Title
Search for b0(s) --> mu+ mu- and b0(d) --> mu+ mu- decays in p anti-p collisions at s**(1/2) = 1.96 tev

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

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Abstract

We report on a search for $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$ decays in $p\overline{p}$ 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 experimentally observed and the best previously published branching ratio limit is $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 2.0 \times 10^{-6}$ at 90% confidence level (CL) [7], while the SM prediction is $(3.5 \pm 0.9) \times 10^{-9}$ [8]. Similarly, the best previously published limit on the related branching ratio, $\mathcal{B}(B_d^0 \to \mu^+\mu^-) < 1.6 \times 10^{-7}$ [9], is about three orders of magnitude larger than its SM expectation. The $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ can be enhanced by one to three orders of magnitude in various supersymmetric (SUSY) extensions of the SM. For example, minimal supergravity models at large $\tan\beta$ [3-5] predict $\mathcal{B}(B_s^0 \to \mu^+\mu^-) \leq \mathcal{O}(10^{-7})$ in regions of parameter space which account for possible deviations of the muon anomalous magnetic moment from its SM expectation [10] and are consistent with the observed relic density of cold dark matter [11]. Similarly, $SO(10)$ models [6], theoretically attractive because they can 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 data recorded by the upgraded Collider Detector at Fermilab (CDF II) at the Tevatron $p\overline{p}$ collider. The CDF II detector consists of a magnetic spectrometer surrounded by calorimeters and muon chambers and is described in detail in Ref. [12]. The components relevant to this analysis are briefly described here. A large-radius cylindrical drift chamber (COT) provides 96 measurement layers, organized into alternating axial and $\pm 2°$ stereo superlayers [13]. A five-layer silicon microstrip detector (SVX II) provides precise tracking information near the beamline [14]. These are immersed in a 1.4 T magnetic field and provide a precise measurement of charged particle momenta in the plane transverse to the beamline, p_T. Four layers of planar drift chambers (CMU) outside the calorimeters detect muons with $p_T > 1.4$ GeV/c which penetrate the five absorption lengths of calorimeter steel [15]. An additional four layers of planar drift chambers (CMP) instrument 0.6 m of steel outside the magnet return yoke and detect muons with $p_T > 2$ GeV/c [16]. The CMU and CMP chambers each provide coverage in the pseudo-rapidity range $|\eta| < 0.6$, where $\eta = -\ln(\tan\frac{\theta}{2})$ and θ is the angle of the particle with respect to the beamline. The dataset reported here corresponds to an integrated luminosity of $\mathcal{L} = 171 \pm 10$ pb^{-1} [17].

The data used in this analysis are selected by the dimuon triggers described here. 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 by a hardware processor using COT axial information [18]. The matched tracks must have $p_T > 1.5$ GeV/c. A complete event reconstruction performed online then confirms the p_T and track-stub matching requirements. If the overlapping CMP chambers contain a confirming muon stub, the matched COT 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. 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. To avoid regions of rapidly changing trigger efficiency, we omit muons which have $p_T < 2$ GeV/c. To reduce backgrounds with at least one fake muon, 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 3-D vertex satisfying vertex quality requirements. The two-dimensional decay length, $|\vec{L}_T|$, is calculated as the transverse distance from the beamline 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 $\lambda = c\, M_{\mu^+\mu^-}|\vec{L}_T|/|\vec{p}_T^{\,\mu^+\mu^-}|$. 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 in which at least one of the legs is a fake muon and events from generic B-hadron decays (e.g. sequential semi-leptonic decays $b \to c\mu^- X \to \mu^+\mu^- X$ or double semi-leptonic decay in gluon splitting events $g \to b\bar{b} \to \mu^+\mu^- X$). Using the best previously published limit as an estimate for the branching ratio, we expect at most about 28 (9) $B^0_{s(d)} \to \mu^+\mu^-$ decays to survive these cuts.

