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Konstantin T. Matchev

Fermi National Laboratory, Batavia, IL 60510

and

Damien M. Pierce

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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Konstantin T. Matchev
Theory Group, Fermi National Laboratory, Batavia, IL 60510

Damien M. Pierce
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

We present new upper limits on the light Higgs boson mass m_h in supersymmetric models. We consider two gravity-mediated models (with and without universal scalar masses) and two gauge-mediated models (with a $\mathbf{5}+\overline{\mathbf{5}}$ or $\mathbf{10}+\overline{\mathbf{10}}$ messenger sector). We impose standard phenomenological constraints, as well as SU(5) Yukawa coupling unification. Requiring that the bottom and tau Yukawa couplings meet at the unification scale to within 15%, we find the upper limit $m_h < 114$ GeV in the universal supergravity model. This reverts to the usual upper bound of 125 GeV with a particular nonuniversality in the scalar spectrum. In the $\mathbf{5}+\overline{\mathbf{5}}$ gauge-mediated model we find $m_h < 97$ GeV for small $\tan\beta$ and $m_h \simeq 116$ GeV for large $\tan\beta$, and in the $\mathbf{10}+\overline{\mathbf{10}}$ model we find $m_h < 94$ GeV. We discuss the implications for upcoming searches at LEP-II and the Tevatron.

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If weak-scale supersymmetry (SUSY) exists it may be a challenge to discover. The superpartners may all be so heavy that they do not appreciably affect any low energy observables, and are below threshold for production at LEP-II and the Tevatron. In that case they will go undiscovered until the LHC turns on in 2005. However, one of the most robust and enticing hallmarks of supersymmetric models is the prediction of a light Higgs boson. At tree level, $m_h \le M_Z$, but it receives large radiative corrections from top and stop loops [1]. Naturalness suggests that the (third generation) squarks should not be too heavy. If we impose that the (top) squark masses are below 1.2 TeV, the upper limit on m_h is about 125 GeV (including recent two-loop corrections [2]). The largest possible value is obtained with heavy stops and large squark mixing.

Supersymmetry goes hand in hand with grand unification. The couple of percent discrepancy in gauge coupling unification finds a ready explanation in grand unified theory (GUT) models, from GUT threshold effects. In typical GUT models the bottom and tau Yukawa couplings (λ_b and λ_τ) are predicted to unify as well. At leading order this only happens for either very small ($\lesssim 2$) or rather large ($\sim m_t/m_b$) values of $\tan\beta$ ($\tan\beta$ is the ratio of expectation values of the two Higgs doublets).

We take the muon decay constant, the Z-boson mass, the fermion masses, $\tan\beta$, and the strong and electromagnetic couplings as inputs to determine λ_b and λ_τ at the GUT scale (the scale where the U(1) and SU(2) gauge couplings meet). We define the Yukawa coupling mismatch at the GUT scale to be $\varepsilon_b \equiv (\lambda_b - \lambda_\tau)/\lambda_\tau$, and, allowing for variations in the input parameters and GUT scale threshold corrections, conservatively expect ε_b to be less than 15% in magnitude.

At next-to-leading order bottom-tau unification is sensitive to the supersymmetric spectrum through radiative corrections. The corrections to λ_b are enhanced at large $\tan\beta$ and can be quite large [3–5]. They broaden the region at large $\tan\beta$ where exact unification is possible to $15 \lesssim \tan\beta \lesssim 50$. The branching ratio $\mathrm{B}(B \to X_s\gamma)$ also receives large $\tan\beta$ enhanced corrections. The requirements of Yukawa unification and compliance with the $\mathrm{B}(B \to X_s\gamma)$ measurement tend to conflict with each other. Depending on the model, imposing both constraints can single out a very particular parameter space, resulting in predictions for the superpartner and Higgs boson masses. In this letter we examine the Higgs boson mass predictions in four supersymmetric models – two gravity-mediated models (with and without universal scalar masses), and two gauge-mediated models (with a $\mathbf{5}+\overline{\mathbf{5}}$ or $\mathbf{10}+\overline{\mathbf{10}}$ messenger sector). Yukawa coupling unification together with the $b \to s\gamma$ constraint has been previously discussed within the context of the gravity-mediated models in Ref. [3], but no conclusions about the light Higgs boson mass were drawn. Ref. [6] uses fine-tuning criteria in addition to the $\mathrm{B}(B \to X_s\gamma)$ constraint to derive some limits on the light Higgs boson mass.

