

## What if the Higgs Boson Weighs 115 GeV?

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### Abstract

If the Higgs boson indeed weighs about 114 to 115 GeV, there must be new physics beyond the Standard Model at some scale  $\lesssim 10^6$  GeV. The most plausible new physics is supersymmetry, which predicts a Higgs boson weighing  $\lesssim 130$  GeV. In the CMSSM with  $R$  and CP conservation, the existence, production and detection of a 114 or 115 GeV Higgs boson is possible if  $\tan\beta \gtrsim 3$ . However, for the radiatively-corrected Higgs mass to be this large, sparticles should be relatively heavy:  $m_{1/2} \gtrsim 250$  GeV, probably not detectable at the Tevatron collider and perhaps not at a low-energy  $e^+e^-$  linear collider. In much of the remaining CMSSM parameter space, neutralino- $\tilde{\tau}$  coannihilation is important for calculating the relic neutralino density, and we explore implications for the elastic neutralino-nucleon scattering cross section.

At the time of writing, the LEP experiments are not yet able to exclude the possibility that the Higgs boson might weigh about 114 to 115 GeV, and there are several candidate events [1] for its production in association with a  $Z$  boson [2], that may be appearing above the Standard Model background. It is hoped that the high-energy LEP luminosity used for the presentations [1] may be increased substantially before the accelerator is closed by the end of this year, enabling the possible signal to be either strengthened or diluted significantly. However, it is unlikely that LEP will be able to answer definitively the question whether there exists a Higgs boson weighing about 114 to 115 GeV. Indeed, a definitive answer may not be available for several years, until either the Fermilab Tevatron collider accumulates enough luminosity [3] and/or the LHC starts up [4].

Even in these circumstances, it is tempting to speculate on the interpretation of a possible discovery of a Higgs boson weighing around 114 to 115 GeV. This might even serve the useful purpose of suggesting other signatures that could be correlated with the existence of such a Higgs boson, whose appearance (absence) might help to confirm (cast doubt upon) any evidence for its existence.

The first clear statement that can be made is that *if* the Higgs boson weighs about 114 to 115 GeV, *there must be new physics at an energy scale*  $\ll M_P$ . This is because of the renormalization of the effective Higgs potential by the Higgs-top interaction  $\lambda_t \bar{t}t\phi$  (related to the known value of  $m_t$ ) and the Higgs self-interaction  $\lambda\phi^4$  (related to the putative value of  $m_H$ ). It is well known that, if either  $\lambda_t$  and/or  $\lambda$  is too large, the renormalization-group equations (RGEs) may cause the couplings to blow up, becoming non-perturbative or even infinite at some energy scale below  $M_P$  [5]. Alternatively, the desired electroweak vacuum may become unstable if  $\lambda$  is too small, since  $\lambda_t$  tends to drive the effective Higgs potential  $V(\phi)$  *negative* at large  $|\phi|$  [6, 7]. Self-renormalization by  $\lambda$  tries to counteract this effect of  $\lambda_t$ , but is overcome if  $\lambda$  is too small. Requiring the absence of a second, undesirable minimum of the effective Higgs potential for any value  $|\phi| \leq \Lambda$  therefore provides a lower limit on  $\lambda$ , and hence  $m_H$ , that depends on  $\Lambda$ ,  $m_t$  and (via higher orders in the RGEs) the strong gauge coupling  $\alpha_s$ . Conversely, given  $m_H$ , and hence  $\lambda$ , one has an upper limit on the scale  $\Lambda$  up to which the Standard Model Higgs potential may remain stable, which depends relatively on the precise values of  $m_t$  and  $\alpha_s$ . If indeed  $m_H = 115$  GeV, one finds that [6]

$$\Lambda \lesssim 10^6 \text{ GeV} \tag{1}$$

for the default values  $m_t = 175$  GeV and  $\alpha_s(m_Z) = 0.118$ <sup>1</sup>. Therefore, *there must be new*

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<sup>1</sup>The upper limit (1) increases (decreases) by about an order of magnitude for  $m_t = 170(180)$  GeV, while being less sensitive to  $\alpha_s(m_Z)$  in the range 0.115 - 0.121.

physics at some scale  $\lesssim 10^6$  GeV that averts this instability of the Standard Model Higgs potential.

It has often been suggested that new physics should be expected at some scale  $\lesssim 1$  TeV, in order to stabilize the gauge hierarchy. Prominent among early suggestions was that of technicolour, new strong interactions that would generate a composite scalar particle weighing about 1 TeV [8]. One generally expects composite models to predict Higgs bosons much heavier than whatever LEP might be seeing, and technicolour bears this out. Technicolour models generally also include light pseudoscalar particles, but these would not be produced copiously in association with a  $Z$  boson [9]. Another class of composite Higgs models invokes  $\bar{t}t$  condensation, but these models also predict [10] a Higgs boson that would be heavier than what LEP might be seeing. In the absence of any viable composite Higgs model, we pursue the hypothesis that the Higgs is elementary, as generally expected for small  $m_h$ , in which case the most plausible new TeV-scale physics is supersymmetry [11].

Circumstantial evidence for supersymmetry around this scale has already been provided by the possible grand unification of the gauge couplings, which works fine if sparticles weighing around 1 TeV are included in their RGEs [12]. Moreover, the minimal supersymmetric extension of the Standard Model (MSSM) predicts the existence of at least one neutral Higgs boson weighing  $\lesssim 130$  GeV [13, 14], perfectly consistent with the possible direct LEP observation [1] and with indirect indications from precision electroweak data of a relatively light Higgs boson [15]:  $m_h = 62_{-30}^{+53}$  GeV, with the one-sided 95% confidence-level upper limit  $m_h < 170$  GeV <sup>2</sup>. Therefore, in the rest of this paper we concentrate on supersymmetric interpretations of the possible LEP observation of a Higgs boson weighing 114 to 115 GeV. We assume the conservation of  $R$  parity, so that the lightest neutralino  $\chi$  may constitute the cold dark matter postulated by astrophysicists and cosmologists [17]. We assume also CP conservation for the tree-level MSSM parameters, simplifying calculations of the Higgs masses [18] and dark matter properties [19].

As we show in this paper, the possible observation of a Higgs boson weighing 114 to 115 GeV would constrain significantly the sparticle spectrum in such models <sup>3</sup>, and hence the prospects for sparticle detection. The principal uncertainty in predicting the sparticle mass spectrum is due to the lack of precision in the measurement of  $m_t$ , which is also manifest in our discussion of the potential of an  $e^+e^-$  linear collider to discover supersymmetry.

We assume a minimal supergravity-inspired model of soft supersymmetry breaking, namely

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<sup>2</sup>The central value may be increased by  $\sim 30$  GeV if new data from BES are used to evaluate  $\alpha_{em}(M_Z)$  [15]: see also [16].

