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Do electroweak precision data and Higgs-mass constraints rule out a scalar bottom quark with mass of $\mathcal{O}(5\ \mathrm{GeV})$?

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Abstract

We investigate the phenomenological implications of a light scalar bottom quark, with a mass of about the bottom quark mass, within the minimal supersymmetric standard model. The study of such a scenario is of theoretical interest, since, depending on their production and decay modes, light sbottoms may have escaped experimental detection up to now and, in addition, may naturally appear for large values of $\tan\beta$. In this article we show that such a light sbottom cannot be ruled out by the constraints from the electroweak precision data and the present bound on the lightest $\mathcal{CP}$-even Higgs-boson mass at LEP. It is inferred that a light sbottom scenario requires in general a relatively light scalar top quark whose mass is typically about the top-quark mass. It is also shown that under these conditions the lightest $\mathcal{CP}$-even Higgs boson decays predominantly into scalar bottom quarks in most of the parameter space and that its mass is restricted to $m_h \lesssim 123$ GeV.

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New light particles, with masses of the order of the weak scale, are an essential ingredient of any scenario beyond the standard model that leads to an explanation of the large hierarchy between the Planck mass and the weak scale. Although it would be natural to expect that the mass of the lightest of such particles would be smaller than the gauge boson masses, no clear evidence of such a particle has been reported so far. New particle searches are usually performed under model-dependent assumptions and hence the quoted bounds may be avoided if such assumptions are relaxed. In particular, a light scalar bottom quark, $\tilde{b}$, with mass close to the bottom quark mass, would be difficult to observe at low-energy experiments since, due to its small mass, it violates the usual missing energy requirements [1]. Furthermore, it has been argued that such light particles are not in contradiction with the measurement of R, the ratio of the cross section of e^+e^- going into hadrons and the one of e^+e^- going into muons [2]. Therefore, irrespectively of recent possible weak experimental hints for the presence of such a particle [3], the question whether a $\tilde{b}$ almost mass-degenerate with the bottom quark is consistent with the strong constraints from electroweak precision data and the present bound on the Higgs mass at LEP is of interest in its own right.

A light $\tilde{b}$ is most naturally obtained within supersymmetric (SUSY) theories, in the large $\tan\beta$ regime. SUSY theories [4] are generally regarded as the best motivated extension of the standard model (SM) of the electroweak and strong interactions. They provide an elegant way to break the electroweak symmetry and to stabilize the huge hierarchy between the GUT and the Fermi scales, and allow for a consistent unification of the gauge coupling constants. Supersymmetry predicts the existence of scalar partners to each SM fermion, and spin–1/2 partners to the gauge and Higgs bosons. Large values of $\tan\beta$ are required in minimal SO(10) scenarios, with unification of the Yukawa couplings of the third generation quarks and leptons [5].

As mentioned above, the exclusion bounds on bottom squarks from low-energy experiments and at colliders in the pre-LEP era depend on the mass splitting between the scalar bottom quarks and their decay products and on the decay characteristics [1]. If the behavior of sbottom quarks in the detector mimics the one of bottom quarks, and their mass is close to the bottom mass, disentangling their signal might be difficult. The same is true, due to its small mass, if it decays via a loop-induced coupling into strange or down jets plus missing energy.

On the other hand, the hadronic observables measured with high precision at the Z peak at LEP1 [6] impose tight and fairly model independent constraints on this kind of new physics, provided that the scalar bottom quarks couple with sufficient strength to the Z boson. A necessary condition in order that such a scenario within the minimal supersymmetric standard model (MSSM) can be phenomenologically viable is thus a relatively small coupling of the scalar bottom quarks to the Z boson (see below).