In each model we randomly pick points in the supersymmetric parameter space (the parameter spaces are discussed below). At each point the Z-boson mass, the top-quark mass, and the electromagnetic and strong couplings at the Z-scale are determined in a global fit to precision data. We construct a χ^2 function and minimize it with respect to the four standard model inputs. The χ^2 function contains 30 electroweak precision observables, and $\mathrm{B}(B \to X_s\gamma)$. The list of observables, the measurements we use, and further details are given in Ref. [7]. We set $m_b(\mathrm{pole}) = 4.9$ GeV.

We impose a number of phenomenological constraints at each point in parameter space. We require radiative electroweak symmetry breaking and determine the CP-odd Higgs boson mass m_A and the absolute value of the Higgsino mass parameter μ to full one-loop order [5]. Very large values of $\tan\beta$ are excluded by this constraint. We require that all Yukawa couplings remain perturbative up to the GUT scale. This rules out very small values of $\tan\beta$. Finally, we require that all the superpartner and Higgs boson masses are above the bounds set by direct particle searches.

We calculate the gauge and Yukawa couplings using the full one-loop threshold corrections [5] and two-loop renormalization group equations [8]. The parameter dependence of the λ_b corrections can be understood from the simplified approximation

$$\frac{\delta\lambda_b}{\lambda_b} \simeq -\frac{1}{16\pi^2}\left(\frac{8}{3}g_3^2 m_{\tilde{g}} + \lambda_t^2 A_t\right)\frac{\mu\tan\beta}{m_{\tilde{q}}^2} . \qquad (1)$$

The first (second) term is the gluino-sbottom (chargino-stop) loop contribution. $m_{\tilde{q}}$ is an average (stop or sbottom) squark mass, $m_{\tilde{g}}$ is the gluino mass, A_t is the stop-stop-Higgs trilinear coupling and g_3 (λ_t) is the strong (top Yukawa) coupling. In a leading-order analysis, where the corrections (1) are neglected, λ_b and λ_τ unify well below the GUT scale for intermediate values of $\tan\beta$. With $\mu > 0$ the corrections (1) make this situation worse, so that with $\tan\beta > 2$ ε_b falls in the range -20 to -60%. This discrepancy is larger than can be accounted for in realistic GUT models [9,10]. Also, variations in the input parameters $\Delta m_t = \pm 3$ GeV, $\Delta m_b = \pm 0.15$ GeV and $\Delta\alpha_s = \pm 0.003$ result in $\Delta\varepsilon_b = \pm 1\%$, $\pm 3\%$, and $\mp 3\%$, respectively. With $\mu < 0$ the threshold corrections (1) help Yukawa unification by increasing λ_b at the weak scale, thus delaying its unification with λ_τ to higher scales. Our conservative requirement $|\varepsilon_b| < 15\%$ restricts us to either $\tan\beta < 2$ with μ of either sign, or $\tan\beta \gtrsim 5$ and $\mu < 0$.

The allowed values of A_t play a central role in our discussion. Each model allows for a different range of values of A_t, with corresponding implications. We start by discussing the results in the gravity-mediated model with universal soft parameters (mSUGRA). In this model three inputs are specified at the GUT scale. They are a universal scalar mass M_0, a universal gaugino mass $M_{1/2}$, and a universal trilinear scalar coupling A_0. The remaining two inputs are $\tan\beta$ and the sign of μ.