<sup>3</sup>We phrase our discussion optimistically in terms of the observation of such a Higgs boson: our lower limits on the sparticle spectrum also apply if LEP only establishes a lower limit  $m_h \geq 114$  GeV.

the constrained MSSM (CMSSM) or minimal supergravity (mSUGRA), in which universal gaugino masses  $m_{1/2}$ , scalar masses  $m_0$  (including those of the Higgs multiplets) and trilinear supersymmetry breaking parameters  $A$  are input at the supersymmetric grand unification scale <sup>4</sup>. In this framework, the Higgs mixing parameter  $\mu$  can be derived from the other MSSM parameters by imposing the electroweak vacuum conditions for any given value of  $\tan\beta$ .

Many ingredients in our analysis are apparent from Fig. 1, including the range of  $(m_{1/2}, m_0)$  where the relic neutralino density is in the range of cosmological interest:  $0.1 \lesssim \Omega_\chi h^2 \lesssim 0.3$ , the excluded region at low  $m_0$  and large  $m_{1/2}$  where the lightest sparticle is a charged  $\tilde{\tau}$ , and a region at low  $m_{1/2}$  for  $\mu < 0$  that is excluded [21] by the experimental value of  $b \rightarrow s\gamma$  decay [22]. We recall that the mass of the lightest neutralino  $m_\chi \simeq 0.4 \times m_{1/2}$  over most of the gaugino parameter region of interest. As discussed in [23], there are important regions of the  $(m_{1/2}, m_0)$  plane where the present electroweak vacuum is at best metastable against decay into a vacuum where charge and colour are broken (CCB) [24]. We do not address here the question of the lifetime of the vacuum, which is much longer than that in the Standard Model for light Higgs mass. However, we do note that there are regions at large  $m_0$  and/or  $m_{1/2}$  that are completely stable against decay into a CCB vacuum [24, 23].

Through radiative corrections [13, 14], the mass  $m_h$  of the lightest Higgs boson depends strongly on  $m_{1/2}$ , but is almost independent of  $m_0$ , at least over the range of  $m_0$  allowed by the upper limit  $\Omega_\chi h^2 \lesssim 0.3$  on the relic neutralino density, as can also be seen in Fig. 1. The Higgs mass  $m_h$  also depends significantly on  $m_t$ , varying typically by  $\pm 3$  GeV, as  $m_t$  is varied by  $\pm 5$  GeV around its nominal value  $m_t = 175$  GeV. The uncertainty in  $m_t$  carries through to our final bounds on the sparticle spectrum <sup>5</sup>, as discussed later. There are believed to be similar uncertainties in  $m_h$  associated with the treatment of higher-order QCD corrections to  $m_t$  [14]. Other uncertainties, associated for example with higher-order electroweak effects, are believed to be  $\mathcal{O}(1)$  GeV. We recall that the preferred range of  $m_h$  suggested by LEP is from 114 to 115 GeV [1]. We derive our lower (upper) limits on the sparticle spectrum by finding the values of  $m_{1/2}$  required to give  $m_h \geq 113$  ( $\leq 116$ ) GeV for  $m_t = 170, 175$  and 180 GeV, so as to include some allowance for these uncertainties.

The most important remaining uncertainty is that in  $A$ . For definiteness, henceforth we use as default value  $A = 0$  at the input scale, motivated theoretically by no-scale supergravity models [26], discussing later the effect of varying  $A$  over a range of a few units in  $m_{1/2}$ . Panels

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<sup>4</sup>It would be an interesting exercise to make a similar analysis in the context of gauge- or anomaly-mediated models [20], but this lies beyond the scope of our work.

<sup>5</sup>On the other hand, the dark matter density calculations are relatively insensitive to  $m_t$ .

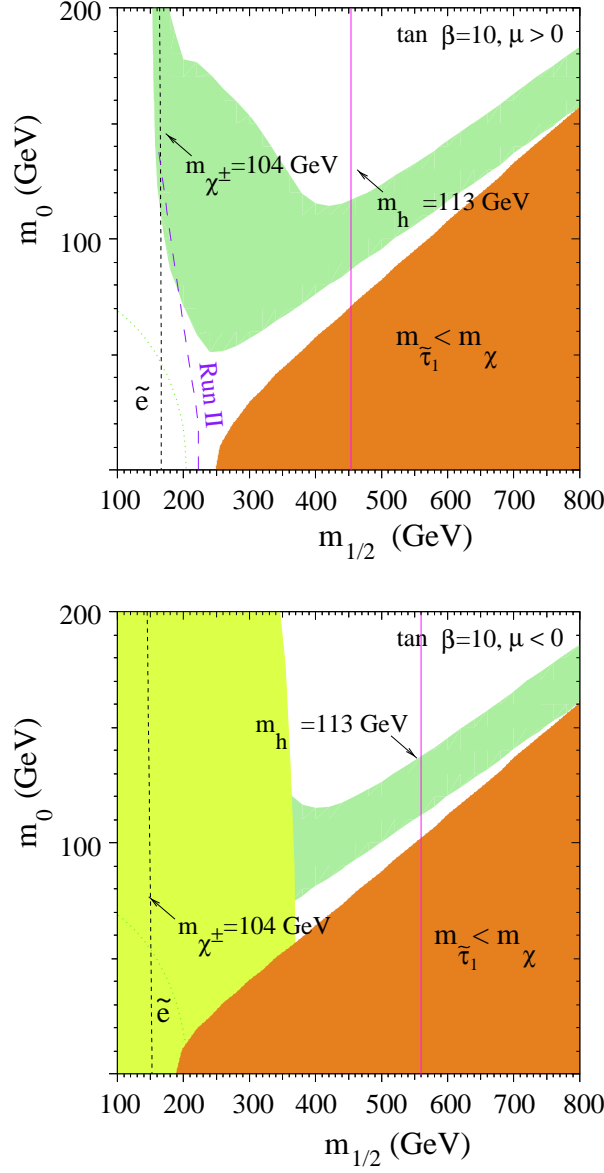


Figure 1: The  $m_{1/2}, m_0$  plane for the CMSSM with  $\tan \beta = 10$ ,  $A = -m_{1/2}$ , and (a)  $\mu > 0$ , (b)  $\mu < 0$ , showing the region preferred by the cosmological relic density constraint  $0.1 \leq \Omega_\chi h^2 \leq 0.3$  (medium, green shading), the excluded region where  $m_{\tilde{\tau}_1} < m_\chi$  (dark, brown shading), and the region disallowed by our  $b \rightarrow s\gamma$  analysis (light shading) [23]. Also shown as a near-vertical line is the contour  $m_h = 113$  GeV for  $m_t = 175$  GeV. For comparison, we also exhibit the reaches of LEP 2 searches for charginos  $\chi^\pm$  and selectrons  $\tilde{e}$ , as well as the estimated reach of the Fermilab Tevatron collider for sparticle production [25].

