtain a kinematic acceptance in the search window $3.9 < M_{\mu\mu} < 4.4$ GeV/c^2 of 5.8×10^{-3}. This is already two times lower than the overall efficiency quoted by UA1. Its product with the detection efficiency is $\epsilon_{\rm UA1} \approx 5.8\times10^{-4}$, which is ≈ 20 times less than the quoted UA1 efficiency.

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[17] From our ISAJET simulation we obtain the UA1 kinematic acceptance for the fragmentation process $b \to B^o$, followed by the decay $B^0 \to \mu^+\mu^-$, to be 0.14. With their mass independent detection efficiency of ≈0.1, the overall effect of the kinematic acceptance and detection efficiency for this decay then is 0.014. UA1 quotes an efficiency of 11465/200000 = 0.057.

[18] While this work was nearing completion, the CLEO Collaboration submitted for publication a 90% confidence level limit of $B(b \to X_s\mu^+\mu^-) < 5.8 \times 10^{-5}$, S. Glenn *et al.*, "Search for Inclusive $b \to sl^+l^-$", CLNS 97/1514, hep-ex/9710003, submitted to Phys. Rev. Lett.

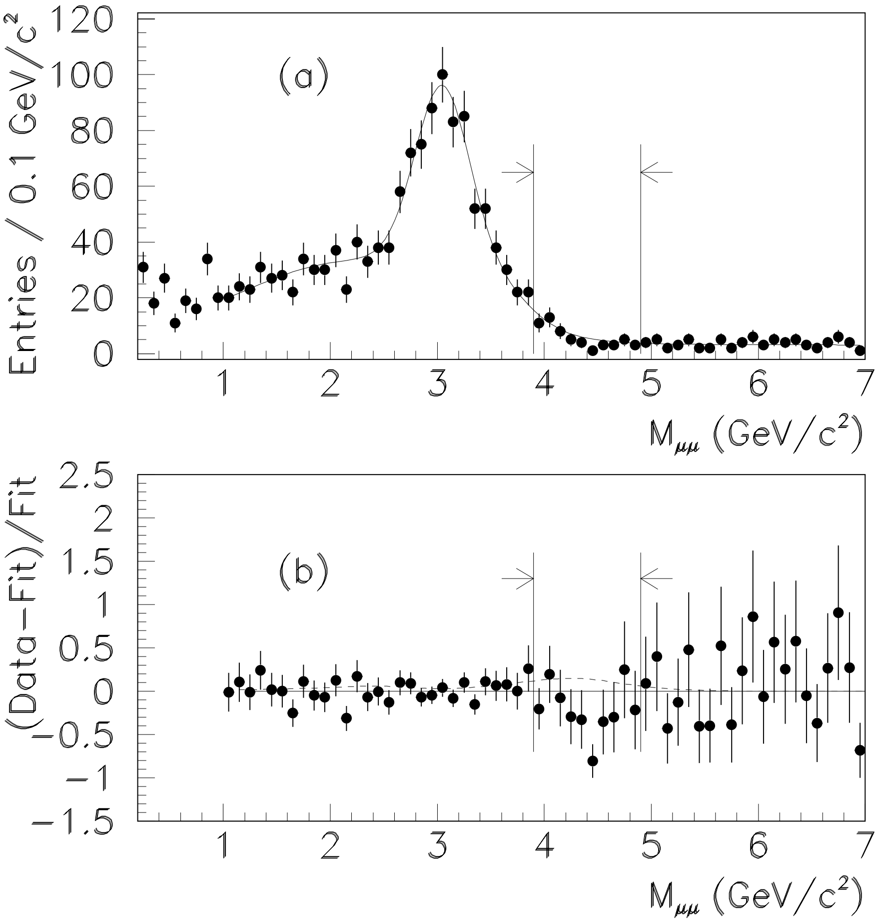

FIG. 1. (a) Dimuon invariant mass spectrum. The solid line is the maximum likelihood fit of the known physics processes to the data (see text); (b) the data points after subtraction of the fitted values, divided by the fitted values. Only statistical uncertainties on the data points are shown. The dashed line corresponds to the 90% confidence level upper limit for the decay $b \to X_s\mu^+\mu^-$ obtained from the fit. The arrows indicate the search window for the decay $b \to X_s\mu^+\mu^-$.