Besides the constraints from the direct search for sbottoms, the considerable splitting between the masses in the scalar bottom and top sector necessary to avoid direct observation of at least one of these particles at LEP gives rise to sensitive restrictions from virtual effects to electroweak precision observables, e.g. $\sin^2\theta_{\rm eff}$, M_W and Γ_l, via contributions to the ρ-parameter. A further crucial question is whether a light $\tilde{b}$ scenario can give rise to a sufficiently large value for the lightest $\mathcal{CP}$-even Higgs-boson mass in the MSSM in view of the bounds arising from the non-observation of this particle at LEP. The latter constraints have meanwhile ruled out a considerable part of the parameter space even in the unconstrained

MSSM (in which no assumptions about the underlying SUSY-breaking mechanism are made), see Ref. [7]. The present bound on the Higgs-boson mass of the SM from the Higgs search is $M_H > 113.3$ GeV at 95% C.L. [8]. The upper bound on the mass of the lightest $\mathcal{CP}$-even Higgs boson within the MSSM is $m_h \lesssim 130$ GeV for $m_t = 175$ GeV. The latter bound arises from the theoretical prediction of m_h in the MSSM up to the two-loop level [9,10].

As we mentioned above, a light sbottom, with a mass of $\mathcal{O}(5\text{ GeV})$, would be ruled out by LEP1 unless its coupling to the Z boson would be relatively small. The squark couplings to the Z depend on the mixing angle, $\theta_{\tilde{q}}$, and are proportional to

$$\begin{aligned}
g_{Z\tilde{q}_1\tilde{q}_1} &\simeq g\left(T_3\cos^2\theta_{\tilde{q}} - Q_{\tilde{q}}\sin^2\theta_W\right), \\
g_{Z\tilde{q}_1\tilde{q}_2} &\simeq g\,T_3\sin\theta_{\tilde{q}}\cos\theta_{\tilde{q}}, \\
g_{Z\tilde{q}_2\tilde{q}_2} &\simeq g\left(T_3\sin^2\theta_{\tilde{q}} - Q_{\tilde{q}}\sin^2\theta_W\right),
\end{aligned} \tag{1}$$

where $\sin^2\theta_W \equiv s_W^2 = 1 - M_W^2/M_Z^2$, and in the following we will use the shorthand notation $s_{\tilde{q}} \equiv \sin\theta_{\tilde{q}}$ and $c_{\tilde{q}} \equiv \cos\theta_{\tilde{q}}$. In the particular case of sbottoms, $Q_{\tilde{b}} = -1/3$, $T_3 = -1/2$, and hence an exact cancellation of the coupling of the lightest sbottom, $\tilde{b}_2$, to the Z is achieved in lowest order when $s_{\tilde{b}}^2 \simeq 2/3 s_W^2$. Similarly an exact cancellation for the lightest $\tilde{t}$, $\tilde{t}_1$, yields $c_{\tilde{t}}^2 \simeq 4/3 s_W^2$. For our conventions in the scalar quark sector, see Ref. [9].

While large couplings of the light $\tilde{b}$ to the Z boson are obviously disfavored, it is not necessary that these couplings are fine tuned to vanish exactly. If the $\tilde{b}$ would decay in a way similar to the bottom quark it would mainly affect those observables associated with bottom production. This would be particularly interesting in view of the fact that the hadronic cross section measured at LEP with high precision is slightly larger (by 1.62σ) than the SM prediction. The situation is similar for R_b and R_l, while A_{FB}^b differs from the SM prediction by -2.4σ. On the other hand, the total Z width measured at LEP is slightly low compared to the SM predictions (by -0.43σ) [6]. The presence of a light $\tilde{b}$ will slightly affect the extrapolated value of the electromagnetic and strong gauge couplings, α_{em} and α_s, at the scale M_Z. While the variation of $\alpha_{em}(M_Z)$ is of about the same size as the difference of the two most precise theoretical estimates of $\alpha_{em}(M_Z)$ [6], the variation of $\alpha_s(M_Z)$ is smaller than the present error on this quantity [1].

