Prospects for Discovering Supersymmetry at the LHC

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Received: date / Revised version: date

Abstract. Supersymmetry is one of the best-motivated candidates for physics beyond the Standard Model that might be discovered at the LHC. There are many reasons to expect that it may appear at the TeV scale, in particular because it provides a natural cold dark matter candidate. The apparent discrepancy between the experimental measurement of $g_\mu - 2$ and the Standard model value calculated using low-energy $e^+e^-$ data favours relatively light sparticles accessible to the LHC. A global likelihood analysis including this, other electroweak precision observables and B-decay observables suggests that the LHC might be able to discover supersymmetry with 1/fb or less of integrated luminosity. The LHC should be able to discover supersymmetry via the classic missing-energy signature, or in alternative phenomenological scenarios. The prospects for discovering supersymmetry at the LHC look very good.

PACS. 12.60.Jv Supersymmetric models – 14.80.Ly Supersymmetric partners of known particles

CERN-PH-TH/2008-208

1 Introduction

Many theorist-years of effort have been invested in work to understand the structure of supersymmetry and how to construct realistic supersymmetric models, as well as how to test them experimentally. Many experimentalist-years have also been invested already in the simulation of possible supersymmetric signals at the LHC, and many more will be invested in searches once the LHC starts to provide high-energy collisions. What are the prospects that all these efforts will be crowned with success? What follows is my personal perspective on this question, with illustrations taken largely from papers in which I have been a co-author: I apologize in advance for not referring correctly to all the relevant literature.

2 Motivations

One’s assessment of the LHC’s prospects for finding supersymmetry depends to great extent on the reasons why one might think that supersymmetry exists, in particular at accessible energies. There are many idealistic motivations for believing in supersymmetry, such as its intrinsic elegance, its ability to link matter particles and force carriers, its ability to link gravity to the other fundamental interactions, its essential role in string theory, etc. However, none of these aesthetic motivations gives any hint as to the energy scale at which supersymmetry might appear. There are, however, various utilitarian reasons to think that supersymmetry might appear at some energy accessible to the LHC.

Historically, the first of these was the observation that supersymmetry could help stabilize the mass scale of electroweak symmetry breaking, by cancelling the quadratic divergences in the radiative corrections to the mass-squared of the Higgs boson [1], and by extension to the masses of other Standard Model particles. This motivation suggests that sparticles weigh less than about 1 TeV, if it had once been in thermal equilibrium in the early Universe. This would have been the case for a neutralino $\chi$ or a sneutrino $\tilde{\nu}$ LSP, and the argument can be extended to a gravitino LSP because it may be produced in the decays of heavier, equilibrated sparticles.

The second motivation for low-scale supersymmetry was the observation that the lightest supersymmetric particle (LSP) in models with conserved $R$ parity, being heavy and naturally neutral and stable, would be an excellent candidate for the dark matter that clutters up the Universe [2]. This motivation requires that the lightest supersymmetric particle should weigh less than about 1 TeV, if it had once been in thermal equilibrium in the early Universe. This would have been the case for a neutralino $\chi$ or a sneutrino $\tilde{\nu}$ LSP, and the argument can be extended to a gravitino LSP because it may be produced in the decays of heavier, equilibrated sparticles.

The third reason for thinking that supersymmetry may appear within the LHC energy range is the observation that including sparticles in the renormalization-group equations (RGEs) for the gauge couplings of the Standard Model would permit them to unify [3], whereas unification would not occur if only the Standard Model particles were included in the RGEs. However, this argument does not constrain the supersymmetric mass scale very precisely: scales up to about 10 TeV or perhaps more could be compatible with grand unification.
The fourth motivation is the fact that the Higgs boson is (presumably) relatively light, according to the precision electroweak data. It has been known for some 20 years that the lightest supersymmetric Higgs boson should weigh no more than about 140 GeV, at least in simple models \[1\]. For around 15 years now, the precision electroweak noise has been tightening, and the best indication now (incorporating the negative results of searches at LEP and the Tevatron) is that the Higgs boson probably weighs less than about 140 GeV \[3\], in perfect agreement with the supersymmetric prediction.

Fifthly, if the Higgs boson is indeed so light, the present electroweak vacuum would be destabilized by radiative corrections due to the top quark, unless the Standard Model is supplemented by additional scalar particles \[9\]. This would be automatic in supersymmetry, and one can extend the argument to ‘prove’ that any mechanism to stabilize the electroweak vacuum must look very much like supersymmetry.