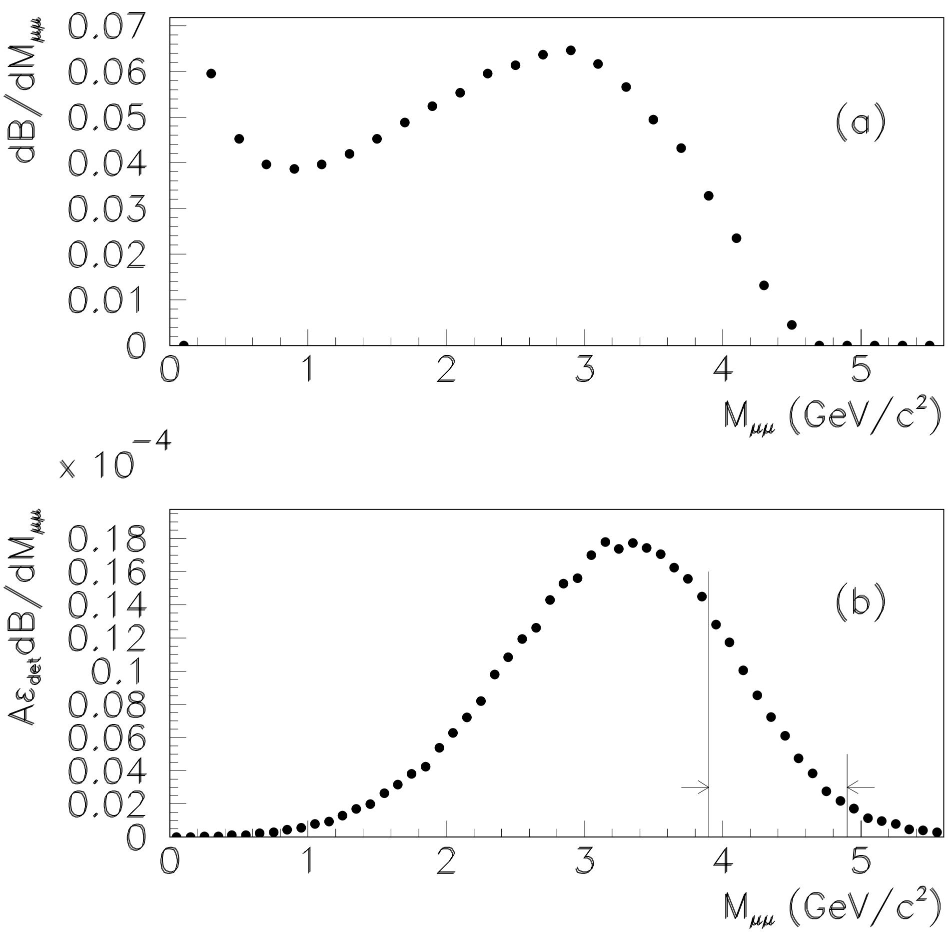

FIG. 2. (a) The calculated differential branching fraction for the decay $b \to X_s \mu^+ \mu^-$, from Ref. [2] as a function of $M_{\mu\mu}$ (multiplied by 0.2 GeV/c^2); (b) the same differential branching fraction modified by the response of the DØ detector (multiplied by 0.1 GeV/c^2). The arrows indicate the search window used in this analysis.

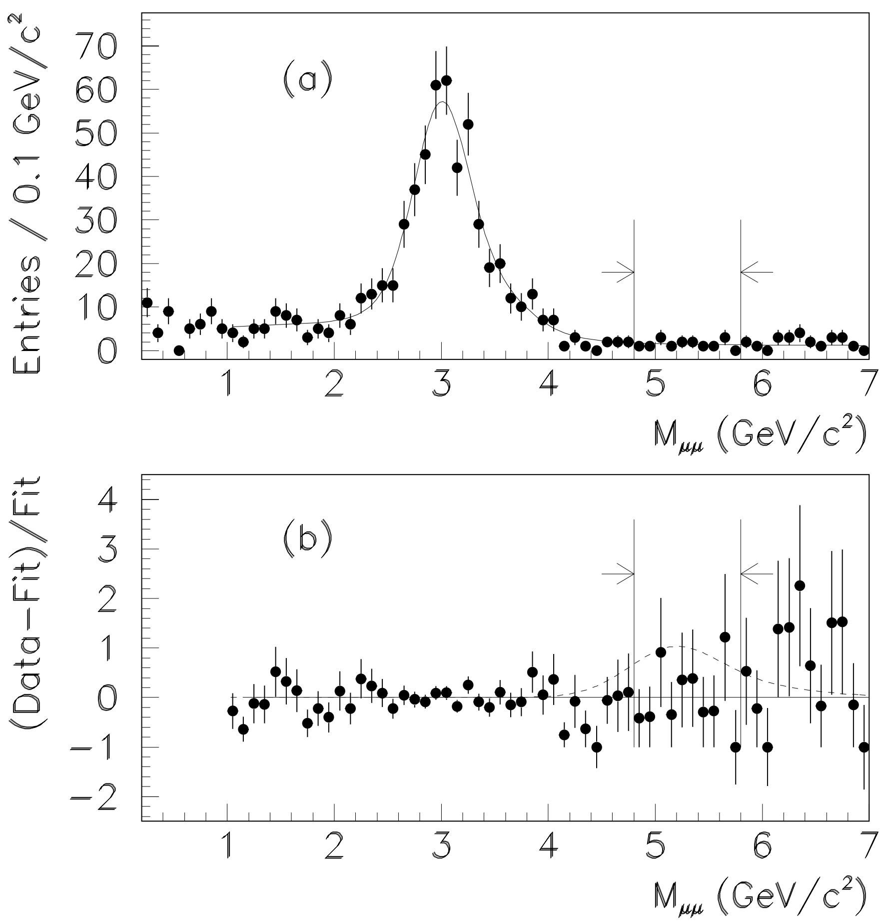

FIG. 3. (a) The invariant mass distribution for isolated dimuons. The solid line is the maximum likelihood fit of the known physics processes to the data (see text); (b) the data points after fit subtraction divided by the fitted values. The dashed line corresponds to the 90% confidence level upper limit for the decay $B^0 \to \mu^+\mu^-$ obtained from the fit. The arrows indicate the search window for the decay $B^0 \to \mu^+\mu^-$.