We have calculated the production cross section for light scalar bottoms as function of the effective $Z\tilde{b}_2\tilde{b}_2$ coupling (throughout this paper we use the tree-level notation for this coupling, although it can be viewed as an effective coupling containing loop corrections). As an additional scenario to the case where this coupling precisely vanishes, we have chosen it such that the $\tilde{b}$ production, interpreted as bottom quarks in the data, shifts the prediction for the hadronic cross section at the Z peak, $\sigma_{\rm had}$, from the SM value (1.62σ below the data) to a value which agrees with the data within 1σ. Analyzing the corresponding effects on the other Z peak observables, R_b, R_c, R_l, A_{FB}^b, A_b, Γ_Z, we find the following results for the comparison of the data with the predictions, given in units of standard deviations: $\delta R_b = 0.40\sigma(1.0\sigma)$, $\delta R_c = -1.01\sigma(-1.04\sigma)$, $\delta R_l = 0.62\sigma(1.08\sigma)$, $\delta A_{FB}^b = -2.29\sigma(-2.42\sigma)$, $\delta A_b = -0.87\sigma(-1.0\sigma)$, $\delta\Gamma_Z = -0.60\sigma(-0.43\sigma)$. The values in brackets correspond to the SM predictions [1,6]. We find that the agreement of the predictions with the data improves in comparison to the SM case for all observables except for Γ_Z. The latter gets slightly worse but still stays well within one standard deviation. Thus, a small but non-vanishing coupling of the light scalar bottom is not only compatible with the hadronic observables at the Z peak, but even slightly improves the agreement with the data.

In the following we investigate the constraints from $\Delta\rho$ and the Higgs mass limit for the two cases:

(I) Vanishing coupling of $\tilde{b}_2$ and $\tilde{t}_1$ to the Z boson, $s_{\tilde{b}} = \pm\sqrt{2/3}s_W$, $c_{\tilde{t}} = \pm\sqrt{4/3}s_W$.

(II) A $Z\tilde{b}_2\tilde{b}_2$ coupling such that $\sigma_{\rm had}$ is in agreement with the data within one standard deviation. This corresponds to $s_{\tilde{b}} \approx \pm 0.300$ or $s_{\tilde{b}} \approx \pm 0.454$. No constraints on the $Z\tilde{t}_1\tilde{t}_1$ coupling are imposed.

In the analysis below $m_{\tilde{b}_2}$ has been fixed to $m_{\tilde{b}_2} = 4$ GeV, but varying its mass by a few GeV would not qualitatively change our results. Since we also restrict $s_{\tilde{b}}$ as specified above, in principle there are four more free parameters left in the scalar bottom and top sector, $m_{\tilde{b}_1}$, $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$ and $s_{\tilde{t}}$. The relation between these parameters in the mass-eigenstate basis and the ones in the basis of the current eigenstates $\tilde{b}_L, \tilde{b}_R, \tilde{t}_L, \tilde{t}_R$ is given by the mixing matrices

$$\mathcal{M}^2_{\tilde{q}} = \begin{pmatrix} M^2_{\tilde{q}_L} + m_q^2 + D_{\tilde{q}_L} & m_q X_q \\ m_q X_q & M^2_{\tilde{q}_R} + m_q^2 + D_{\tilde{q}_R} \end{pmatrix} \tag{2}$$

for $q = t, b$, and $X_t = A_t - \mu\cot\beta$, $X_b = A_b - \mu\tan\beta$. The D-term contributions $D_{\tilde{q}_L}$, $D_{\tilde{q}_R}$ have not explicitly been written. In the above, $A_{t,b}$ denote the trilinear Higgs–$\tilde{t}$, –$\tilde{b}$ couplings, respectively, and μ is the Higgs mixing parameter. SU(2) gauge invariance leads to the relation $M_{\tilde{t}_L} = M_{\tilde{b}_L}$. Thus only three of the four parameters $m_{\tilde{b}_1}$, $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, $s_{\tilde{t}}$ are independent.