(a) and (b) of Fig. 2 show, for  $\mu < 0$  and  $> 0$ , contours of the values of  $m_{1/2}$  (vertical axis) required to obtain any given value of  $m_h$  (horizontal axis) for  $\tan\beta = 3, 5$  and  $20$  (from left to right) and  $m_t = 170, 175, 180$  GeV (also from left to right). We have truncated the vertical axis at  $m_{1/2} = 1400$  GeV, which corresponds approximately to the maximum value of  $m_\chi$  allowed by cosmology, which is attained when  $m_\chi = m_{\tilde{\tau}_R}$  for  $\Omega_\chi h^2 = 0.3$ , including coannihilation effects [27, 28]. Since the curves for  $\tan\beta = 10, 20$  are rather similar, for clarity we do not plot any curves for  $\tan\beta = 10$ , nor for  $\tan\beta > 20$ . We note also that the high- $\tan\beta$  curves are relatively insensitive to the sign of  $\mu$ . On the other hand, the curves are quite different for smaller  $\tan\beta$ , particularly  $\tan\beta = 3$ . The vertical bands in Fig. 2 correspond to  $113 \text{ GeV} \leq m_h \leq 116 \text{ GeV}$ , including the ‘observed’ range of 114 to 115 GeV, combined with a theoretical error as discussed above. Requiring  $m_h \geq 113$  GeV clearly imposes a non-trivial lower limit on  $m_{1/2}$  and hence the sparticle masses, as we discuss in more detail below.

Fig. 3 illustrates the effect of varying  $A$ . We see that, for given values of  $m_{1/2}$ ,  $\tan\beta$  and the sign of  $\mu$ , slightly lower values of  $m_h$  are found for  $A = -m_{1/2}$  than for  $A = 0$ . Conversely, somewhat higher values of  $m_h$  are found for  $A = +2m_{1/2}$ .<sup>6</sup> We note that the differences in  $m_h$  for these different values of  $A$  and  $m_t = 175$  GeV are typically less than those found by fixing  $A$  and increasing (decreasing)  $m_t$  to 180(170) GeV. Therefore, in the following we restrict our attention to the value  $A = 0$  that we prefer on theoretical grounds [26], varying  $m_t$  between 170 and 180 GeV.

It is apparent from Fig. 1 that for  $\tan\beta = 10$  the LEP ‘value’ of  $m_h$  pushes  $m_{1/2}$  up into the  $\chi - \tilde{\tau}$  coannihilation region, which extends up to  $m_{1/2} \sim 1400$  GeV [27]. The necessity of including coannihilation effects is even more pronounced for lower  $\tan\beta$ , since then the LEP ‘value’ of  $m_h$  pushes  $m_{1/2}$  even higher. The  $m_h$  constraint is more relaxed for larger  $\tan\beta$ , but then, for  $\mu < 0$ , the  $b \rightarrow s\gamma$  constraint also pushes  $m_{1/2}$  into the coannihilation region<sup>7</sup>.

We show in Fig. 4(a) the lower bounds on  $m_{1/2}$  obtained assuming  $m_h \geq 113$  GeV, for  $\mu > 0$  (solid, red lines) and  $\mu < 0$  (dashed, blue lines), and  $m_t = 170, 175$  and  $180$  GeV (from bottom to top). We note immediately a lower bound

$$m_{1/2} \gtrsim 240 \text{ GeV}, \quad (2)$$

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<sup>6</sup>We have also studied the case  $A/m_{1/2} = 4$ , for which the trend to higher  $m_h$  continues. This is near the maximum value of  $A$  possible for  $\tan\beta = 3$  or  $5$ , and is disallowed for  $\tan\beta = 20$ , because of troubles with a light or tachyonic  $\tilde{\tau}$  [23].

<sup>7</sup>There has recently been a suggestion [29] that the  $b \rightarrow s\gamma$  constraint at large  $\tan\beta$  may be more important for  $\mu > 0$ , but this is not supported by a recent NLO analysis [30].

corresponding to a lower limit on the lightest neutralino  $\chi$  of

$$m_\chi \gtrsim 95 \text{ GeV}, \quad (3)$$

which is saturated for  $\mu > 0$ ,  $\tan\beta \sim 30$ , and  $m_t = 180 \text{ GeV}$ . With the nominal value  $m_t = 175 \text{ GeV}$  we would obtain  $m_{1/2} \gtrsim 310 \text{ GeV}$  ( $m_\chi \gtrsim 125 \text{ GeV}$ ). The lower bound on  $m_{1/2}$  is not very sensitive to the sign of  $\mu$ , particularly at large  $\tan\beta$  as can be discerned from Fig. 4(a). On the other hand, the lower bound on  $m_{1/2}$  rises steeply for  $\tan\beta \lesssim 10$ , where it depends more on the sign of  $\mu$ . Recalling that  $m_{1/2} \sim 1400 \text{ GeV}$  is the maximum value of  $m_\chi$  allowed by cosmology [27, 28], we infer a lower bound

$$\tan\beta \gtrsim 3 \quad (4)$$

attained again for  $\mu > 0$  and  $m_t = 180 \text{ GeV}$ . The corresponding lower limit for the nominal  $m_t = 175 \text{ GeV}$  would be  $\tan\beta \gtrsim 4$ . For  $\mu < 0$ , the corresponding limits are  $\tan\beta \gtrsim 4$  (5) for  $m_t = 180$  (175).

As we see in Fig. 4(b), it is also possible in some cases to derive an upper bound on  $m_{1/2}$ , obtained by requiring  $m_h \leq 116 \text{ GeV}$ . The upper bound is relatively insensitive to the sign of  $\mu$  at large  $\tan\beta$ , and more sensitive at lower  $\tan\beta$ . However, its greatest sensitivity is to the value of  $m_t$ , as seen in Fig. 4(b) for the cases  $m_t = 175$  and  $180 \text{ GeV}$ : the corresponding maximum values of  $m_{1/2}$  are  $\sim 650$  and  $400 \text{ GeV}$  for large  $\tan\beta$ , respectively. If  $m_t = 170 \text{ GeV}$ , the upper limit on  $m_{1/2}$  in fact exceeds the upper value  $\sim 1400 \text{ GeV}$  allowed by the cosmological relic density, so this case is not shown in Fig. 4(b).

The Tevatron collider may well be able to confirm at the  $3\text{-}\sigma$  level or refute the LEP ‘observation’ of a Higgs boson with about  $3fb^{-1}$  of luminosity in each of CDF and D0 [3]. On the other hand, the lower bound (2) does not offer much encouragement for  $\tilde{q}$  and  $\tilde{g}$  searches at the Tevatron collider [31], since one expects

$$m_{\tilde{q}} \gtrsim 600 \text{ GeV}, \quad m_{\tilde{g}} \gtrsim 700 \text{ GeV} \quad (5)$$

for  $m_{1/2} \gtrsim 240 \text{ GeV}$ <sup>8</sup>. The search for associated production of charginos and neutralinos may offer brighter prospects [25], but a definite conclusion on this would require a more detailed study than is currently available. Examples of the estimated Tevatron sensitivity in this channel are shown in Fig. 1 [31]. We see that, in these particular cases, the chargino/neutralino process is also expected to be unobservable<sup>9</sup>. However, ATLAS and

<sup>8</sup>The third-generation squarks might be somewhat lighter, because of mixing.

<sup>9</sup>Less glamorously, an improved measurement of  $m_t$  from the Tevatron would be a significant contribution to pinning down the interpretation of the LEP Higgs ‘signal’.