For all these reasons, I believe there is a high likelihood that supersymmetry will appear at or near the electroweak scale. The next question is whether, even accepting all these arguments, it is nevertheless guaranteed to appear at the LHC.

The clinching argument could be provided by the anomalous magnetic moment of the muon, $g_\mu - 2$. As is well known, the experimental measurement of this quantity \[7\] disagrees with the Standard Model prediction \[8\], if this is calculated using low-energy $e^+e^-$ annihilation data. On the other hand, the discrepancy with the Standard Model is greatly reduced if one uses $\tau$ decay data to estimate the Standard Model contribution to $g_\mu - 2$. Normally, one would prefer to use $e^+e^-$ data, since they are related more directly to $g_\mu - 2$, with no need to worry about isospin violations, etc. Until very recently, the $e^+e^-$ data seemed to be agreeing very nicely, but preliminary measurements by BABAR using the radiative-return method \[9\] do not agree so well. Until these discrepancies get ironed out, one should take $g_\mu - 2 \text{ cum grano salis!}$

3 The Role of the Cold Dark Matter Constraint

The most precise constraint on supersymmetry may be that provided by the density of cold dark matter, as determined from astrophysical and cosmological measurements by WMAP et al \[10\]:

$$\Omega_{CDM} = 0.1099 \pm 0.0062.$$  \hspace{1cm} (1)

Applied straightforwardly to the relic LSP density $\Omega_{LSP} h^2$, this would give a very tight relation between supersymmetric model parameters, fixing some combination of them at the \% level. This would essentially reduce the dimensionality of the supersymmetric parameter space by one unit. Let us assume for now that the LSP is the lightest neutralino $\chi$, whose density is usually thought to be fixed by freeze-out from thermal equilibrium in the early Universe, and concentrate our attention on the minimal supersymmetric extension of the Standard Model (MSSM).

In this case, respecting the constraint \[11\] would force one into narrow WMAP ‘strips’ in planar projections of the MSSM parameters \[11\]. However, caution should be exercised before jumping to this conclusion.

The $\chi$ density would depend on the expansion rate at the freeze-out temperature, which is typically about 1/25 of $m_\chi$, and hence in the multi-GeV range. It is usually assumed that the standard Big-Bang expansion rate applied at that epoch, but we have no evidence that this was the case before the epoch of Big-Bang nucleosynthesis. Indeed, a successful calculation of the relic $\chi$ density using information from the LHC and other accelerators would be the best confirmation that standard Big-Bang cosmology applied earlier than that epoch \[12\].

Moreover, supersymmetry might not be the only contribution to the cold dark matter, in which case \[11\] should be interpreted as an upper limit on $\Omega_{LSP} h^2$. However, most of the supersymmetric parameter space in simple models gives a supersymmetric relic density that exceeds the WMAP range \[11\], e.g., above the WMAP ‘strip’ in Fig. 1(a), and the regions with lower density generally correspond to (if anything) lower values of the particle masses, e.g., below the WMAP ‘strip’ in Fig. 1(a). So this may not be a big deal.

However, even if one takes them seriously, the locations of these WMAP ‘strips’ do vary significantly with the choices of other supersymmetric parameters, as can be seen by comparing the cases of $\tan \beta = 10, 50$ in Fig. 1(a, b) \[13\]. These two plots are in the CMSSM, where the super-symmetry-breaking scalar masses $m_0$ and gaugino masses $m_{1/2}$ are each assumed to be universal at the GUT scale. As one varies $\tan \beta$, the WMAP ‘strips’ cover much of the $(m_{1/2}, m_0)$ plane.

Several different regions of the CMSSM $(m_{1/2}, m_0)$ plane can be distinguished, in which different dynamical processes are dominant. At low values of $m_{1/2}$ and $m_0$, simple $\chi - \chi$ annihilations via crossed-channel sfermion exchange are dominant, but this ‘bulk’ region is now largely excluded by the LEP lower limit on the Higgs mass, $m_h$. At larger $m_{1/2}$, but relatively small $m_0$, close to the boundary of the region where the lighter stau is lighter than the lightest neutralino: $m_{\tilde{\tau}_1} < m_\chi$, coannihilation between the $\chi$ and sleptons is important in suppressing the relic $\chi$ density into the WMAP range \[11\], as seen in Fig. 1(a). At larger $m_{1/2}$, $m_0$ and $\tan \beta$, the relic $\chi$ density may be reduced by rapid annihilation through direct-channel $H, A$ Higgs bosons, as seen in Fig. 1(b). Finally, the relic density can again be brought down into the WMAP range \[11\] at large $m_0$ not shown in Fig. 1 in the ‘focus-point’ region close the boundary where electroweak symmetry breaking ceases to be possible and the lightest neutralino $\chi$ acquires a significant higgsino component.

