SUSY Predictions for the LHC

S. HEINEMEYER

Instituto de Física de Cantabria (CSIC-UC), Santander, Spain

Abstract

On the basis of frequentist analyses of experimental constraints from electroweak precision data, \((g - 2)\mu\), \(B\) physics and cosmological data, we predict the masses of Higgs bosons and SUSY particles of the constrained MSSM (CMSSM) with universal soft supersymmetry-breaking mass parameters, and a model with common non-universal Higgs masses (NUHM1). In the CMSSM we find preferences for sparticle masses that are relatively light. In the NUHM1 the best-fit values for many sparticle masses are even slightly smaller, but with greater uncertainties. We find that at the 95% C.L. all colored particles are in the reach of the LHC. While the light Higgs boson is bounded from above by \(M_h \lesssim 125\) GeV, the heavy Higgs bosons could well escape the LHC searches, but might be accessible at the ILC.
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Keywords: MSSM, LHC, fit, prediction
PACS: 11.30.Pb; 14.80.Ly; 12.15Lk

INTRODUCTION

Supersymmetry (SUSY) [1,2,3] is one of the favored ideas for physics beyond the Standard Model (SM) that may soon be explored at the Large Hadron Collider (LHC). In several recent papers [4,5,6], we presented results from frequentist analyses of the parameter spaces of the constrained minimal supersymmetric extension of the Standard Model (CMSSM) — in which the soft supersymmetry-breaking scalar and gaugino masses are each constrained to universal values $m_0$ and $m_{1/2}$, respectively (see [6] for a comprehensive list of references) — and the NUHM1 — in which the soft supersymmetry-breaking contributions to the Higgs masses are allowed a different but common value (see [6] for a comprehensive list of references). Other statistical analyses in these models can be found in [7,8,9,10,11,12,13,14,15,16,17,18] and Markov Chain Monte Carlo (MCMC) analyses in [19,20,21,22,23,24,25,26,27,28,29,30,31,4,32,33,34,35].

Here we review the results presented in [6]. They include the parameters of the best-fit points in the CMSSM and the NUHM1, as well as the 68 and 95% C.L. regions applying the phenomenological, experimental and cosmological constraints. These include precision electroweak data, the anomalous magnetic moment of the muon, $(g-2)_\mu$, $B$-physics observables (the rates for $BR(b \to s\gamma)$ and $BR(B_u \to \tau\nu\tau)$, $B_s$ mixing, and the upper limit on $BR(B_s \to \mu^+\mu^-)$), the bound on the lightest MSSM Higgs boson mass, $M_h$, and the cold dark matter (CDM) density inferred from astrophysical and cosmological data, assuming that this is dominated by the relic density of the lightest neutralino, $\Omega_\chi h^2$. In [5] we also discussed the sensitivities of the areas of the preferred regions to changes in the ways in which the major constraints are implemented. We found that the smallest sensitivity was to the CDM density, and the greatest sensitivity was that to $(g-2)_\mu$. 
DESCRIPTION OF OUR FREQUENTIST APPROACH

We define a global $\chi^2$ likelihood function, which combines all theoretical predictions with experimental constraints:

$$\chi^2 = \sum_i \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \chi^2(M_h) + \chi^2(BR(B_s \rightarrow \mu\mu)) + \chi^2(\text{SUSY search limits}) + \sum_i \frac{(f_{\text{SM}i}^{\text{obs}} - f_{\text{SM}i}^{\text{fit}})^2}{\sigma(f_{\text{SM}i})^2}$$

(1)

Here $N$ is the number of observables studied, $C_i$ represents an experimentally measured value (constraint) and each $P_i$ defines a prediction for the corresponding constraint that depends on the supersymmetric parameters. The experimental uncertainty, $\sigma(C_i)$, of each measurement is taken to be both statistically and systematically independent of the corresponding theoretical uncertainty, $\sigma(P_i)$, in its prediction. We denote by $\chi^2(M_h)$ and $\chi^2(BR(B_s \rightarrow \mu\mu))$ the $\chi^2$ contributions from the two measurements for which only one-sided bounds are available so far, as discussed below. Furthermore we include the lower limits from the direct searches for SUSY particles at LEP [36] as one-sided limits, denoted by “$\chi^2(\text{SUSY search limits})$” in eq. (1).