Because of the large top Yukawa coupling, the value of A_t at the weak scale exhibits a quasi-fixed point behavior. Hence, the sensitivity to its high scale boundary condition is reduced. The quasi-fixed point behavior is illustrated in Fig. 1(a), where we plot the dimensionless parameter $a_t \equiv A_t/M_{\tilde{q}}$ as a function of the renormalization scale Q in the mSUGRA model ($M_{\tilde{q}} \equiv \sqrt{M_0^2 + 4M_{1/2}^2}$ is approximately equal to the first or second generation squark mass). We see that A_t tends to be negative at the weak scale. In that case the stop-chargino contribution in Eq. (1) partially cancels the sbottom-gluino contribution. At intermediate values of $\tan\beta$ ($10 \lesssim \tan\beta \lesssim 20$) Yukawa unification requires that the correction (1) be maximized. This happens when $A_t > 0$, so that the stop-chargino contribution adds constructively to the sbottom-gluino contribution. Hence, at intermediate $\tan\beta$ large and positive values of $a_0 \equiv A_0/M_{\tilde{q}}$ are necessary in the mSUGRA model. This is illustrated in Fig. 1(b), where we show the results of a scan over the mSUGRA parameter space with the requirement that $|\varepsilon_b| < 5\%$. The figure shows a striking correlation between a_0 and $\tan\beta$ at intermediate values of $\tan\beta$. At large $\tan\beta$ the $\tan\beta$ enhancement in Eq. (1) is by itself enough for successful Yukawa unification. In fact, at some points cancellation between the two terms in (1) is necessary, so small or negative values of a_0 are preferred. We also see from Fig. 1(b) that in the small $\tan\beta$ region large positive A_0 is required, signifying that the corrections in Eq. (1) are relevant. The points in this region have values of the Higgs boson mass below 100 GeV.

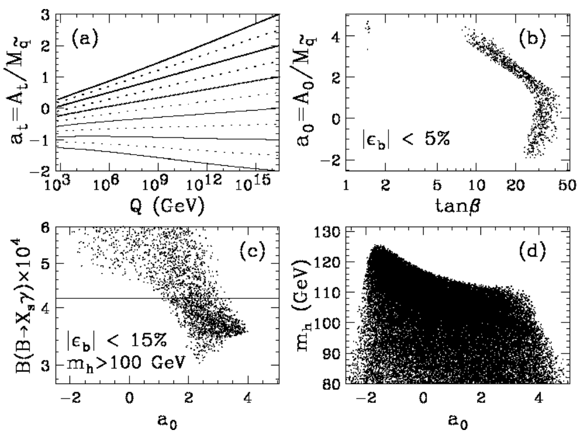

FIG. 1. (a) Renormalization group trajectories of a_t for $M_0 = 500$ GeV, $M_{1/2} = 200$ GeV, $\tan\beta = 20$ and $\mu < 0$; (b) The stop mixing parameter a_0 vs. $\tan\beta$ with $|\varepsilon_b| < 5\%$; (c) The branching ratio $\mathrm{B}(B \to X_s\gamma)$ versus a_0, with the additional constraints $|\varepsilon_b| < 15\%$ and $m_h > 100$ GeV. (d) The light Higgs boson mass as a function of a_0, scanned over the mSUGRA parameter space with no additional constraints.

The CLEO collaboration's 95% upper bound on the $b \to s\gamma$ rate, $\mathrm{B}(B \to X_s\gamma) < 4.2 \times 10^{-4}$ [11], imposes strong constraints on supersymmetric models. If $\mu < 0$ the chargino-stop and Higgs boson contributions to the $b \to s\gamma$ amplitude add constructively to the SM amplitude. Due to the $\tan\beta$ enhancement of the chargino loop contribution, very large total amplitudes can result, leading to predictions for $\mathrm{B}(B \to X_s\gamma)$ well above the upper bound. As a result, significant regions of the SUSY parameter space are excluded. We can identify those by considering the following approximate formula for the leading supersymmetric corrections to the O_7 operator coefficient. With $\mu < 0$ and $\tan\beta$ large, we have

$$\delta C_7(M_W) \simeq -\frac{3\tan\beta}{16\pi^2|\mu|}\left[\frac{M_W^2}{M_2} - \frac{1}{2}\frac{A_t m_t^2}{m_{\tilde{t}}^2}\right] , \qquad (2)$$

where the first (second) term is the contribution from the $\tilde{t}_L - \tilde{\chi}^+$ ($\tilde{t} - \tilde{h}^+$) loop (we work to first order in stop and chargino mixing). M_W (m_t) is the W-boson (top-quark) mass, M_2 is the SU(2) gaugino soft mass, and $m_{\tilde{t}}$ is the average stop mass. If $A_t > 0$ there is destructive interference between the two terms, and the supersymmetric contribution to the $b \to s\gamma$ amplitude is reduced. In Fig. 1(c) we show the full one-loop prediction for $\mathrm{B}(B \to X_s\gamma)$ in the mSUGRA model, subject to the $b - \tau$ unification constraint $|\varepsilon_b| < 15\%$. As expected, the rate is suppressed for large and positive values of a_0.