Since the heaviest $\tilde{b}$ has not been observed at LEP2, and it can be in principle produced in association with the lightest one, its mass should be larger than ~200 GeV. Neglecting terms of order $m^2_{\tilde{b}_2}/m^2_{\tilde{b}_1}$, the mass of the heavier scalar bottom quark is given as $m^2_{\tilde{b}_1} = m_b X_b/(s_{\tilde{b}} c_{\tilde{b}})$. In order to generate a sufficiently large value of $m_{\tilde{b}_1}$, relatively large values of X_b are required. Since $X_b = A_b - \mu\tan\beta$, these large values of X_b can naturally be obtained for values of $|\mu|$ and A_b of about the squark masses if $\tan\beta \approx |s_{\tilde{b}} c_{\tilde{b}}| m_{\tilde{b}_1}/m_b$, where $m_b \approx 3$ GeV is the $\overline{\rm MS}$ running bottom mass at the weak scale. For heavy $\tilde{b}$ masses of order 400 GeV and $\tilde{b}$ mixing angles of the cases (I,II) this implies values of $\tan\beta \gtrsim 30$. A relatively large value of $\tan\beta$ is also important for the Higgs-mass constraints (see below).

Concerning the constraints from contributions of the $\tilde{t}$ and $\tilde{b}$ sector to $\Delta\rho$, the present data leave some room for a small but non-zero contribution to $\Delta\rho$. We use 2×10^{-3} as upper bound for SUSY contributions [1]. We have checked that a limit on $\Delta\rho^{\rm SUSY}$ as tight as 3×10^{-4} does not qualitatively change our results.

Regarding the Higgs mass constraints, beyond the tree-level, the main correction to m_h stems from the t–$\tilde{t}$ sector, and for large values of $\tan\beta$ also from the b–$\tilde{b}$ sector. For a light $\tilde{t}$ and $\tilde{b}$ sector, the Higgs tends to be light. For large values of $\tan\beta$ and M_A, however, the Higgs may be heavy enough to avoid present LEP constraints, but tends naturally to be in the range 110–120 GeV. Concerning the bounds obtained at LEP2, one should note that the presence of an off-diagonal term in the $\tilde{b}$ mass matrix of order of the square of the weak scale (i.e. a large value of $(\mu\tan\beta)$) is associated with a large coupling of these sbottoms to the lightest $\mathcal{CP}$-even Higgs boson. Therefore, for large $\tan\beta$ the width of the decay of this Higgs into sbottoms,

$$\Gamma(h \to \tilde{b}_2\bar{\tilde{b}}_2) \sim G_F\sqrt{2}(m_b\mu\tan\beta s_{\tilde{b}}c_{\tilde{b}})^2/(8\pi m_h), \qquad (3)$$

will be much larger than the corresponding one into bottoms, $\Gamma(h \to b\bar{b}) \sim G_F\sqrt{2}(m_h m_b^2)/(4\pi)$.

The limits from LEP will depend strongly on the decay modes of the sbottoms. As a conservative bound, we adopt the present lower bound on the Higgs boson of the SM at LEP2, $m_h \gtrsim 113.3$ GeV [8]. This is consistent with the assumption that the light $\tilde{b}$ decay channels are similar to the bottom quark ones. However, if it decays mostly into down (or strange) quarks and missing energy, much weaker Higgs mass bounds would be obtained.

For the case of a very light $\tilde{b}$, with non-negligible component on the left-handed $\tilde{b}$, the constraint from the ρ-parameter demands a relatively light $\tilde{t}$. The simultaneous requirement that the lightest $\mathcal{CP}$-even Higgs mass should be above the experimental bound leads to strong restrictions in the $\tilde{t}$ sector. In the numerical analysis of the allowed MSSM parameter space we use the following parameters: $m_t = 174.3$ GeV, $m_b = 3$ GeV, $\tan\beta = 40$, $M_A = 800$ GeV, $m_{\tilde{g}} = 200$ GeV, $\mu = \pm 250$ GeV, $M_2 = 200$ GeV. We have chosen a large value for M_A, yielding that the upper bound for m_h within this scenario is only weakly dependent on the actual value of this parameter [11]. The dependence on $m_{\tilde{g}}$, μ and M_2 is also weak. The unconstrained parameters in the $\tilde{t}$ sector have been varied, taking into account the SU(2) relation $M_{\tilde{t}_L} = M_{\tilde{b}_L}$.