We stress that in [6] (as in [4, 5]) the three SM parameters $f_{\text{SM}} = \{\Delta\alpha_{\text{had}}, m_t, M_Z\}$ are included as fit parameters and allowed to vary with their current experimental resolutions $\sigma(f_{\text{SM}})$. We do not include $\alpha_s$ as a fit parameter, which would have only a minor impact on the analysis.

Formulating the fit in this fashion has the advantage that the $\chi^2$ probability, $P(\chi^2, N_{\text{dof}})$, properly accounts for the number of degrees of freedom, $N_{\text{dof}}$, in the fit and thus represents a quantitative and meaningful measure for the “goodness-of-fit.” In previous studies [4], $P(\chi^2, N_{\text{dof}})$ has been verified to have a flat distribution, thus yielding a reliable estimate of the confidence level for any particular point in parameter space. Further, an important aspect of the formulation is that all model parameters are varied simultaneously in our MCMC sampling, and care is exercised to fully explore the multi-dimensional space, including possible interdependencies between parameters. All confidence levels for selected model parameters are performed by scanning over the desired parameters while minimizing the $\chi^2$ function with respect to all other model parameters. The function values where $\chi^2(x)$ is found to be equal to $\chi^2_{\text{min}} + \Delta\chi^2$ determine the confidence level contour. For two-dimensional parameter scans we use $\Delta\chi^2 = 2.28(5.99)$ to determine the 68% (95%) confidence level contours. Only experimental constraints are imposed when deriving confidence level contours, without any arbitrary or direct constraints placed on model parameters themselves. This leads to robust and statistically meaningful estimates of the total 68% and 95% confidence levels, which may be composed of multiple separated contours.

The experimental constraints used in our analyses are listed in Table 1 in [6]. One important comment concerns our implementation of the LEP constraint on $M_h$. The value quoted in the Table, $M_h > 114.4$ GeV, was derived within the SM [37], and is applicable to the CMSSM, in which the relevant Higgs couplings are very similar to those in the SM [38, 39], so that the SM exclusion results can be used, supplemented
with an additional theoretical uncertainty: we evaluate the $\chi^2(M_h)$ contribution within the CMSSM using the formula

$$\chi^2(M_h) = \frac{(M_h - M_{\text{limit}}^{\text{h}})^2}{(1.1 \text{ GeV})^2 + (1.5 \text{ GeV})^2},$$

(2)

with $M_{\text{limit}}^{\text{h}} = 115.0 \text{ GeV}$ for $M_h < 115.0 \text{ GeV}$. Larger masses do not receive a $\chi^2(M_h)$ contribution. We use 115.0 GeV so as to incorporate a conservative consideration of experimental systematic effects. The 1.5 GeV in the denominator corresponds to a convolution of the likelihood function with a Gaussian function, $\tilde{\Phi}_{1.5}(x)$, normalized to unity and centered around $M_h$, whose width is 1.5 GeV, representing the theory uncertainty on $M_h$ [40]. In this way, a theoretical uncertainty of up to 3 GeV is assigned for $\sim 95\%$ of all $M_h$ values corresponding to one CMSSM parameter point. The 1.1 GeV term in the denominator corresponds to a parametrization of the CLs curve given in the final SM LEP Higgs result [37].