CMS at the LHC should be able to detect both the Higgs boson and sparticles with high significance [4].

A Higgs boson weighing 114 to 115 GeV would be a bonanza for a sub-TeV linear  $e^+e^-$  collider (LC), which would produce it copiously and study its properties in detail [32]. However, its prospects for detecting supersymmetry would depend on the threshold for producing sparticle pairs [33], for which the best prospects may be sleptons:

$$m_{\tilde{\ell}_R}^2 \simeq m_0^2 + 0.15m_{1/2}^2, \quad m_{\tilde{\ell}_L}^2 \simeq m_0^2 + 0.52m_{1/2}^2. \quad (6)$$

and charginos  $\chi^\pm$ . The upper bound on  $m_{1/2}$  imposed by the cold dark matter constraint  $\Omega_\chi h^2 \leq 0.3$  was used previously to estimate the maximum energy required by a LC to be sure of seeing supersymmetry, namely  $E_{cm} \simeq 1.25$  TeV [33]. Looking back at Fig. 1, in the context of our analysis we see that the conservative way to bound sparticle production from above is first to take the lowest possible value of  $m_{1/2}$ . Then one should choose the lowest value of  $m_0$  for this value of  $m_{1/2}$ , allowing the relic density to fall below  $\Omega_\chi h^2 = 0.1$ , as could occur if there is another source of cold dark matter. Generically, this absolute lower bound  $m_0^{\min}$  is found by requiring  $m_\chi \geq m_{\tilde{\tau}}$ , so as to avoid charged dark matter, but in some cases this is not a constraint, and  $m_0 = 0$  is allowed.

We show in Fig. 5 as thick lines the conservative upper limits on the sum of the production cross sections for  $\tilde{\ell}^+\tilde{\ell}^-$  and chargino pairs found in this way. The kinks in the curves reflect the different  $\tilde{\ell}_{L,R}$  and  $\chi_i^\pm$  thresholds. There are in general three lines for each choice of  $\tan\beta$ , the sign of  $\mu$  and  $m_t$ , corresponding to the values of  $m_0$  that yield  $\Omega_\chi h^2 = 0.3$  and 0.1, and the lowest value  $m_0^{\min}$ , disregarding the relic density. The latter generally gives the largest cross sections of all. We see in panel (a) of Fig. 5, for  $\tan\beta = 20$  and  $\mu > 0$ , that in this case a LC with  $\sqrt{s} = 500$  GeV would be well placed to discover supersymmetry, *if  $m_{1/2}$  is close to its minimum value*, whatever the value of  $m_t$ . Although panel (b) for  $\tan\beta = 20$  and  $\mu < 0$  is qualitatively similar, we see that in this case the discovery of supersymmetry might be possible *only if  $m_t \geq 175$  GeV*. Panel (c) for  $\tan\beta = 5$  and  $\mu > 0$  is an example where the discovery of supersymmetry might be possible with a  $\sqrt{s} = 500$  GeV LC only if  $m_t = 180$  GeV, and panel (c) for  $\tan\beta = 5$  and  $\mu < 0$  is an example where discovery would not be possible for any of the values of  $m_t$  studied.

The thinner lines in Fig. 5 correspond to the maximum values of  $m_{1/2}$  discussed earlier, corresponding to  $m_h \lesssim 116$  GeV. In panels (a) and (b) for  $\tan\beta = 20$ , only the case  $m_t = 175$  GeV is shown: the thresholds for  $m_t = 170$  GeV are beyond  $\sqrt{s} = 1200$  GeV, and those for  $m_t = 180$  GeV are similar to the curves for minimal  $m_{1/2}$  and  $m_t = 175$  GeV. Discovery of supersymmetry with a  $\sqrt{s} = 500$  GeV LC could be ‘guaranteed’ only if  $m_t = 180$  GeV,



not for  $m_t \leq 175$  GeV. In panels (c) and (d) for  $\tan\beta = 5$ , we see that the discovery of supersymmetry cannot be ‘guaranteed’ for any value of  $m_t$ . In panel (c), the cross sections for the maximum value of  $m_{1/2}$  when  $m_t = 175$  GeV are similar to those for the minimum value of  $m_{1/2}$  when  $m_t = 180$  GeV.

This analysis is not conclusive, but it does suggest that a linear  $e^+e^-$  collider with  $\sqrt{s} = 500$  GeV has a chance of discovering supersymmetric particles. However, its prospects depend on unknowns such as  $m_t$ ,  $\tan\beta$  and the sign of  $\mu$ , and the ‘measurement’ of  $m_h$  does not guarantee success.

We now discuss the impact of combining the ‘observed’ value of  $m_h$  with the measured rate [22] for  $b \rightarrow s\gamma$  decay [21]. For either sign of  $\mu$ , the  $b \rightarrow s\gamma$  constraint excludes a region of the  $(m_{1/2}, m_0)$  plane that extends to larger  $m_{1/2}$  as  $\tan\beta$  increases, as exemplified in Fig. 1(b) for  $\tan\beta = 10, \mu < 0$ . On the other hand, the value of  $m_{1/2}$  required to allow  $m_h \leq 116$  GeV decreases as  $\tan\beta$  increases. Comparing the two constraints, we find for  $m_t = 175$  GeV that

$$\tan\beta \lesssim 25 \tag{7}$$

for  $\mu < 0$ , and for  $m_t = 180$  GeV that  $\tan\beta \lesssim 13(33)$  for  $\mu < 0(> 0)$ . On the other hand, there is no reasonable upper limit on  $\tan\beta$  for  $m_t = 170$  GeV, or for  $m_t = 175$  GeV and  $\mu > 0$ , since the upper bound imposed on  $m_{1/2}$  is beyond the reach of the constraints from  $b \rightarrow s\gamma$ .

We comment finally on the prospects for direct detection of cold dark matter by elastic scattering, within the CMSSM. The lower limit on the lightest neutralino mass suggested by our analysis is  $m_\chi \gtrsim 95$  GeV. This is considerably stronger than was quoted in [23], essentially for two reasons. One is that the sensitivity of the LEP experiments to MSSM Higgs bosons has exceeded our prognostications. More significantly, here we estimate the  $m_h$  sensitivity of the LEP experiments by calculating for each CMSSM parameter choice the corresponding  $ZZh$  coupling strength, whereas previously we (too) conservatively used the prospective LEP limits based on the maximal mixing scenario [34]. In this scenario, the  $ZH$  production cross section may be suppressed by a factor  $\sin^2(\alpha - \beta) \ll 1$ , which we do not find in the CMSSM.

The strengthened lower limit on  $m_\chi$  has the immediate effect of decreasing the maximum elastic scattering cross section attainable in the CMSSM [35], from  $\sim 10^{-4}$  pb to  $\sim 10^{-5}$  pb in the spin-dependent case and  $\sim 10^{-7}$  pb to  $\sim 10^{-8}$  pb in the spin-independent case. However, we emphasize that these upper limits apply for  $\tan\beta \leq 10$ . For larger  $\tan\beta$ , the scalar elastic scattering cross sections may be an order of magnitude larger [36] (though we note that the scalar cross section is most sensitive to  $\tan\beta$  for  $\mu < 0$  where the constraints from  $b \rightarrow s\gamma$

are most restrictive). Larger cross sections may also be obtained if our CMSSM assumption of universal scalar masses at the GUT scale is relaxed [37].

