Implications of a large B_{s}→μ^{+}μ^{-} branching fraction for the minimal supersymmetric standard model

Dan Hooper and Chris Kelso

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Implications of the $B_s \to \mu^+\mu^-$ Branching Fraction for the Minimal Supersymmetric Standard Model

Dan Hooper[1,2] and Chris Kelso[1,3]

[1]Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

[2]Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA and

[3]Department of Physics, University of Chicago, Chicago, IL 60637, USA

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Recently, the CDF Collaboration reported the first non-zero measurement of the $B_s \to \mu^+\mu^-$ branching fraction. The LHCb, CMS and ATLAS, collaborations have reported upper limits that are in tension with the CDF result. We consider the implications of these measurements for the specific case of the Minimal Supersymmetric Standard Model (MSSM). We also discuss the implications of these measurements for neutralino dark matter and the supersymmetric contribution to the anomalous magnetic moment of the muon.

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The study of rare decay modes can provide valuable probes of physics beyond the Standard Model, not easily accessible by other means. Of particular interest are the leptonic decays of the B_s ($s\bar{b}$, $\bar{s}b$) and B_d ($d\bar{b}$, $\bar{d}b$) mesons. In the Standard Model, such decays are dominated by Z penguin and box diagrams which include a top quark loop. As the amplitudes for these processes are helicity suppressed and thus proportional to the mass of the final state leptons, one might expect B_s and B_d decays to $\tau^+\tau^-$ to be most easily measured. Searches involving tau leptons are very difficult at hadron colliders, however, making such decays currently experimentally inaccessible. For these and other reasons, the rare decay modes $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ are among the most promising channels with which to constrain or infer physics beyond the Standard Model.

Over the past several years, the CDF [1] and D0 [2] collaborations have reported increasingly stringent upper limits on the $B_s \to \mu^+\mu^-$ branching fraction, steadily moving closer to the value predicted in the Standard Model, $(3.2 \pm 0.2) \times 10^{-9}$ [3]. Recently, the CDF collaboration reported the first measurement of the $B_s \to \mu^+\mu^-$ branching fraction inconsistent with a value of zero (at the level of $2.8\,\sigma$). Furthermore, CDF's measurement, $\mathcal{B}(B_s \to \mu^+\mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$, favors a central value that is 5-6 times larger than predicted in the Standard Model. From this result, the CDF collaboration excludes the branching fraction predicted by the Standard Model at the 98.1% confidence level (C.L.) [4]. The measurement created significant interest, especially within the context of supersymmetry. The most recent analyses of LHCb [7], CMS [8], and ATLAS [9] do not confirm the CDF result and present a 95% C.L. upper limits of 4.5×10^{-9}, 7.7×10^{-9} and 2.2×10^{-8}, repectively.

It has long been appreciated that extensions of the Standard Model, including supersymmetry, can lead to large enhancements of the $B_s \to \mu^+\mu^-$ branching fraction [10, 11]. In particular, in supersymmetric models with large values of $\tan\beta$ (the ratio of the vacuum expectation values of the two higgs doublets), this branching fraction can be as large as ∼10-100 times the value predicted in the Standard Model [12–14]. In this letter, we explore the implications of these new measurements for supersymmetry, focusing for concreteness on the Minimal Supersymmetric Standard Model (MSSM).

The branching fraction for $B_s \to \mu^+\mu^-$ can be written as [15, 16]:

$$\begin{aligned}\mathcal{B}[B_s \to \mu^+\mu^-] &= \frac{\tau_B m_{B_s}^5}{32\pi} f_{B_s}^2 \sqrt{1 - 4m_\mu^2/m_{B_s}^2} \\ &\times \left[\left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right)\left|\frac{(C_S - C_S')}{(m_b + m_s)}\right|^2 \right. \\ &+ \left.\left|\frac{(C_P - C_P')}{(m_b + m_s)} + 2\frac{m_\mu}{m_{B_s}^2}(C_A - C_A')\right|^2\right],\end{aligned} \tag{1}$$