We see from Fig. 1(c) that in the mSUGRA model with $\tan\beta > 2$, reasonably small $|\varepsilon_b|$ and $\mathrm{B}(B \to X_s\gamma)$ can occur only for relatively large and positive a_0 ($a_0 > 1.1$). Because of the focusing towards negative values, the resulting values of a_t at the squark mass scale are rather small ($-0.4 < a_t < 0.7$). Hence, top squark mixing is suppressed and the corrections to the Higgs boson mass are minimized. The scatter plot in Fig. 1(d) shows m_h vs. a_0 in the mSUGRA model. The Higgs boson mass is maximal at $a_0 = -1.7$ and decreases with increasing a_0.

In Fig. 2(a) we show the scatter plot of m_h vs. ε_b in the mSUGRA model. We have imposed the $b \to s\gamma$ constraint in Fig. 2. The vertical lines indicate the region $|\varepsilon_b| < 15\%$. We see that the Higgs boson mass is below 114 GeV in this region.

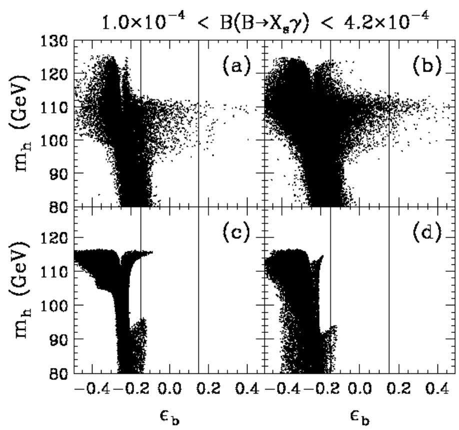

FIG. 2. Scatter plots of m_h vs. ε_b in four supersymmetric models: SUGRA with (a) universal or (b) nonuniversal scalar masses; and minimal gauge mediation with a (c) $\mathbf{5}+\overline{\mathbf{5}}$ or (d) $\mathbf{10}+\overline{\mathbf{10}}$ messenger sector. In each case, we require $1.0 \times 10^{-4} < \mathrm{B}(B \to X_s\gamma) < 4.2 \times 10^{-4}$. The vertical lines on the plots delineate the region $|\varepsilon_b| < 15\%$.

The mSUGRA model suffers from the rather ad hoc assumption of scalar mass unification. While we see no compelling justification for this boundary condition, if it did apply it would naturally hold at the Planck scale. The effects of running between the Planck scale and the GUT scale can be significant [12]. Regardless of the boundary condition at the Planck scale, a GUT symmetry will ensure that GUT multiplets remain degenerate above the GUT scale. In SU(5), the parameter space at the GUT scale includes the soft mass parameters M_{H_1}, M_{H_2}, M_5 and M_{10}, corresponding to the $\overline{\mathbf{5}}$ and $\mathbf{5}$ representations of Higgs fields, and the $\overline{\mathbf{5}}$ and $\mathbf{10}$ representations of sfermion fields, respectively. (Although we impose generation independence of the M_5 and M_{10} masses, the phenomenology we consider here only depends on the third generation scalar masses.)