These regions move around if one abandons the universality assumptions of the CMSSM. For example, if one allows the supersymmetry-breaking contributions to the Higgs masses to be non-universal (NUHM), the rapid-annihilation WMAP ‘strip’ can appear at different values of $\tan \beta$ and $m_{1/2}$, as seen in Fig. 2 \[14\]. Rapid annihilation through the direct-channel $H, A$ poles suppresses the relic density...
between the two parallel vertical WMAP strips, and the relic density is suppressed in the right-hand strip because the neutralino LSP has a significant higgsino component.

The appearance of the \((m_{1/2}, m_0)\) plane is also changed significantly if one assumes that the universality of soft super-symmetry-breaking masses in the CMSSM occurs not at the GUT scale, but at some lower renormalization scale \([15]\), as occurs in some ‘mirage unification’ models. In this case, the sparticle masses are generally closer together, and the bulk, coannihilation, rapid-annihilation and focus-point regions approach each other and eventually merge as the mirage unification scale is reduced, as illustrated in Fig. 3. In such ‘GUTless’ models, \(\Omega_{LSP}h^2\) falls below the WMAP range \([11]\) in larger regions of the \((m_{1/2}, m_0)\) plane.
So far, it has been assumed that the lightest neutralino \( \chi \) is the LSP. A sneutrino LSP is ruled out by a combination of LEP searches that exclude lower masses and direct dark matter searches that exclude higher sneutrino masses. How about a gravitino LSP (GDM)? In this case, the next-to-lightest supersymmetric particle (NLSP) must be metastable, since it decays by gravitational-strength interactions. What might the NLSP be in such a gravitino LSP scenario? In the CMSSM at low \( m_0 \) and large \( m_{3/2} \) it would be the \( \tilde{\tau}_1 \), which would have a distinctive experimental signature at the LHC, as discussed later. This GDM scenario is tightly constrained by the astrophysical constraints on the cosmological abundances of light elements, as seen in Fig. 4. However, such a scenario might have some advantages, e.g., by enabling the cosmological prediction for the abundance of \( ^7\text{Li} \) to be improved, as also shown in Fig. 4.

If one goes beyond the CMSSM, there are other possibilities for the NLSP in a gravitino LSP scenario. For example, within the NUHM the NLSP might be the lighter stop squark, \( \tilde{t}_1 \) \cite{18}, which would also have a spectacular signature at the LHC, as also discussed later. Alternatively, the NLSP could be one of the sneutrinos \cite{19}, as illustrated in Fig. 5.

As this brief review has indicated, there are many ways in which supersymmetry may choose to obey the WMAP constraint (even assuming that \( R \) parity is conserved). Considering specifically the CMSSM and the NUHM, and assuming that the LSP is the lightest neutralino \( \chi \), what are the prospects for discovering supersymmetry at the LHC in light of WMAP? In the two panels of Fig. 6 you see large samples of CMSSM and NUHM models, respectively \cite{20}. The full sample is shown in red, the blue points are compatible with WMAP, the green points are accessible to the LHC, and the yellow points are accessible to direct dark matter searches. It is apparent that the LHC will be able to explore most, but not all, of the WMAP-compatible models, and its prospects look brighter than those for direct dark matter searches. However, there is no guarantee that supersymmetry will be within the reach of the LHC.

4 Results from a Global Likelihood Analysis

If one wishes to go further in assessing the prospects for discovering supersymmetry at the LHC, one must introduce some supplementary considerations. A theoretical argument that is often invoked is that of minimizing the amount of fine-tuning required to obtain the electroweak scale and/or the right cold dark matter density. It is true that, generally speaking the heavier the sparticles, the more fine-tuning is required \cite{21}. Although this argument is encouraging for the LHC, how much fine-tuning is too much? It is difficult to state an objective criterion. Alternatively, let us not feed in any theoretical prejudice, but instead ask the available experimental data, and make likelihood analyses of the parameter spaces of simple supersymmetric models, such as the CMSSM or the NUHM.