We have shown in this paper how a measurement of the mass of the Higgs boson may provide much valuable information, at least in a particular theoretical context. We re-emphasize that there may well not be a Higgs boson weighing around 115 GeV, that supersymmetry may not exist, that our model-dependent assumptions within the MSSM may be unjustified, that the cold dark matter may not consist of neutralinos, etc. Nevertheless, we hope this paper serves a useful purpose in helping to focus attention on ways in which any Higgs signal might be corroborated by other experiments, in particular those looking for sparticle production at colliders. Even if we must wait several years for the truth about a possible Higgs boson weighing around 115 GeV to emerge, experiments at the Tevatron and elsewhere may aid in the interpretation of the possible ‘signal’.

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## References

- [1] Presentations at the open LEPC seminar, Sept. 5th, 2000:  
ALEPH Collaboration, W.-D. Schlatter,  
<http://alephwww.cern.ch/>;  
DELPHI Collaboration, T. Camporesi,  
[http://delphiwww.cern.ch/~offline/physics\\_links/lepc.html](http://delphiwww.cern.ch/~offline/physics_links/lepc.html);  
L3 Collaboration, J.-J. Blaising,  
<http://l3www.cern.ch/analysis/latestresults.html>;  
OPAL Collaboration, C. Rembser,  
<http://opal.web.cern.ch/Opal/PPwelcome.html>;  
C. Tully, for the LEP Working Group on Higgs boson searches,  
<http://lephiggs.web.cern.ch/LEPHIGGS/talks/index.html>.
- [2] J. Ellis, M.K. Gaillard and D.V. Nanopoulos, Nucl. Phys. **B106** (1976) 292; B.L. Ioffe and V.A. Khoze, Sov. J. Part. Nucl. **9** (1978) 50; B.W. Lee, C. Quigg and H.B. Thacker, Phys. Rev. **D16** (1977) 1519

- [3] M. Carena, S. Mrenna and C. E. Wagner, Phys. Rev. **D62** (2000) 055008; see also H. Frisch, talk at SUSY2K, 8th International Conference on Supersymmetries in Physics, CERN, Geneva, Switzerland, 26 June - 1 July 2000, <http://wwwth.cern.ch/susy2k/susy2kfinalprog.html>.
- [4] ATLAS Collaboration, Detector and Physics Performance Technical Design Report, <http://atlasinfo.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html>; CMS Collaboration, Technical Proposal, <http://cmsinfo.cern.ch/TP/TP.html>.
- [5] L. Maiani, G. Parisi and R. Petronzio, Nucl. Phys. **B136** (1978) 115; N. Cabibbo, L. Maiani, G. Parisi and R. Petronzio, Nucl. Phys. **B158** (1979) 295.
- [6] G. Altarelli and G. Isidori, Phys. Lett. **B337** (1994) 141; J. A. Casas, J. R. Espinosa and M. Quirós, Phys. Lett. **B342** (1995) 171; J. A. Casas, J. R. Espinosa and M. Quirós, Phys. Lett. **B382** (1996) 374.
- [7] T. Hambye and K. Riesselmann, Phys. Rev. **D55** (1997) 7255.
- [8] E. Farhi and L. Susskind, Phys. Rept. **74** (1981) 277.
- [9] J. Ellis, M. K. Gaillard, D. V. Nanopoulos and P. Sikivie, Nucl. Phys. **B182** (1981) 529.
- [10] See, for example, Fig. 3 of C. T. Hill, Phys. Lett. **B266** (1991) 419, and references therein.
- [11] For reviews, see: H.P. Nilles, Phys. Rep. **110** (1984) 1; H.E. Haber and G.L. Kane, Phys. Rep. **117** (1995) 75.
- [12] J. Ellis, S. Kelley and D. V. Nanopoulos, Phys. Lett. **B249** (1990) 441 and Phys. Lett. **B260** (1991) 131; U. Amaldi, W. de Boer and H. Furstenau, Phys. Lett. **B260** (1991) 447; C. Giunti, C. W. Kim and U. W. Lee, Mod. Phys. Lett. **A6** (1991) 1745; P. Langacker and M. Luo, Phys. Rev. **D44** (1991) 817.
- [13] J. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. **B257** (1991) 83; M.S. Berger, Phys. Rev. **D41** (1990) 225; Y. Okada, M. Yamaguchi and T. Yanagida, Prog. Theor. Phys. **85** (1991) 1; Phys. Lett. **B262** (1991) 54; H.E. Haber and R. Hempfling, Phys. Rev. Lett. **66** (1991) 1815.

- [14] For our numerical analysis, we use the results of: H.E. Haber, R. Hempfling and A.H. Hoang, *Zeit. für Phys.* **C75** 539; see also M. Carena, M. Quiros and C.E.M. Wagner, *Nucl. Phys.* **B461** (1996) 407. We have checked that, over the parameter domain we study and within our uncertainties, their results are equivalent to those of M. Carena, H. E. Haber, S. Heinemeyer, W. Hollik, C. E. Wagner and G. Weiglein, hep-ph/0001002.
- [15] LEP and SLD experiments, *A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model*, CERN EP/2000-016, as updated by B. Pietrzyk, Talk at XXXth International Conference on High Energy Physics, 27 July - 2 August, 2000, Osaka, Japan:  
[http://lepewwg.web.cern.ch/LEPEWWG/lepww/talks\\_notes/welcome.html](http://lepewwg.web.cern.ch/LEPEWWG/lepww/talks_notes/welcome.html).
- [16] A. D. Martin, J. Outhwaite and M. G. Ryskin, hep-ph/0008078.
- [17] J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive and M. Srednicki, *Nucl. Phys.* **B238** (1984) 453; see also H. Goldberg, *Phys. Rev. Lett.* **50** (1983) 1419.
- [18] M. Carena, J. Ellis, A. Pilaftsis and C. E. Wagner, hep-ph/0009212, and references therein.
- [19] T. Falk, K.A. Olive, M. Srednicki *Phys. Lett.* **354** (1995) 99; T. Falk and K.A. Olive, *Phys. Lett.* **B375** (1996) 196; *Phys. Lett.* **B439** (1998) 71; T. Ibrahim and P. Nath, *Phys. Rev.* **D58** (1998) 111301; T. Falk, A. Ferstl and K. A. Olive, *Phys. Rev.* **D59** (1999) 055009; *Astropart. Phys.* **13** (2000) 301; U. Chattopadhyay, T. Ibrahim and P. Nath, *Phys. Rev.* **D60** (1999) 063505; S. Khalil and Q. Shafi, hep-ph/9904448.
- [20] G. A. Blair, W. Porod and P. M. Zerwas, hep-ph/0007107.
- [21] M. Ciuchini, G. Degrassi, P. Gambino, G.F. Giudice, *Nucl.Phys.* **B527** (1998) 21; P. Ciafaloni, A. Romanino, A. Strumia, *Nucl.Phys.***B524** (1998) 361; F. Borzumati, C. Greub, *Phys.Rev.***D58** (1998) 074004; M. Ciuchini, G. Degrassi, P. Gambino and G.F. Giudice, *Nucl. Phys.* **B534** (1998) 3.
- [22] CLEO Collaboration, M.S. Alam et al., *Phys. Rev. Lett.* **74** (1995) 2885 and S. Ahmed et al., *CLEO CONF 99-10*; ALEPH Collaboration, R. Barate *et al.*, *Phys. Lett.* **B429** (1998) 169.
- [23] J. Ellis, T. Falk, G. Ganis and K. A. Olive, hep-ph/0004169.