where f_{B_s} is the B_s decay constant, and m_{B_s} and τ_B are the mass and lifetime of the B_s meson, respectively. The Wilson coefficients, C_S, C_S', C_P and C_P', describe the relevant short distance physics, including any contributions from supersymmetric particles. In the case of large $\tan\beta$, the process of $B_s \to \mu^+\mu^-$ is dominated by diagrams with a higgs boson (A or H) and a chargino-stop loop, leading to a contribution (neglecting QCD corrections) approximately given by:

$$\begin{aligned}C_P &\approx -C_S \approx \frac{-G_F\,\alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left(\frac{\tan^3\beta\, m_b\, m_\mu\, m_t\, \mu \sin 2\theta_{\tilde{t}}}{8 m_W^2\, m_A^2\, \sin^2\theta_W}\right) \\ &\times \left(\frac{m_{\tilde{t}_1}^2 \log[m_{\tilde{t}_1}^2/\mu^2]}{\mu^2 - m_{\tilde{t}_1}^2} - \frac{m_{\tilde{t}_2}^2 \log[m_{\tilde{t}_2}^2/\mu^2]}{\mu^2 - m_{\tilde{t}_2}^2}\right),\end{aligned} \tag{2}$$

where $m_{\tilde{t}_{1,2}}$ are the masses of the top squarks, m_A is the mass of the pseudoscalar higgs, $\theta_{\tilde{t}}$ is the angle that diagonalizes the stop mass matrix, and V_{tb}, V_{ts} are elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. C_P' and C_S' are each suppressed by a factor of m_s/m_b and thus provide only subdominant contributions. By inspection, we see that the dominant supersymmetric contributions to the $B_s \to \mu^+\mu^-$ branching fraction scale with $\tan^6\beta$, as well as with m_A^{-4} from the propagator, $\mu^2 A_t^2$ from the mass insertions in the sparticle loop, and with