In addition to WMAP \textit{et al}., the available data include electroweak precision observables (EWPO), B-decay observables, and \( g_\mu -2 \). The EWPO give no firm evidence for...
any new physics beyond the Standard Model: \( m_W \) is somewhat higher than might have been expected, but there is no indication from \( \sin^2 \theta \) or other EWPO. Likewise, the B-decay observables, including \( b \to s\gamma \), \( B \to \tau\nu \), \( B_s \) mixing and \( B_s \to \mu^+\mu^- \) decay give only upper limits on the possible effects of supersymmetry.

As already mentioned, the only real experimental hint for new physics comes from \( g_\mu - 2 \). In the analysis of this Section we assume the following discrepancy between experiment [7] and the Standard Model calculation based on \( e^+e^- \) data [8]:

\[
a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (30.2 \pm 8.8) \times 10^{-10},
\]

with an additional theoretical uncertainty of \( 2 \times 10^{-10} \). I emphasize again that this number has not yet settled down [9], and specifically that the discrepancy would be much reduced if one used \( \tau \) data. Nevertheless, what are the prospect for the LHC if one incorporates [2] into a global likelihood analysis?

We have recently published such an analysis [22], using a Markov-Chain Monte Carlo (MCMC) technique to explore efficiently the likelihood function in the parameter spaces of the CMSSM and the NUHM (the simplest version of the NUHM, in which the two Higgs soft supersymmetry-breaking masses are assumed equal) [23]. A full list of the observables and the values assumed for them in this global analysis are given in [24], as updated in [22].

The 68% and 95% confidence-level (C.L.) regions in the \( (m_{1/2}, m_0) \) planes of the CMSSM and NUHM1 are shown in Fig. 6 [22]. Also shown for comparison are the physics reaches of ATLAS and CMS with 1/fb of integrated luminosity [25]. (MET stands for missing transverse energy, SS stands for same-sign dilepton pairs, and the sensitivity for finding the lightest Higgs boson in cascade decays of supersymmetric particles is calculated for 2/fb of data.) Our likelihood analysis assumes \( \mu > 0 \), as motivated by the sign of the apparent discrepancy in \( g_\mu - 2 \), but sampled all values of \( \tan \beta \) and \( A_0 \); the experimental sensitivities were estimated assuming \( \tan \beta = 10 \) and \( A_0 = 0 \), but are probably not very sensitive to these assumptions. The global maxima of the likelihood function (indicated by the black dots) are as follows: in the CMSSM \( m_{1/2} = 310 \) GeV, \( m_0 = 60 \) GeV, \( A_0 = 240 \) GeV, \( \tan \beta = 11 \) and \( \chi^2/N_{\text{dof}} = 20.4/19 \) (37% probability), and in the NUHM1 \( m_{1/2} = 240 \) GeV, \( m_0 = 100 \) GeV, \( A_0 = -930 \) GeV, \( \tan \beta = 7 \) and \( \chi^2/N_{\text{dof}} = 18.0 \) (39% probability). It is encouraging that the best-fit points lie well within the LHC discovery range, as do the 68% and most of the 95% C.L. regions. It is also encouraging that the two best-fit points have similar values of \( m_{1/2}, m_0 \) and \( \tan \beta \), the most important parameters for the sparticle spectrum, indicating that the likelihood analysis is relatively insensitive to the theoretical model assumptions.

The sparticle spectra for the best fits in the CMSSM and NUHM1 are displayed in Fig. 8 [22]. The main differences are the following. The lightest Higgs boson is appreciably lighter in the CMSSM, 113 GeV vs 118 GeV (indeed this is the main reason the \( \chi^2 \) of the CMSSM fit is higher, and it is acceptable only because of the theoretical uncertainty in the calculation of \( m_h \)), whereas the heavier MSSM Higgs bosons are lighter in the NUHM1. The heavier neutralinos and charginos are significantly heavier in the NUHM1 than in the CMSSM, reflecting the larger best-fit value of \( \mu \) (870 GeV compared to 380 GeV). The gluino and squarks are somewhat lighter in the NUHM1, reflecting the smaller value of \( m_{1/2} \).