Within the NUHM1 the situation is somewhat more involved, since, for instance, a strong suppression of the $ZZh$ coupling can occur, invalidating the SM exclusion bounds. In order to find a more reliable 95\% C.L. exclusion limit for $M_h$ in the case that the SM limit cannot be applied, we use the following procedure. The main exclusion bound from LEP searches comes from the channel $e^+e^- \rightarrow ZH, H \rightarrow b\bar{b}$. The Higgs boson mass limit in this channel is given as a function of the $ZZH$ coupling in [41]. A reduction in the $ZZh$ coupling in the NUHM1 relative to its SM value can be translated into a lower limit on the lightest NUHM1 Higgs mass, $M_{\text{limit}}^{\text{h},0}$, shifted to lower values with respect to the SM limit of 114.4 GeV. (The actual number is obtained using the code HiggsBounds [42] that incorporates the LEP (and Tevatron) limits on neutral Higgs boson searches.) For values of $M_h \lesssim 86 \text{ GeV}$ the reduction of the $ZZh$ couplings required to evade the LEP bounds becomes very strong, and we add a brick-wall contribution to the $\chi^2$ function below this value (which has no influence on our results). Finally, eq. (2) is used with $M_{\text{limit}}^{\text{h}} = M_{\text{limit}}^{\text{h},0} + 0.6 \text{ GeV}$ to ensure a smooth transition to the SM case, see [6] for more details.

The numerical evaluation of the frequentist likelihood function using the constraints has been performed with the MasterCode [4, 5, 6], which includes the following theoretical codes. For the RGE running of the soft SUSY-breaking parameters, it uses SoftSUSY [43], which is combined consistently with the codes used for the various low-energy observables. At the electroweak scale we have included various codes: FeynHiggs [40, 44, 45, 46] is used for the evaluation of the Higgs masses and $a_\mu^{\text{SUSY}}$ (see also [47, 48, 49, 50]). For the difference between the SM and the experimental value we used $\Delta a_\mu = (30.2 \pm 8.8) \times 10^{-10}$ [51] based on $e^+e^-$ data, see also [52, 53, 54]. A new evaluation, including new $B_B$ data, yields $\Delta a_\mu = (24.6 \pm 8.0) \times 10^{-10}$ [55]. Using this value could have a small impact on our results. We note that recently a new $\tau$ based analysis has appeared [56], which yields a $\sim 1.9 \sigma$ deviation from the SM prediction. For flavor-related observables we use SuFla [57, 58] as well as SuperIso [59, 60], and for the electroweak precision data we have included a code based on [61, 62]. Finally, for dark-matter-related observables, MicrOMEGAs [63, 64, 65] and DarkSUSY [66, 67] have been used. We made extensive use of the SUSY Les Houches Accord [68, 69] in the combination of the various codes within the MasterCode.
RESULTS FOR SPARTICLE MASSES

For the parameters of the best-fit CMSSM point we find $m_0 = 60$ GeV, $m_{1/2} = 310$ GeV, $A_0 = 130$ GeV, $\tan \beta = 11$ and $\mu = 400$ GeV, yielding the overall $\chi^2/N_{\text{dof}} = 20.6/19$ (36% probability) and nominally $M_h = 114.2$ GeV. The corresponding parameters of the best-fit NUHM1 point are $m_0 = 150$ GeV, $m_{1/2} = 270$ GeV, $A_0 = -1300$ GeV, $\tan \beta = 11$ and $m_{h_1} = m_{h_2} = -1.2 \times 10^6$ GeV$^2$ or, equivalently, $\mu = 1140$ GeV, yielding $\chi^2 = 18.4$ (corresponding to a similar fit probability to the CMSSM) and $M_h = 120.7$ GeV.