The theoretical predictions for m_h employed here are based on the two-loop results of Refs. [9, 10, 12], implemented in the programs *FeynHiggs* [13] and *subhpole* [10, 12]. We have checked that the results for m_h obtained with the two programs are close to each other and therefore lead to similar conclusions. The SUSY contributions to $\Delta\rho$, including leading two-loop contributions [14], have been evaluated with the program *FeynHiggs*.

The analysis is performed for the two cases (I) and (II) defined above. It should be emphasized that, although the case (I) seems highly constrained, if one started from just the requirement of a small $\tilde{b}$ mass and a vanishing coupling to the Z, and one required the left-handed $\tilde{t}$ mass to be larger than the right-handed $\tilde{t}$ one, most solutions to the precision electroweak measurements and Higgs mass constraints lead to a small coupling of the lightest $\tilde{t}$ to the Z.

In Fig. 1 the allowed parameter regions for $m_{\tilde{t}_1}$ and $m_{\tilde{t}_2}$ for the cases (I) and (II) are shown, obeying the m_h and $\Delta\rho^{\rm SUSY}$ constraints. For both cases a considerable part of the parameter space is consistent with the constraints. In case (I) the allowed regions are 70 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 220 GeV, 450 GeV $\lesssim m_{\tilde{t}_2} \lesssim$ 600 GeV. In case (II) the $\tilde{t}$ masses obey the constraints for 70 GeV $\lesssim m_{\tilde{t}_1} \lesssim$ 330 GeV, 400 GeV $\lesssim m_{\tilde{t}_2}$, and we have considered only values of $m_{\tilde{t}_2} \leq 1000$ GeV.

In Fig. 2 the allowed parameter regions for m_h are shown. In case (I) the lightest $\mathcal{CP}$-even Higgs will be always lighter than 120 GeV, while in the case (II) slightly larger values of m_h can be obtained, $m_h \lesssim 123$ GeV. Since the width of the Higgs in this case will be much larger than the SM Higgs width, the branching ratio of its decays into photons will be small, and, for example, the LHC will not be able to use the photon channel to search for the Higgs. If the light sbottoms decay in a way similar to the b quarks, the Higgs, if not discovered at LEP2, may be observed at the Tevatron or at the LHC using its associated production with the gauge bosons [15] or with the top quark [16, 17].

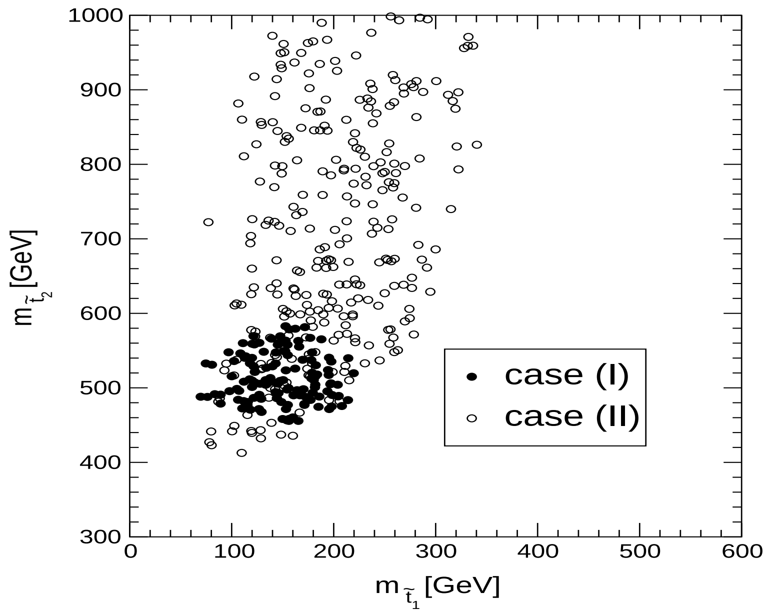

Figure 1: Regions in the $m_{\tilde{t}_1}$–$m_{\tilde{t}_2}$ plane for the cases (I) and (II), allowed by the requirements $m_h \gtrsim 113.3$ GeV and $\Delta\rho^{\rm SUSY} < 0.002$. (See text for the other parameters.)