According to this analysis, the prospects for discovering supersymmetry at the LHC look quite bright, in both the CMSSM and the NUHM1. How soon might the discovery be made? As seen in Fig. 9 the best-fit points in both the CMSSM and the NUHM1 lie within the region accessible to the LHC with 50/pb of integrated luminosity at 10 TeV, and the 68% C.L. regions lie within the reach of the LHC with 100/pb of data. (The hatched regions at the bottom of each panel of Fig. 9 are those excluded by searches for supersymmetry at LEP and the Tevatron collider.) We see that even modest LHC luminosity, not
necessarily at the design energy, would already explore substantial new regions of the CMSSM and NUHM1 parameter spaces, and might already have a good chance of discovering supersymmetry!

How dependent are these results on the inputs used? Fig. 10(a) shows the effect on the 95% C.L. region in the CMSSM \((m_{1/2}, m_0)\) plane of removing the WMAP constraint [22]. There is surprisingly little effect, basically because (although they are individually very narrow) the WMAP strips for different values of \(\tan \beta\) and \(A_0\) largely cover the \((m_{1/2}, m_0)\) plane. Hence, an analysis such as ours that samples different values of \(\tan \beta\) and \(A_0\) does not spot the reduction in the dimensionality of the parameter space. On the other hand, we see in Fig. 10(b) that relaxing the \(g_\mu - 2\) constraint even slightly, by increasing the relative error, has a dramatic effect on the preferred region of the CMSSM \((m_{1/2}, m_0)\) plane [22]. If the \(g_\mu - 2\) constraint was relaxed much more, it would encompass the focus-point region, which is disfavoured in the default version of our MCMC likelihood analysis.

5 Alternative Supersymmetric Phenomenologies

All the above discussion has assumed that \(R\) parity is conserved, in which case the LSP is stable and hence must be neutral, leading to a missing-energy signature at the LHC. If \(R\) parity is not conserved, the dark matter constraint evaporates, and sparticle decays may be observable at the LHC. For example, the neutralino may decay visibly into a combination of three jets and/or leptons.

A less radical possibility is that \(R\) parity is conserved, but the LSP is the gravitino, in which case the NLSP is metastable. The NLSP might be the lighter stau \(\tilde{\tau}_1\), which would be easily distinguishable as a non-relativistic charged particle. Studies have shown that the mass of the \(\tilde{\tau}_1\) could be measured very accurately, and that one could...
easily reconstruct heavier sparticles that decay into the \( \tilde{\tau}_1 \), as seen in Fig. 11 [26].

Alternatively, the NLSP might be the lighter stop \( \tilde{t}_1 \) [18]. Immediately after production at the LHC, it would become confined inside a charged or neutral hadron. As it moves through an LHC detector, it would have a high probability of changing its charge as it interacts with the material in the detector. This combined with its non-relativistic velocity would provide a truly distinctive signature.

Yet another possibility is that the NLSP might be some flavour of sneutrino [19], in which case the characteristic signature would be missing energy carried away by the metastable sneutrino. This could nevertheless be distinguished from the conventional missing-energy signature of a neutralino LSP (or NLSP), because the final states would be more likely to include the charged lepton with the same flavour as the sneutrino NLSP, either \( e \), \( \mu \) or \( \tau \).

These are just a few examples of the possible alternatives to the conventional missing-energy signature of supersymmetry. Studies have shown that the LHC would also have good prospects for detecting such signatures.

6 Playing for High Stakes

The start-up of the LHC resembles a high-stakes game of roulette. We have good reasons for expecting the LHC will reveal the mechanism of electroweak symmetry breaking, whether it is the Higgs boson of the Standard Model or something more complicated. Supersymmetry is just one of the theories jostling for consideration as physics beyond the Standard Model that might be revealed by the LHC.

As I discussed earlier, I believe there are many good motivations for expecting supersymmetry to appear at the TeV scale. On the other hand, I think it was Feynman who once remarked that if you had one good reason you would not need to give any more! Anyway, I believe that there are excellent prospects for producing supersymmetry at the LHC, and equally excellent prospects for detecting it if it is produced.

The stakes in the LHC supersymmetry search are certainly high: it would be a completely novel symmetry of Nature, linking bosons and fermions; it could be considered as circumstantial evidence for string theory; it could pave the way to unification of the fundamental forces; it could stabilize the puzzling hierarchy of mass scales in fundamental physics; it might explain 80% of the mat-
ter in the Universe. LHC roulette is not a game for the faint-hearted: let the protons turn!

Acknowledgements

I gratefully acknowledge my many collaborators on the topics discussed here, particularly Keith Olive.

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