Because of the larger parameter space of the nonuniversal SU(5) model, the upper limit on the Higgs boson mass, including the $\mathrm{B}(B \to X_s\gamma)$ and approximate bottom-tau unification constraints, reverts to the general upper limit of 125 GeV (see Fig. 2(b)). We can contrast the situation here with the standard mSUGRA case. Large splitting between M_{H_2} and M_{10} can lead to much larger values of μ and m_A for a given $\tan\beta$. The larger value of μ gives larger corrections to the bottom Yukawa coupling, making bottom-tau unification possible for smaller values of $\tan\beta$. The smaller values of $\tan\beta$, with larger μ and m_A, lead to reductions in the supersymmetric contributions to the $b \to s\gamma$ amplitude. This, in turn, allows compliance with the $\mathrm{B}(B \to X_s\gamma)$ upper bound with large and negative values of A_0. Such A_0 values result in large squark mixing contributions to the Higgs boson mass (see Fig. 1(d)). The points with the largest m_h have $M_{10} \simeq 1$ TeV, $M_{1/2} \simeq 400 \pm 100$ GeV, $\tan\beta \simeq 14 \pm 3$, A_0 in the range -1 to -2 TeV and, typically, $M_{H_2} \lesssim 100$ GeV.

Gauge mediation is an attractive alternative to gravity-mediated supersymmetry breaking. One of the nice features of gauge-mediated models is the automatic scalar mass degeneracy. All sfermions with identical quantum numbers have the same mass at the messenger scale. This provides a natural solution to the supersymmetric flavor problem.

In order to preserve gauge coupling unification we consider two models with full SU(5) messenger sector representations, the $\mathbf{5}+\overline{\mathbf{5}}$ and $\mathbf{10}+\overline{\mathbf{10}}$ models. We assume a minimal Higgs sector, where the mechanism which gives rise to the B and μ terms does not give additional contributions to the scalar masses. In the canonical models [13] the interactions between the dynamical supersymmetry breaking sector and a standard model singlet give rise to a vev in its scalar and F components. The coupling of the singlet to the messenger fields results in supersymmetry breaking and conserving messenger masses. To determine the effective theory below the messenger mass scale, the messenger fields are integrated out. The MSSM superpartners then receive masses proportional to $\Lambda = F/S$, where F (S) is the singlet F-term (scalar) vev. At this order, there is no A-term generated. Hence, we set $A_0 = 0$ at the messenger scale. The messenger scale determines the amount of running of the soft parameters. The smallest allowed value of the messenger scale is Λ. Since we do not want the gravity-mediated contributions to the scalar masses to spoil the solution to the supersymmetric flavor problem, we suppress the gravity-mediated contributions by requiring the messenger scale to be below $M_{\mathrm{GUT}}/10$.

In the mSUGRA model we found that the $\mathrm{B}(B \to$

$X_s\gamma$) and bottom-tau unification constraints required $a_0 > 1.1$ at intermediate to large $\tan\beta$. Since the gauge-mediated models have $a_0 = 0$, one would expect that these models would not be compatible with the constraints at intermediate to large $\tan\beta$ if the spectrum did not significantly differ from the mSUGRA model. However, it is well known that the spectra in gauge- and gravity-mediated models can be quite different [14]. For example, in the $\mathbf{5}+\overline{\mathbf{5}}$ gauge-mediated model, the scalar masses and the μ-term are significantly heavier for a given gaugino mass than in the mSUGRA model. Just as in the nonuniversal model, the larger μ allows for bottom-tau unification with smaller values of $\tan\beta$, and the reduced $\tan\beta$ and larger μ and m_A suppress the supersymmetric contribution to the $b \to s\gamma$ amplitude. Hence, in the $\mathbf{5}+\overline{\mathbf{5}}$ model there is a small amount of parameter space at intermediate $\tan\beta$ where the constraints are satisfied, even though $A_t < 0$. In this region we find the prediction $m_h \simeq 116$ GeV. In the small $\tan\beta$ region $m_h < 97$ GeV. The results are shown in Fig. 2(c).

For a given gaugino mass, larger messenger sector representations result in lighter scalar masses. Hence, the $\mathbf{10}+\overline{\mathbf{10}}$ model has relatively lighter scalars than the $\mathbf{5}+\overline{\mathbf{5}}$ model. The lighter scalars make Yukawa unification more difficult, and readily result in too large values of $\mathrm{B}(B \to X_s\gamma)$ at intermediate to large $\tan\beta$. As can be seen in Fig. 2(d), the two constraints taken together exclude the $\mathbf{10}+\overline{\mathbf{10}}$ model outright for intermediate to large values of $\tan\beta$. The only allowed points with $|\varepsilon_b| < 15\%$ correspond to values of $\tan\beta < 2$. In this region m_h is less than 94 GeV.