- [24] J. A. Casas, A. Lleyda and C. Munoz, Nucl. Phys. **B471** (1996) 3; H. Baer, M. Brhlik and D. Castano, Phys. Rev. **D54** (1996) 6944; S. Abel and T. Falk, Phys. Lett. **B444** (1998) 427.
- [25] V. Barger and C. Kao, Phys. Rev. **D60** (1999) 115015; K. T. Matchev and D. M. Pierce, Phys. Rev. **D60** (1999) 075004; H. Baer, M. Drees, F. Paige, P. Quintana and X. Tata, Phys. Rev. **D61** (2000) 095007.
- [26] J. Ellis, A. B. Lahanas, D. V. Nanopoulos and K. Tamvakis, Phys. Lett. **B134** (1984) 429; A. B. Lahanas and D. V. Nanopoulos, Phys. Rept. **145** (1987) 1.
- [27] J. Ellis, T. Falk and K. A. Olive, Phys. Lett. **B444**, 367 (1998); J. Ellis, T. Falk, K. A. Olive and M. Srednicki, Astropart. Phys. **13** (2000) 181.
- [28] For recent analyses taking these coannihilation effects into account, see:  
A. B. Lahanas, D. V. Nanopoulos and V. C. Spanos, Phys. Lett. **B464** (1999) 213 and hep-ph/9909497; M. E. Gómez, G. Lazarides and C. Pallis, hep-ph/9907261 and hep-ph/0004028.
- [29] W. de Boer, M. Huber, A. Gladyshev and D. I. Kazakov, hep-ph/0007078.
- [30] C. Degrandi, P. Gambino and G. F. Giudice, hep-ph/0009337.
- [31] See S. Abel *et al.*, Tevatron SUGRA Working Group Collaboration, hep-ph/0003154, and references therein.
- [32] P. M. Zerwas, hep-ph/0003221; and references therein.
- [33] J. Ellis, G. Gani and K. A. Olive, Phys. Lett. **B474** (2000) 314.
- [34] M. Carena, S. Heinemeyer, C. E. Wagner and G. Weiglein, hep-ph/9912223.
- [35] J. Ellis, A. Ferstl and K. A. Olive, Phys. Lett. **B481** (2000) 304.
- [36] E. Accomando, R. Arnowitt, B. Dutta and Y. Santoso, hep-ph/0001019; R. Arnowitt, B. Dutta and Y. Santoso, hep-ph/0008336; A. B. Lahanas, D. V. Nanopoulos and V. C. Spanos, hep-ph/0009065.
- [37] J. Ellis, A. Ferstl and K. A. Olive, hep-ph/0007113.

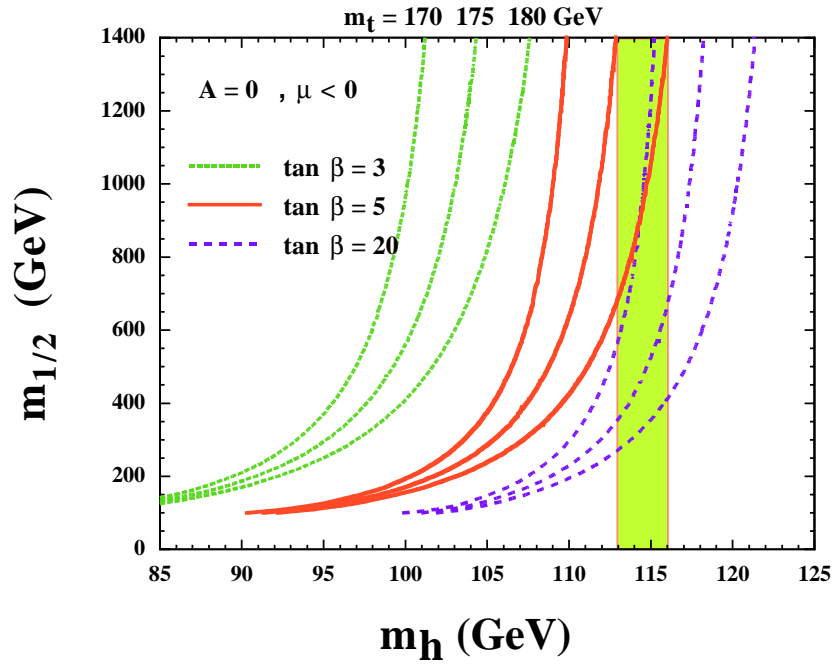
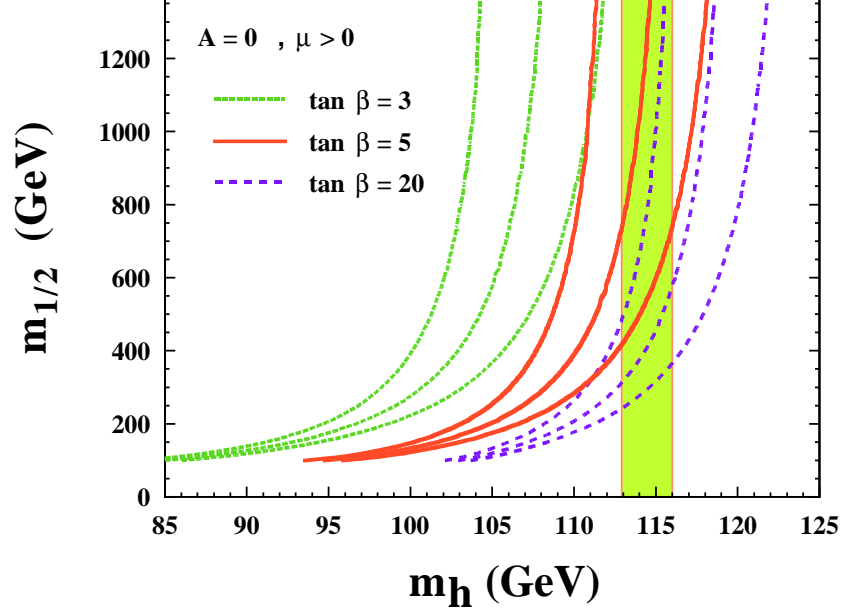


Figure 2: The sensitivity of  $m_h$  to  $m_{1/2}$  in the CMSSM for (a)  $\mu > 0$  and (b)  $\mu < 0$ . The no-scale value  $A = 0$  is assumed for definiteness. The dotted (green), solid (red) and dashed (blue) lines are for  $\tan \beta = 3, 5$  and  $20$ , each for  $m_t = 170, 175$  and  $180 \text{ GeV}$  (from left to right). The lines are relatively unchanged as one varies  $\tan \beta \gtrsim 10$ , where they are also insensitive to the sign of  $\mu$ . The shaded vertical strip corresponds to  $113 \text{ GeV} \leq m_h \leq 116 \text{ GeV}$ .