We now review the results for the predictions of sparticles masses in the CMSSM and the NUHM1, which are summarized in Fig. 1. The results for the CMSSM spectrum are shown in the left plot, and for the NUHM1 in the right plot. We start our discussion with the gluino mass, $m_\tilde{g}$. In both the CMSSM and the NUHM1, the best-fit points have relatively low values of $m_\tilde{g} \sim 750$ and $\sim 600$ GeV, respectively. These favored values are well within the range even of the early operations of the LHC with reduced centre-of-mass energy and limited luminosity. However, even quite large values of $m_\tilde{g} < \sim 2.5$ TeV are allowed at the 3-$\sigma$ ($\Delta \chi^2 = 9$) level (not shown in Fig. 1). The LHC should be able to discover a gluino with $m_\tilde{g} \sim 2.5$ TeV with 100/fb of integrated luminosity at $\sqrt{s} = 14$ TeV \cite{70,71}, and the proposed SLHC luminosity upgrade to 1000/fb of integrated luminosity at $\sqrt{s} = 14$ TeV should permit the discovery of a gluino with $m_\tilde{g} \sim 3$ TeV \cite{72}. However, Fig. 1 does demonstrate that, whilst there are good prospects for discovering SUSY in early LHC running \cite{6}, this cannot be ‘guaranteed’.

The central values of the masses of the supersymmetric partners of the $u,d,s,c,b$ quarks are slightly lighter than the gluino, as seen in Fig. 1. The difference between the gluino and the squark masses is sensitive primarily to $m_0$. The reason is that the preferred regions of the parameter space in both the CMSSM and the NUHM1 are in the $\tilde{\chi}^0_1$-slepton coannihilation region \cite{5,6} where $m_0 < m_{1/2}$. Here $m_0$ makes only small contributions to the central values of the squark masses. The SUSY partners of the left-handed components of the four lightest quarks, $\tilde{q}_L$, are predicted to be slightly heavier than the corresponding right-handed squarks, $\tilde{q}_R$, as seen by comparing the mass ranges in Fig. 1. As in the case of the gluino, squark masses up to $\sim 2.5$ TeV are allowed at the 3-$\sigma$ level. Comparing the left and right panels, we see that the squarks are predicted to be somewhat lighter in the NUHM1 than in the CMSSM, but this difference is small compared with the widths of the corresponding likelihood functions.

Turning now to the likelihood functions for the mass of the lighter stop, $m_{\tilde{t}_1}$, we find that it is shifted to values somewhat lower than for the other squark flavors. It can also be seen that the 2-$\sigma$ range of its likelihood function differ from those of the gluino and the other squarks, reflecting the importance of scalar top mixing. We recall that this depends strongly on the trilinear soft SUSY-breaking parameter $A_t$ and the Higgs mixing parameter $\mu$, as well as on the precise value of $m_t$.

In the case of the lighter stau $\tilde{\tau}_1$, see its range in Fig. 1, the mass is very similar to that of the LSP $\tilde{\chi}^0_1$ in the coannihilation region, but this is not the case in the rapid-annihilation $H,A$ funnel region, see \cite{6} for details. In the case of the NUHM1 rapid annihilation is possible also for low $\tan \beta$, leading to larger values of $m_0$ than in the CMSSM also for relatively small values of $m_{\tilde{\tau}_1}$.

The scalar taus as well as the other scalar leptons are expected to be relatively light,
as can be seen in Fig. 1. They would partially be in the reach of the ILC(500) (i.e., with $\sqrt{s} = 500$ GeV) and at the 95% C.L. nearly all be in the reach of the ILC(1000) \[73, 74\]. This also holds for the two lighter neutralinos and the light chargino.