We model the signal $B^0_{s(d)} \to \mu^+\mu^-$ decays using the Pythia Monte Carlo (MC) [19] tuned to reproduce the underlying event contributions and the inclusive B-hadron p_T spectrum as determined from the data [20]. The Pythia generated events are passed through a full detec-

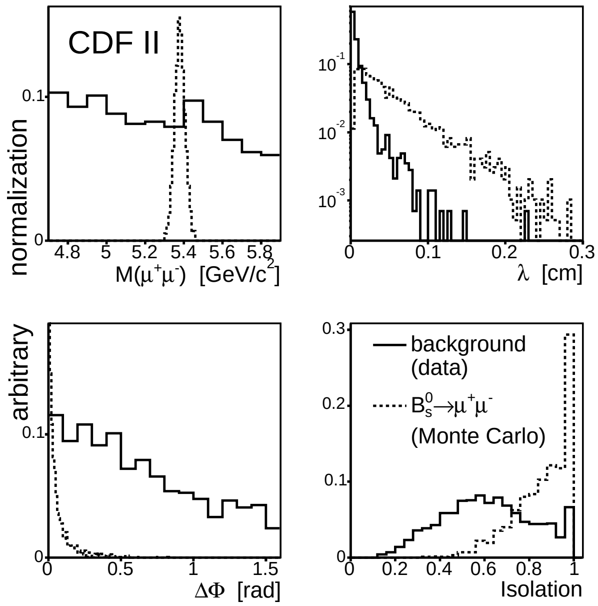

FIG. 1: Distributions of the discriminating variables for events in our background-dominated data sample (solid histograms) compared to Monte Carlo $B_s^0 \to \mu^+\mu^-$ events (dashed histograms). Only events which survive the trigger and offline reconstruction requirements and have $\lambda > 0$ are included. The histograms are arbitrarily normalized.

tor simulation and satisfy the same requirements as data. To normalize to experimentally determined cross-sections, we require the $B^0_{s(d)}$ to have $p_T(B^0_{s(d)}) > 6$ GeV/c and rapidity $|y| < 1$.

To further discriminate $B^0_{s(d)} \to \mu^+\mu^-$ decays from background events we use the following 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 simulated signal events.

To avoid biasing our result, a “blind” analysis technique is employed to determine the optimal selection criteria for these four variables. The data in the search mass window $5.169 < M_{\mu^+\mu^-} < 5.469$ GeV/c^2 are hidden and the optimization performed using only data in the mass 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 mass windows approximately ± 4 times the two-track invariant mass resolution centered on the B_s^0 and B_d^0 masses [22]. We consider a wide range of requirements and use the set of ($M_{\mu^+\mu^-}$, λ, $\Delta\Phi$, I) criteria which minimize the *a priori* expected 90% CL 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:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \leq \frac{N(n, n_{\rm bg})}{2\,\sigma_{B_s^0}\,\mathcal{L}\,\alpha\,\epsilon_{\rm total}}, \tag{1}$$

where $N(n, n_{\rm bg})$ is the number of candidate $B_s^0 \to \mu^+\mu^-$ decays at 90% CL, 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 at the Tevatron, $\sigma_{B_s^0}$, is estimated as $\sigma_{B_s^0} = \frac{f_s}{f_u}\sigma_{B^+}$, where $\frac{f_s}{f_u} = \frac{0.100}{0.391}$ [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 two 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 as described below.

For both signal and background, the variables λ and $\Delta\Phi$ are the only significantly correlated variables and have a linear correlation coefficient of -0.3. This allows us to 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 expected to survive a given I requirement, and f_M is the ratio of the number of events in the search mass 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 can 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 described above for a variety of possible thresholds. We investigate possible sources of systematic bias by calculating f_I in bins of $M_{\mu^+\mu^-}$ and λ and conservatively assign a relative systematic uncertainty of $\pm 5\%$. 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.

Monte Carlo studies demonstrate that our estimate of $n_{\rm bg}$ accurately accounts for generic $b\bar{b}$ contributions to the background, 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 two orders of magnitude below our expected sensitivity.

To build confidence in the background estimate, we check our prediction against observation using these background-dominated control samples: $\mu^\pm\mu^\pm$ events and $\mu^+\mu^-$ events with $\lambda < 0$. In each sample we compare the background predictions to the number of events observed in the search mass window for a wide range of (λ, $\Delta\Phi$, 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 5. An additional 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 three. In this sample, using the optimized requirements, we predict 6 ± 1 and observe 7 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 $B^0_{s(d)} \to \mu^+\mu^-$ MC events which fall within the geometric acceptance and satisfy the kinematic requirements of at least one of the triggers employed for this analysis. 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 beamline offsets and of the detector material description used in the simulation.