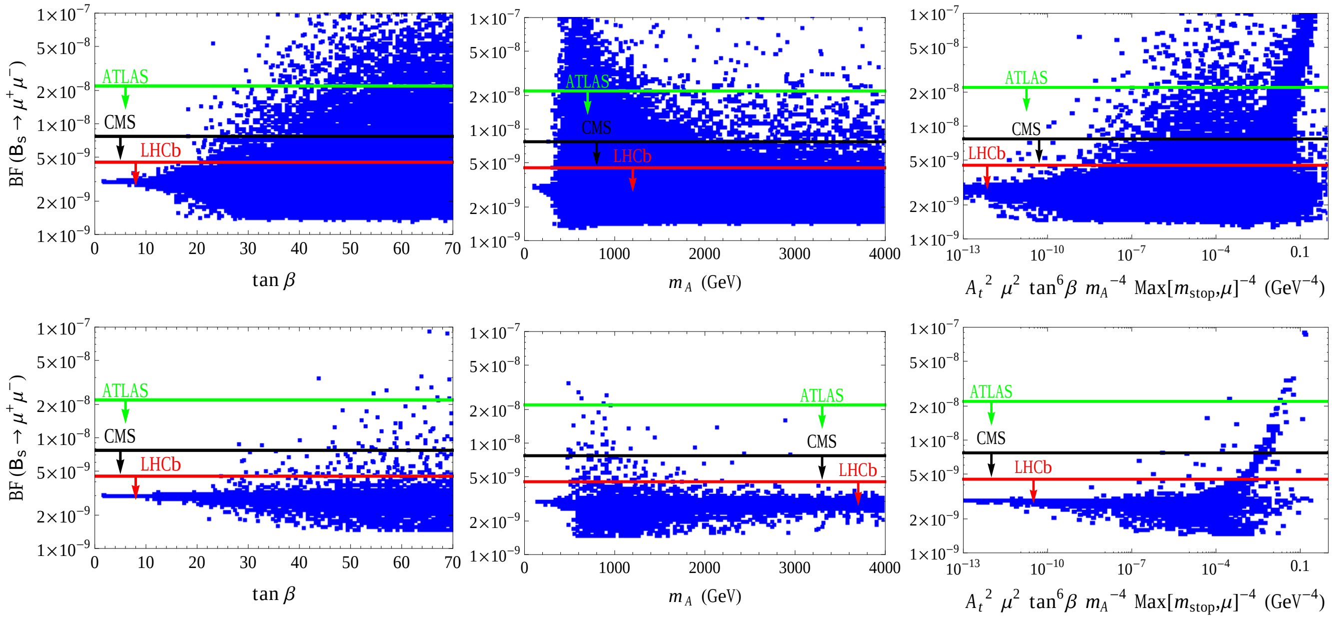

FIG. 1: Values of the $B_s \to \mu^+\mu^-$ branching fraction over MSSM parameter space as a function of $\tan\beta$ (left), m_A (center), and $A_t^2\,\mu^2\,\tan^6\beta\, m_A^{-4}\,\mathrm{Max}(\mu, m_{\rm stop})^{-4}$ (right), where $m_{\rm stop}$ is the average of the two stop masses. In the lower frames, the thermal relic abundance of neutralino dark matter is required to fall within the measured range of the dark matter density (no such constraint was imposed in the upper frames). In each frame, we have applied the collider constraints as described in the text. The red, black, and green lines denote the 95% upper limit from LHCb [7], CMS [8], and ATLAS [9]. For clarity, these plots include approximately one-tenth of the total number of models scanned.

either μ^{-4} or $m_{\tilde{t}}^{-4}$ (depending on which mass in the sparticle loop is heavier).

To explore this quantitatively, we have used the program MicrOMEGAs [17] to calculate the $B_s \to \mu^+\mu^-$ branching fraction over a large range of the MSSM parameter space. In calculating the branching fraction, MicrOMEGAs includes the loop contributions due to chargino, sneutrino, stop and Higgs exchange and the QCD corrections to Δm_b relevant for high $\tan\beta$. In scanning over supersymmetric parameters, we do not assume any particular supersymmetric breaking mechanism(s) but instead allow the parameters to be chosen independently from one another. We consider parameters over the following ranges: M_1 and slepton mass parameters up to 2 TeV, μ up to 3 TeV, M_2 and m_A up to 4 TeV, squark and gluino mass parameters up to 10 TeV, A_t up to 4 TeV (but not in excess of the stop masses) and $\tan\beta$ up to 70. For all mass parameters, we allow both positive and negative values. We require that the lightest supersymmetric particle be uncolored and electrically neutral, and impose constraints on higgs and charged sparticle masses from LEP-II. We also impose the recent constraints on squark and gluino masses from ATLAS (based on 1.04 fb^{-1} of data) [18], and constraints on the $\tan\beta$-m_A plane from CMS (based on 1.6 fb^{-1}) [19]. Lastly, we impose that the $b \to \tau^\pm\nu$ [20] and $b \to s\gamma$ [21] branching fractions fall within 2σ of their measured values. At this point, we apply only the upper limit on the magnetic moment of the muon, but will return to this issue later in this letter.

In Fig. 1, we show the distribution of values of the $B_s \to \mu^+\mu^-$ branching fraction (after imposing the previously described constraints) as a function of $\tan\beta$ (left), m_A (center), and $A_t^2\,\mu^2\,\tan^6\beta\, m_A^{-4}\,\mathrm{Max}(\mu, m_{\rm stop})^{-4}$ (right), where $m_{\rm stop}$ is the average of the two stop masses. We only plot approximately one-tenth of the total models scanned for clarity of the plots. The correlation between this branching fraction and $\tan\beta$ is particularly striking, essentially requiring large to moderate values of this quantity ($\tan\beta \gtrsim 30$) to accomodate a branching fraction as large as indicated by CDF's measurement. A large value for $B_s \to \mu^+\mu^-$ branching fraction measurement also favors moderate or low values of m_A, although a number of acceptable models were found with quite heavy m_A. (Note that although models with $m_A \lesssim 300$ GeV and large $\tan\beta$ often lead to a large $B_s \to \mu^+\mu^-$ branching fraction, this combination is inconsistent with the constraints from CMS's di-tau searches [19].)