Our results are particularly interesting in light of the upcoming Higgs boson searches at LEP and the Tevatron. LEP-II should be able to either discover or rule out a light Higgs boson up to about 105 GeV. If LEP finds a Higgs boson *heavier* than 96 (94) GeV, the minimal $\mathbf{5}+\overline{\mathbf{5}}$ ($\mathbf{10}+\overline{\mathbf{10}}$) gauge-mediated model will require some modification in order to be compatible with bottom-tau unification. If, on the other hand, LEP does not find a light Higgs boson, the Yukawa unification criterion excludes the minimal $\mathbf{10}+\overline{\mathbf{10}}$ gauge-mediated model.

What is more, if bottom-tau unification is taken seriously, upcoming runs at the Tevatron stand a chance to explore both the mSUGRA and minimal $\mathbf{5}+\overline{\mathbf{5}}$ gauge-mediated models. The Tevatron reach in m_h as a function of its total integrated luminosity is currently under active investigation and no definite conclusions can be made at this point, but the upper limits of 114 and 116 GeV, correspondingly, can serve as important benchmarks in the design of an extended Run 2. Finally, if the Tevatron can place a limit on the Higgs boson mass above 116 GeV, this would point towards particular nonunified scenarios in the gravity-mediated models, and exclude Yukawa coupling unification in minimal gauge-mediation altogether.

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[1] H. Haber, hep-ph/9707213 and references therein.
[2] J.R. Espinosa and M. Quiros, Phys. Lett. **B266**, 389 (1991); J. Kodaira, Y. Yasui and K. Sasaki, Phys. Rev. **D50**, 7035 (1994); R. Hempfling and A. Hoang, Phys. Lett. **B331**, 99 (1994); J.A. Casas, J.R. Espinosa, M. Quiros and A. Riotto, Nucl. Phys. **B436**, 3 (1995); M. Carena, M. Quiros and C.E.M. Wagner, Nucl. Phys. **B461**, 407 (1996); S. Heinemeyer, W. Hollik and G. Weiglein, hep-ph/9803277.
[3] M. Carena, M. Olechowski, S. Pokorski and C.E.M. Wagner, Nucl. Phys. **B426**, 269 (1994); M. Carena, and C.E.M. Wagner, hep-ph/9407209.
[4] L. Hall, R. Rattazzi and U. Sarid, Phys. Rev. **D50**, 7048 (1994).
[5] J. Bagger, K. Matchev, D. Pierce and R.-J. Zhang, Nucl. Phys. **B491**, 3 (1997).
[6] P. Chankowski and S. Pokorski, hep-ph/9702431.
[7] J. Erler and D. Pierce, hep-ph/9801238, to appear in Nucl. Phys. **B**.
[8] Y. Yamada, Phys. Rev. **D50**, 3537 (1994); S. Martin and M. Vaughn, Phys. Lett. **B318**, 331 (1993); *ibid.*, Phys. Rev. **D50**, 2282 (1994); I. Jack and D.R.T. Jones, Phys. Lett. **B333**, 372 (1994).
[9] B.D. Wright, hep-ph/9404217.
[10] J. Bagger, K. Matchev, D. Pierce and R.-J. Zhang, Phys. Rev. Lett. **78**, 2497 (1997).
[11] CLEO collaboration: M.S. Alam *et al.*, Phys. Rev. Lett. **74**, 2885 (1995).
[12] N. Polonsky and A. Pomarol, Phys. Rev. Lett. **73**, 2292 (1994),Phys. Rev. **D51**, 6532 (1995).
[13] M. Dine and A. Nelson, Phys. Rev. **D48**, 1277 (1993); M. Dine, A. Nelson and Y. Shirman, Phys. Rev. **D51**, 1362 (1995); M. Dine, A. Nelson, Y. Nir and Y. Shirman, Phys. Rev. **D53**, 2658 (1996).
[14] J. Bagger, K. Matchev, D. Pierce and R.-J. Zhang, Phys. Rev. **D55**, 437 (1997).