The trigger efficiency 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 parameterize the trigger efficiency as a function of p_T and η for the unbiased muon. The efficiency for $B^0_{s(d)} \to \mu^+\mu^-$ decays is determined by the convolution of this parameterization with the $(p_T^{\mu^+}, \eta^{\mu^+}, p_T^{\mu^-}, \eta^{\mu^-})$ spectra of signal MC events satisfying the acceptance requirements. Including the online reconstruction and selection requirements, the total 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 $B^0_{s(d)} \to \mu^+\mu^-$ decays. It also includes contributions from variations in the functional form used in the parameterization, 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 for charged particles within the geometric acceptance, 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 $\epsilon_{\rm COT}$ as follows. 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 $J/\psi \to \mu^+\mu^-$ samples, we estimate the muon reconstruction efficiency, including the track-stub matching requirements, to be 96%. A sample of $J/\psi \to \mu^+\mu^-$ 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 $J/\psi \to \mu^+\mu^-$ and $B^0_{s(d)} \to \mu^+\mu^-$ decays. It also includes contributions from the variation of the COT simulation parameters and sample statistics.

The efficiency $\epsilon_{\rm final}$ is determined from the $B^0_{s(d)} \to \mu^+\mu^-$ MC sample and varies from $28-78\%$ over the range of ($M_{\mu^+\mu^-}$, 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 $B^+ \to J/\psi K^+ (J/\psi \to \mu^+\mu^-)$ events. The $B^+ \to J/\psi K^+$ MC sample is produced in the same manner as the $B^0_s \to \mu^+\mu^-$ sample. The $B^+ \to J/\psi K^+$ data sample is collected using dimuon triggers very similar to the triggers used in the analysis, but with a larger acceptance for $B^+ \to J/\psi K^+$ decays. We make the same requirements on the dimuon tracks and vertex as employed in the analysis. The MC efficiency reproduces the sideband-subtracted data efficiency for a range of cut thresholds and is consistent within 5% (relative), which is assigned as a systematic uncertainty on $\epsilon_{\rm final}$. In both the data and the MC 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 also well described by the MC.

Using the procedure described above, the optimal set of selection criteria is determined to be a ± 80 MeV/c^2 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_d^0 and B_s^0 masses are readily resolved. We define a separate search window centered on the world average B_d^0 mass. We use the same set of selection criteria for the $B_d^0 \to \mu^+\mu^-$ search. The total acceptance times efficiency is $\alpha\,\epsilon_{\rm total} = (2.0 \pm 0.2)\%$ for both the $B_s^0 \to \mu^+\mu^-$ and $B_d^0 \to \mu^+\mu^-$ decays.

Using the optimized set of selection 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_s^0 and B_d^0 search windows as shown in Figure 2. This is consistent with the 1.1 ± 0.3 background events expected in each of the B_s^0 and B_d^0 mass windows. Using Equation 1 we derive 90% (95%) CL limits of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 5.8 \times 10^{-7}$ (7.5×10^{-7}) and $\mathcal{B}(B_d^0 \to \mu^+\mu^-) < 1.5 \times 10^{-7}$ (1.9×10^{-7}). The new $B_s^0 \to \mu^+\mu^-$ limit improves the previously best published limit [7] by a factor of three and significantly reduces the allowed parameter space of R-parity violating and $SO(10)$ SUSY models [4, 6]. The $B_d^0 \to \mu^+\mu^-$ limit is slightly better than the recently published limit of the Belle Collaboration [9].

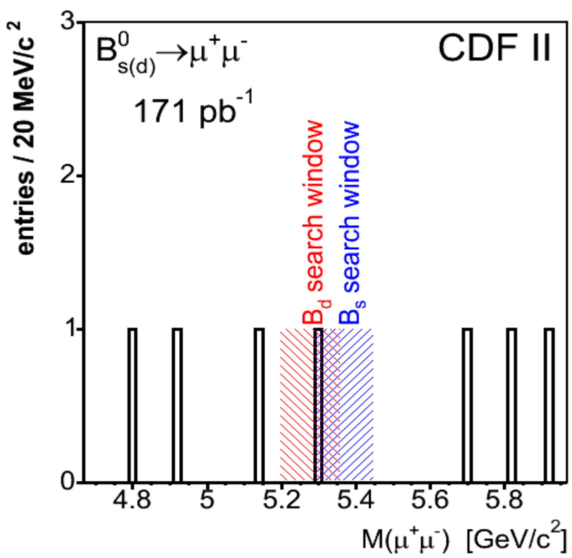

FIG. 2: The $\mu^+\mu^-$ invariant mass distribution of the events in the sideband and search regions satisfying all requirements. The one event in the search region falls into both the B_s^0 and the B_d^0 search windows.