The latest measurements at the LHC have excluded the above possibilties for a large branching fraction. As evident in Fig. 1, our scan finds that a branching fraction near the value predicted by the standard model will provide very little information about the values of supersymmetric parameters shown. Early indications at LHCb [7] do favor of a measurement of the branching fraction below the standard model value. If this suppression is confirmed, then there is the possibility that some conclusions about these supersymmetric parameters may still be made.

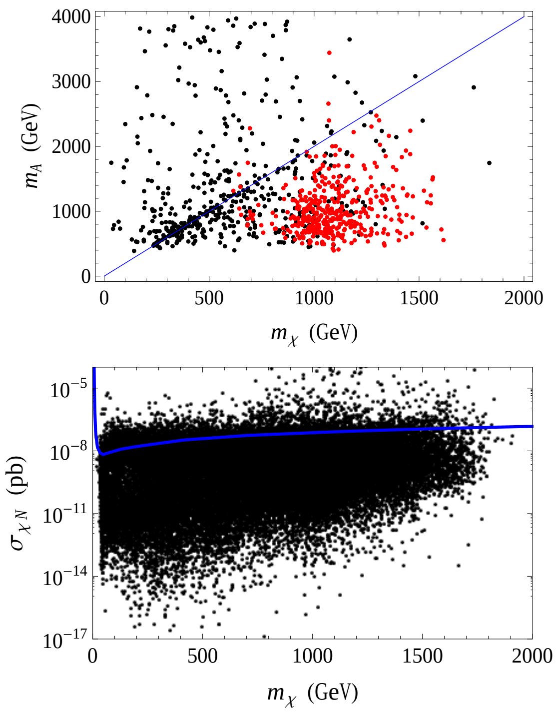

FIG. 2: Implications of the measurement of $\mathcal{B}(B_s \to \mu^+\mu^-)$ for neutralino dark matter. In the upper frame, we compare the mass of the lightest neutralino to the mass of the pseudoscalar higgs in models which fall above the 95% upper limit from LHCb and CMS collaborations from our full scan set, demonstrating that many of the models excluded by this branching fraction measurement fall near the A-resonance ($2m_\chi \approx m_A$). In this frame, black (red) points denote models with a bino-like neutralino (wino or higgsino-like neutralino). In the lower frame, we show the spin-independent elastic scattering cross section for neutralinos with nucleons, for our full set of models (now all shown in black) satsifying all constraints (including LHCb 95% upper limit) along with the current constraint from XENON-100 [23].

In the lower three frames of Fig. 1, we also require that the lightest neutralino freezes-out in the early universe with a relic abundance within the range inferred by WMAP ($\Omega_{\rm CDM}h^2 = 0.1120 \pm 0.0056$) [22]. This requirement removes a large fraction of the models found by our scan. In particular, the lightest neutralino is predicted to be overproduced in the early universe over much of supersymmetric parameter space. Regions of parameter space which do not suffer from this problem include those in which the lightest neutralino efficiently coannihilates with a nearly degenerate sparticle, efficiently annihilates due to its large couplings (made possible by sizable higgsino or wino components of its composition), or efficiently annihilates through the resonant exchange of the pseudoscalar higgs boson, A. As the cross section for neutralino annihilation to $b\bar{b}$ and $\tau^+\tau^-$ through A-exchange is proportional to $\tan^2\beta$ and $1/m_A^4$, we expect the A-resonance to be highly efficient in many of the models yielding a large value for $\mathcal{B}[B_s \to \mu^+\mu^-]$. In the upper frame of Fig. 2, we compare the masses of the lightest neutralino and the pseudoscalar higgs in models in our full scan set which yield $\mathcal{B}(B_s \to \mu^+\mu^-)$ above the 95% upper limit from the LHCb and which predict a neutralino relic abundance consistent with WMAP. We find that many of these now excluded models in which the lightest neutralino is mostly bino-like (black points) fall near the A-resonance ($2m_\chi \approx m_A$). Those models with wino-like or higgsino-like neutralinos (red points), however, can annihilate efficiently through chargino and/or neutralino exchange and thus need not (and often do not) lie near this contour.