**PREDICTION OF HIGGS BOSON MASSES**

In Fig. 2 we display the favored regions in the $(M_A, \tan \beta)$ planes for the CMSSM and NUHM1. We see that they are broadly similar, with little correlation between the two parameters. Concerning $\tan \beta$, one can observe that while the best fit values lie at $\tan \beta \approx 11$, the 68 (95)% C.L. areas reach up to $30 \tan \beta \approx 30(50-60)$. The existing Higgs discovery analyses (performed in the various benchmark scenarios \[13, 14, 75, 76\]) cannot directly be applied to the $(M_A, \tan \beta)$ planes in Fig. 2. In order to assess the
prospects for discovering heavy Higgs bosons at the LHC in this context, we follow the analysis in [77], which assumed 30 or 60 fb$^{-1}$ collected with the CMS detector. For evaluating the Higgs-sector observables including higher-order corrections we use the soft SUSY-breaking parameters of the best-fit points in the CMSSM and the NUHM1, respectively. We show in Fig. 2 the 5-$\sigma$ discovery contours for the three decay channels $H, A \rightarrow \tau^+\tau^- \rightarrow$ jets (solid lines), jet + $\mu$ (dashed lines) and jet + $e$ (dotted lines). The parameter regions above and to the left of the curves are within reach of the LHC with about 30 fb$^{-1}$ of integrated luminosity. We see that most of the highest-CL regions lie beyond this reach, particularly in the CMSSM. At the ILC(1000) masses up to $M_A \lesssim 500$ GeV can be probed. Within the CMSSM this includes the best-fit point, and within the NUHM1 nearly the whole 68% C.L. area can be covered.

**FIGURE 2.** The correlations between $M_A$ and $\tan\beta$ in the CMSSM (left panel) and in the NUHM1 (right panel) [6]. Also shown are the 5-$\sigma$ discovery contours for observing the heavy MSSM Higgs bosons $H, A$ in the three decay channels $H, A \rightarrow \tau^+\tau^- \rightarrow$ jets (solid line), jet + $\mu$ (dashed line), jet + $e$ (dotted line) at the LHC. The discovery contours have been obtained using an analysis that assumed 30 or 60 fb$^{-1}$ collected with the CMS detector [71, 77].

Finally we discuss the likelihood functions for $M_h$ within the CMSSM and NUHM1 frameworks obtained when dropping the contribution to $\chi^2$ from the direct Higgs searches at LEP. The results are shown in the left and right panels of Fig. 3, respectively. The left plot updates that for the CMSSM given in [4].

It is well known that the central value of the Higgs mass in a SM fit to the precision electroweak data lies below 100 GeV [78, 79], but the theoretical (blue band) and experimental uncertainties in the SM fit are such that they are still compatible at the 95% C.L. with the direct lower limit of 114.4 GeV [37] derived from searches at LEP. In the case of the CMSSM and NUHM1, one may predict $M_h$ on the basis of the underlying model parameters, with a 1-$\sigma$ uncertainty of 1.5 GeV [40], shown as a red band in Fig. 3. Also shown in Fig. 3 are the LEP exclusion on a SM Higgs (yellow shading) and the ranges that are theoretically inaccessible in the supersymmetric models studied (beige shading). The LEP exclusion is directly applicable to the CMSSM, since the $h$ couplings are essentially indistinguishable from those of the SM Higgs boson [38, 39], but this is not necessarily the case in the NUHM1, as discussed earlier.

In the case of the CMSSM, we see in the left panel of Fig. 3 that the minimum of the $\chi^2$ function occurs below the LEP exclusion limit. While the tension between the $\chi^2$ function for $M_h$ arising from the CMSSM fit and the LEP exclusion limit has
slightly increased compared to the earlier analysis performed in [4], the fit result is still compatible at the 95% C.L. with the search limit, similarly to the SM case. As we found in [6] a global fit including the LEP constraint has acceptable $\chi^2$. In the case of the NUHM1, shown in the right panel of Fig. 3, we see that the minimum of the $\chi^2$ function occurs above the LEP lower limit on the mass of a SM Higgs. Thus, within the NUHM1 the combination of all other experimental constraints naturally evades the LEP Higgs constraints, and no tension between $M_h$ and the experimental bounds exists.

ACKNOWLEDGMENTS

We thank O. Buchmüller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, G. Isidori, K. Olive, F. Ronga and G. Weiglein with whom the results presented here have been obtained. This work has been supported in part by the European Community’s Marie-Curie Research Training Network under contract MRTN-CT-2006-035505 ‘Tools and Precision Calculations for Physics Discoveries at Colliders’ (HEPTOOLS).

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