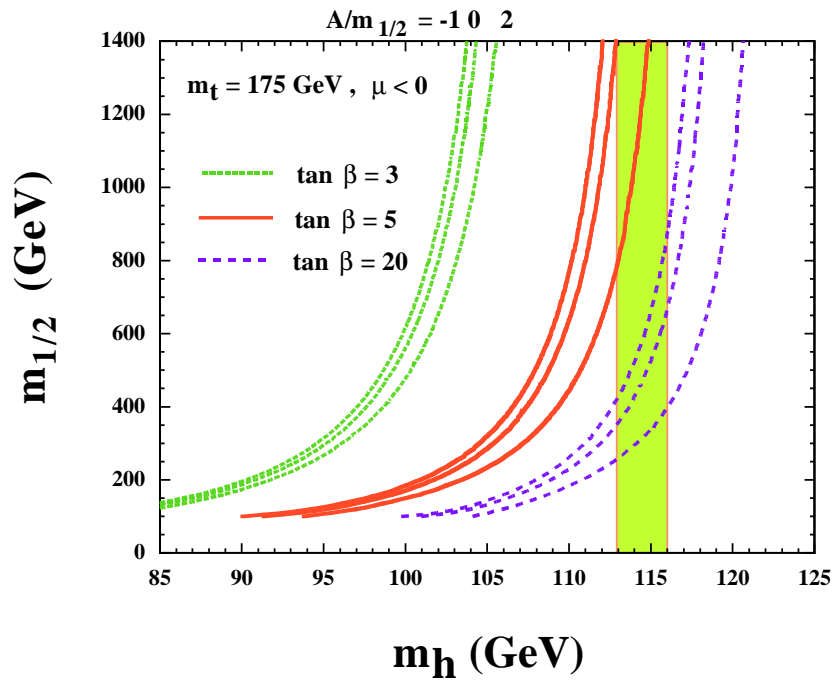
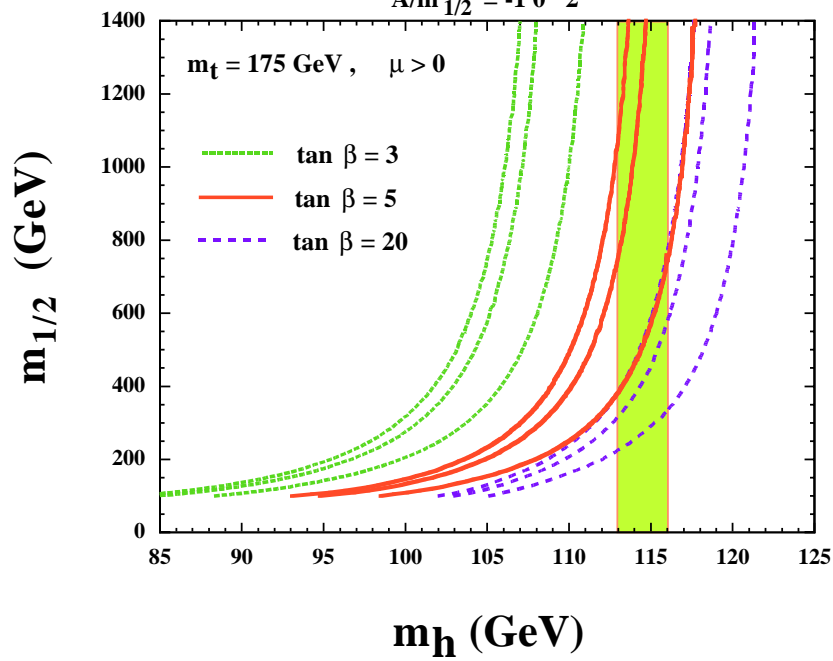


Figure 3: The sensitivity of  $m_h$  to  $m_{1/2}$  in the CMSSM for (a)  $\mu > 0$  and (b)  $\mu < 0$ , this time showing the sensitivity to  $A$ , varied between  $-m_{1/2}, 0$  and  $+2m_{1/2}$  (from left to right). The dotted (green), solid (red) and dashed (blue) lines are again for  $\tan \beta = 3, 5$  and  $20$ , for  $m_t = 175 \text{ GeV}$ . The shaded vertical strip again corresponds to  $113 \text{ GeV} \leq m_h \leq 116 \text{ GeV}$ .