In the lower frame of Fig. 2, we plot the spin-independent elastic scattering cross section of the neutralino with nucleons for our full scan set passing all the above constraints (including the LHCb 95% upper limit on the branching fraction). We compare this to the current upper limits from the XENON-100 experiment [23]. Although we find that direct detection experiments only rule out a small fraction of the allowed models, the elastic scattering cross sections predicted in many of these models are not far from the current constraints and are expected to fall within the reach of next generation experiments. Another point to note is that many of the allowed models have elastic scattering cross sections well below $\sim 10^{-12}$ pb where atmospheric neutrinos limit the background free direct detection of dark matter[24].

Next, we turn out attention to the anomalous magnetic moment of the muon, which has been measured to be $a_\mu^{\rm exp} = 11\,659\,2080(63) \times 10^{-11}$ [25]. When compared to the prediction of the Standard Model, $a_\mu^{\rm SM} = 11\,659\,1790(65) \times 10^{-11}$ [26], this measurement constitutes a 3.2σ discrepancy, $\delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (290 \pm 90) \times 10^{-11}$. To an extent, the supersymmetric contributions to δa_μ and $\mathcal{B}(B_s \to \mu^+\mu^-)$ are correlated. In particular, as with the B_s rare decay, large contributions to δa_μ are found predominately within the parameter space with large $\tan\beta$ and with light sparticles. Fig. 3 shows the branching fraction and δa_μ for the models in our full scan set that pass all of the constraints (including the relic density). We find that most of the models that are excluded by the $\mathcal{B}(B_s \to \mu^+\mu^-)$ have only a modest contribution to δa_μ. The majority of the models that would contribute significantly to δa_μ have branching fractions much closer to the standard model prediction, and are thus still viable as a possibility for explaining the value of δa_μ.

In summary, we find that the recent upper limits at the LHC of the $B_s \to \mu^+\mu^-$ branching fraction, within the context of the Minimal Supersymmetric Standard Model (MSSM), excludes mostly models with large values of $\tan\beta$ and (in most cases) modest values of m_A. We find that a branching fraction near the value predicted by the standard model will provide very little information about the values of the above supersymmetric parameters, unless the indications of a supression of the branching fraction at LHCb are confirmed. In much of the supersymmetric parameter space still allowed by these measure-

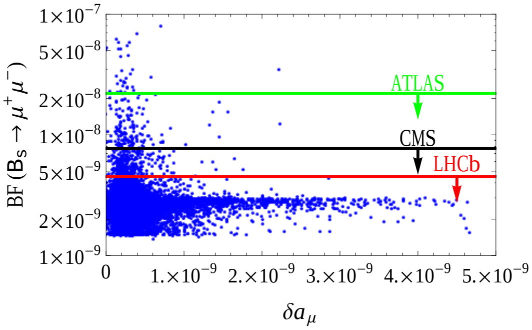

FIG. 3: Implications of the measurement of $\mathcal{B}(B_s \to \mu^+\mu^-)$ for the supersymmetric contribution to the anomalous magnetic moment of the muon, $\delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.9 \pm 0.9) \times 10^{-9}$. Models from our full scan set that pass all of the constraints (including the relic density) are shown.

ments, neutralino dark matter scatters elastically with nuclei at a rate not far below current constraints from direct detection experiments. We also find that even with branching fractions at the standard model value (or lower), the supersymmetric contributions to the anomalous magnetic moment of the muon can still be significant.

The LHCb experiment is expected to become sensitive to a branching fraction for $B_s \to \mu^+\mu^-$ as small as that predicted by the standard model by the end of 2012 [28]. This will provide an opportunity to confirm the indications of a supression, or any other possibilities for new physics in this channel very soon.

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