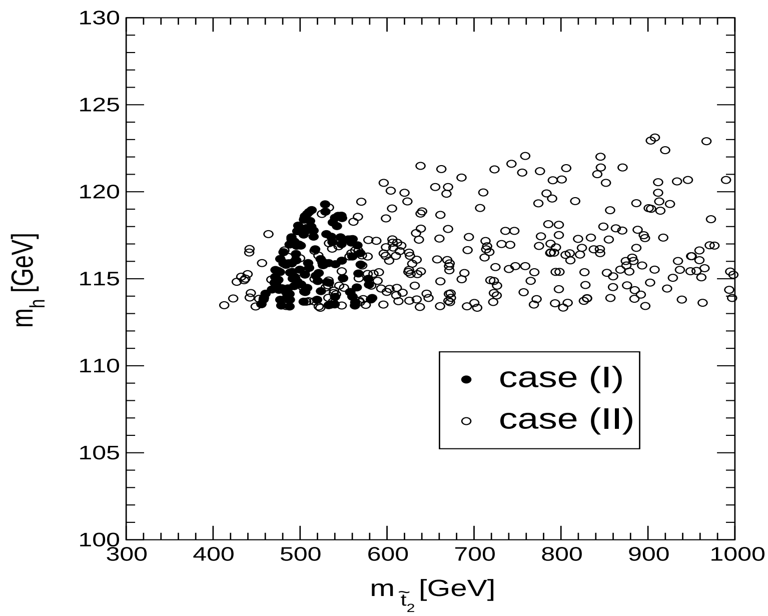

Figure 2: Regions in the $m_{\tilde{t}_2}$–m_h plane for the cases (I) and (II), allowed by the requirements $m_h \gtrsim 113.3$ GeV and $\Delta\rho^{\rm SUSY} < 0.002$. (See text for the other parameters.)

Observe that stop masses below or about 100 GeV are constrained by LEP data, in particular in case II, for which no constraints on the $Z\tilde{t}_1\tilde{t}_2$ coupling were imposed, therefore allowing for larger contributions from the Z exchange channel to the stop production cross section. As it is clear from Fig. 1 and Fig. 2 only small changes would be obtained if this bound were applied.

In conclusion, a light $\tilde{b}$ within the MSSM can at present not be ruled out by the electroweak precision data and the Higgs mass constraints from LEP2. Even in the most extreme case of vanishing couplings of the lightest $\tilde{t}$ and the lightest $\tilde{b}$ to the Z, an allowed parameter region within the MSSM is found, resulting in an upper value for m_h, $m_h \lesssim 120$ GeV, for $m_t = 174.3$ GeV. If the light $\tilde{b}$ decays like a bottom quark and has a small but non-vanishing coupling to the Z boson, this would contribute to the Z peak observables, yielding in fact a slightly better agreement with the experimental data compared to the SM. In this case m_h is restricted to be $m_h \lesssim 123$ GeV. An important finding in both cases is that the scenario with a $\tilde{b}$ being almost mass-degenerate to the bottom quark requires, in general, also a light $\tilde{t}$ whose mass is typically about the top quark mass. If it is light enough, such a $\tilde{t}$ should be accessible at RunII at the Tevatron. If the sbottoms decay similar to bottom quarks, these light stops and sbottoms could contribute to the third generation quark cross sections, whereas the measured Tevatron cross sections are, in general, larger than the SM expectations [18]. Besides promising very interesting phenomenological implications for RunII of the Tevatron and the LHC, a scenario with a light $\tilde{b}$ could also be studied in detail at the upcoming b factories.

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