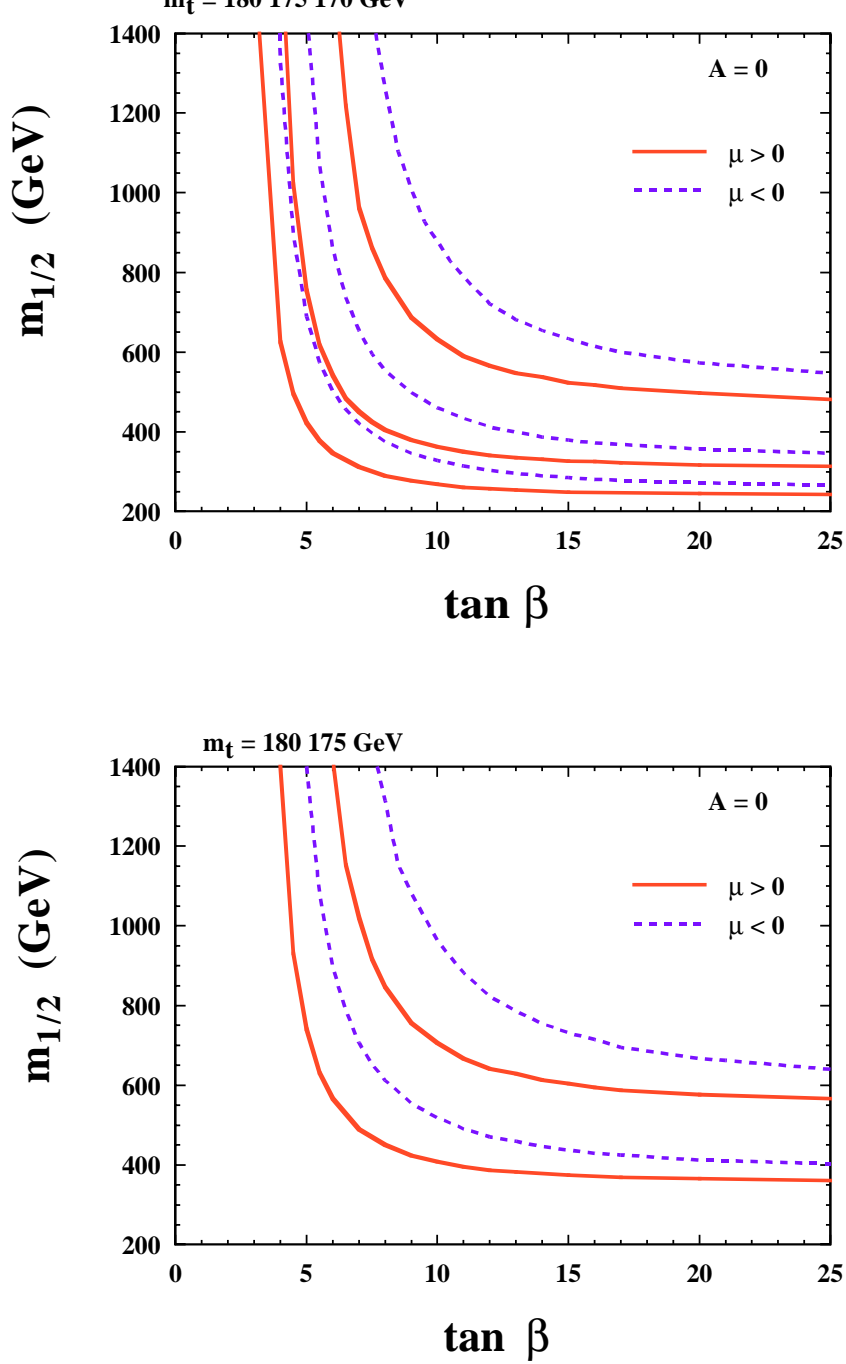


Figure 4: (a) The lower limit on  $m_{1/2}$  required to obtain  $m_h \geq 113$  GeV for  $\mu > 0$  (solid, red lines) and  $\mu < 0$  (dashed, blue lines), and  $m_t = 170, 175$  and  $180$  GeV, and (b) the upper limit on  $m_{1/2}$  required to obtain  $m_h \leq 116$  GeV for both signs of  $\mu$  and  $m_t = 175$  and  $180$  GeV: if  $m_t = 170$  GeV,  $m_{1/2}$  may be as large as the cosmological upper limit  $\sim 1400$  GeV. The corresponding values of the lightest neutralino mass  $m_\chi \simeq 0.4 \times m_{1/2}$ .



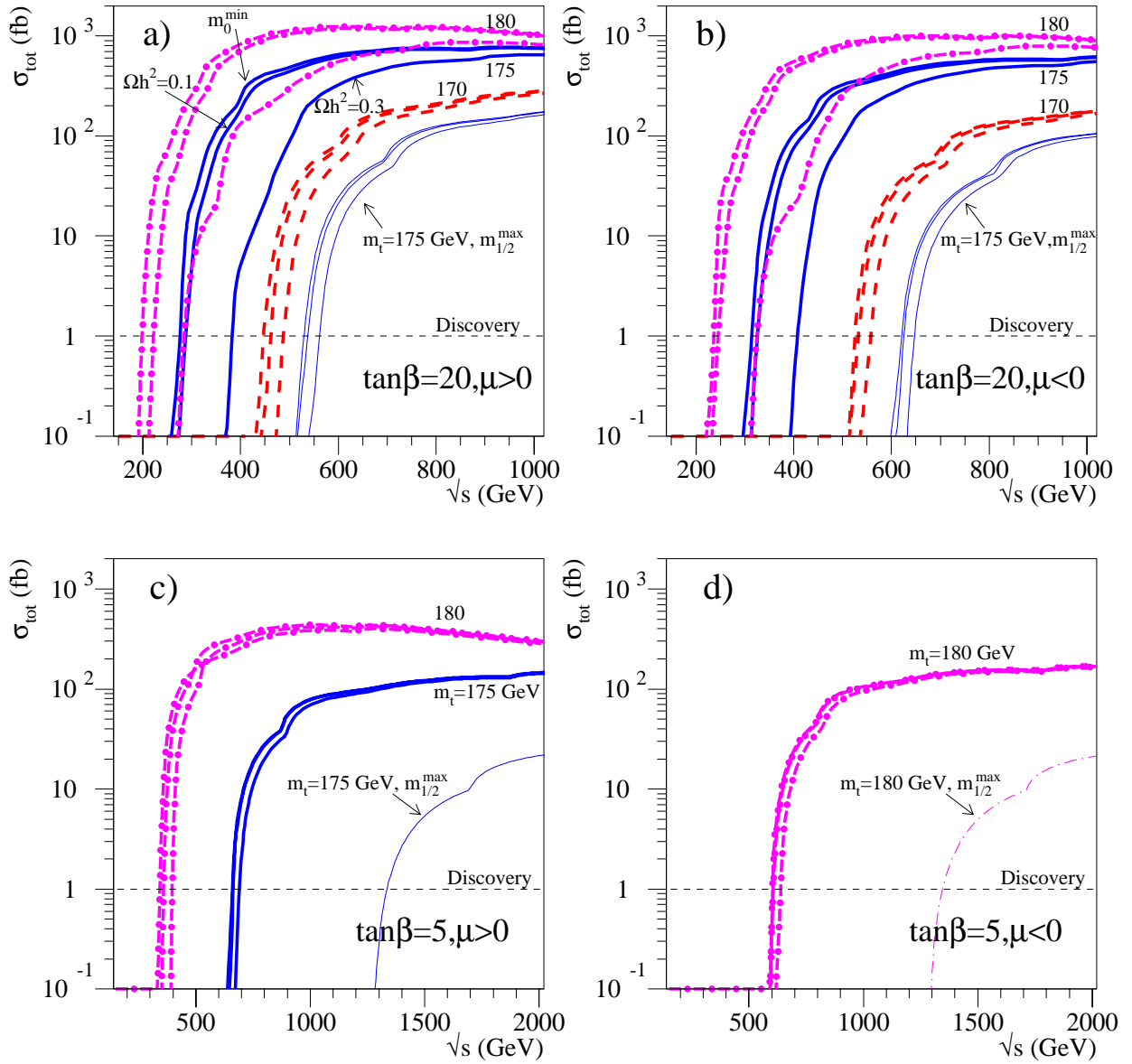


Figure 5: Cross sections for sparticle pair production at a linear  $e^+e^-$  collider, for (a)  $\tan\beta = 20, \mu > 0$ , (b)  $\tan\beta = 20, \mu < 0$ , (c)  $\tan\beta = 5, \mu > 0$  and (d)  $\tan\beta = 5, \mu < 0$ , as functions of the centre-of-mass energy  $\sqrt{s}$ , compared with a nominal discovery limit [33]. The dashed (red), solid (blue) and dot-dashed (pink) lines are for  $m_t = 170, 175$  and  $180$  GeV, respectively. The thicker (thinner) lines are for the minimum (maximum) values of  $m_{1/2}$ . The different lines in each style correspond to different choices of  $m_0$ : those leading to  $\Omega_\chi h^2 = 0.3$  and  $0.1$ , and the lowest allowed value, disregarding the value of the relic density. In panels (c) and (d), the maximum  $m_{1/2} \simeq 1400$  GeV is taken, for which there is only one allowed value of  $m_0$ .