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[1] Throughout this paper inclusion of charge conjugate modes is implicit.

[2] K.S. Babu and C. Kolda, Phys. Rev. Lett. **84**, 228 (2000); P.H. Chankowski and L. Slawianowska, Phys. Rev. D **63**, 054012 (2001); C. Bobeth *et al.*, Phys. Rev. D **64**, 074014 (2001); A.J. Buras *et al.*, Phys. Lett. **B546**, 96 (2002); S. Baek, P. Ko, and W.Y. Song, Phys. Rev. Lett. **89**, 271801 (2002); G.L. Kane, C. Kolda, and J.E. Lennon, \protect\vrule width0pt\protect\href{http://arXiv.org/abs/hep-ph/0310042}{hep-ph/0310042}.

[3] A. Dedes, H.K. Dreiner, and U. Nierste, Phys. Rev. Lett. **87**, 251804 (2001).

[4] R. Arnowitt *et al.*, Phys. Lett. **B538**, 121 (2002).

[5] H. Baer *et al.*, JHEP **07**, 050 (2002).

[6] R. Dermisek *et al.*, JHEP **04**, 037 (2003); D. Auto *et al.*, JHEP **06**, 023 (2003).

[7] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **57**, 3811(R) (1998).

[8] G. Buchalla and A.J. Buras, Nucl. Phys. **B398**, 285 (1993); *ibid.* Nucl. Phys. **B400**, 225 (1993); M. Misiak and J. Urban, Phys. Lett. **B451**, 161 (1999); G. Buchalla and A.J. Buras, Nucl. Phys. **B398**, 285 (1993); *ibid.* Nucl. Phys. **B548**, 309 (1999).

[9] Belle Collaboration, M.C. Chang *et al.*, Phys. Rev. D **68**, 111101(R) (2003).

[10] Muon g-2 Collaboration, G.W. Bennett *et al.*, \protect\vrule width0pt\protect\href{http://arXiv.org submitted to Phys. Rev. Letters.

[11] D.N. Spergel *et al.*, Astrophys. J. Suppl. **148**, 175 (2003).

[12] CDF II Collaboration, R. Blair *et al.*, FERMILAB-PUB-96/390-E.

[13] T. Affolder *et al.*, FERMILAB-PUB-03/355-E, submitted to Nucl. Instrum. Meth. A.

[14] A. Sill *et al.*, Nucl. Instrum. Meth. A **447**, 1 (2000).

[15] G. Ascoli *et al.*, Nucl. Instrum. Meth. A **268**, 33 (1988).

[16] T. Dorigo *et al.*, Nucl. Instrum. Meth. A **461**, 560 (2001).

[17] D. Acosta *et al.*, Nucl. Instrum. Meth. A **494**, 57 (2002); S. Klimenko, J. Konigsberg, and T.M. Liss, FERMILAB-FN-0741.

[18] E.J. Thomson *et al.*, IEEE Trans. Nucl. Sci. **49**, 1063 (2002).

[19] T. Sjöstrand *et al.*, Comp. Phys. Commun. **135**, 238 (2001).

[20] K. Lannon, Ph.D. thesis, University of Illinois at Urbana-Champaign, 2003, `http://www-lib.fnal.gov/archive/thesis/fermilab-thesis-2003-21.shtml`.

[21] The B-candidate isolation is defined as $I = |\vec{p}_T^{\,\mu^+\mu^-}|/(\sum_i p_T^i + |\vec{p}_T^{\,\mu^+\mu^-}|)$, where the sum is over all tracks within an η-ϕ cone radius of 1, centered on the dimuon momentum vector and satisfying standard track quality requirements; ϕ is azimuthal angle defined in the plane transverse to the beamline and η is the pseudo-rapidity as defined in the text.

[22] The mass windows are centered on $5.369\,\mathrm{GeV}/c^2$ and $5.279\,\mathrm{GeV}/c^2$ for the B_s^0 and B_d^0 searches, respectively.

[23] K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).

[24] f_x is the probability that a b quark fragments to produce a B_x hadron. We use the most recent preliminary estimates from the Particle Data Group, `http://pdg.lbl.gov/`.

[25] CDF Collaboration, D. Acosta *et al.*, Phys. Rev. D **65**, 052005 (2002). Note that this corresponds to a measurement at $\sqrt{s} = 1.8$ TeV. No correction is made to account for the increased $\sqrt{s}$ since it is small compared to the uncertainties on the measured σ_{B^+}.