Outlook from SUSY07

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Abstract. Make-or-break time is near for the Higgs boson and supersymmetry. The LHC will soon put to the sword many theoretical ideas, and define the future for collider physics.

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1 Introduction

I was in Karlsruhe in 1969 when the first astronauts landed on the Moon, realizing President Kennedy’s commitment: ‘this nation should commit itself to achieving the goal ... of landing a man on the Moon and returning him safely to the Earth’. Likewise, in 1994 the CERN Council committed the Organization to the goal of discovering the Higgs boson and supersymmetry (if they exist) at the LHC. Now, back in Karlsruhe, we supersymmetrists face the exhilarating prospect that our cherished ideas will soon be subjected to the ordeal of experimental test [1].

The organizers of this meeting explicitly exonerated me from giving a summary talk, asking me instead to present a personal outlook on the future (as offered by the LHC et al.). Nevertheless, I have not quite taken them at their words, and base (at least some of) my talk on presentations made at SUSY07.

2 Hunting for the Higgs Boson

The LHC, with its centre-of-mass energy of 14 TeV and its nominal luminosity of 10^{34} cm^{-2}s^{-1} and the possibility of an upgrade to 10^{35} cm^{-2}s^{-1} [2], offers the best prospects for discovering new physics beyond the Standard Model (SM). Since interesting cross sections such as those for supersymmetry and the Higgs boson are typically \( O(1)/(1 \text{ TeV})^2 \), possibly with small prefactors \( O(\alpha^2) \), whereas the total cross section is \( O(1)/(100 \text{ MeV})^2 \), looking for this interesting new physics will be like looking for a needle in 100,000 haystacks.

The Tevatron may have a chance of pipping the LHC in the race for the Higgs boson. Already, as seen in Fig. 1 the sensitivity of the combined CDF and D0 searches is within an order of magnitude of the cross section expected for the SM Higgs boson from the LEP lower limit up to \( m_H \sim 190 \text{ GeV} \), the mass range allowed at the 95% confidence level [3], and the sensitivity is within a factor 2 of the SM for \( m_H \sim 160 \text{ GeV} \). Soon we may know whether the Higgs is either close to the LEP limit or in an ‘unlikely’ range.

The search for the Higgs boson at the LHC will require combining various different signatures [4], including \( \gamma\gamma \), four-lepton final states, \( \tau\tau \), \( bb \), \( WW \) and \( ZZ \). As seen in in Fig. 2 combining searches by ATLAS and CMS, 200 pb^{-1} should suffice to exclude a SM between about 140 and 500 GeV, 1 fb^{-1} should enable a SM Higgs boson to be discovered with 5-\( \sigma \) significance over a similar mass range, and 5 fb^{-1} should enable a discovery discover whatever its mass [5]. Eventually, if the Higgs mass \( \sim 120 \text{ GeV} \), it should be possible at the LHC to measure SM Higgs couplings to \( \tau\tau \), \( bb \), \( WW \) and \( ZZ \) with an accuracy \( \sim 20 \% \), and there are also prospects for measuring the Higgs spin via its decays into \( ZZ \) [6].

One of the biggest puzzles in Higgs physics is its contribution to vacuum energy. The naive Higgs potential \(-\mu^2|H|^2 + \lambda|H|^4\) makes a negative contribution to the vacuum energy that is negative and some 60 orders of magnitude larger than the physical value of the dark energy. Some mysterious mechanism is needed to cancel this Higgs contribution to 60 decimal places. What are we missing? Are we barking up the wrong tree?
3 Why Supersymmetry?

There are many motivations for supersymmetry, including its intrinsic beauty, its help in rendering the hierarchy of mass scales in fundamental physics more natural, its help in unifying the gauge couplings, its prediction that the Higgs boson should be relatively light: \( m_H < 150 \text{ GeV} \) as suggested by precision electroweak data, and its offer of a natural cold dark matter candidate \([7]\). Moreover, it is (almost) an essential ingredient in string theory.

There have recently been several impressive pieces of direct observational evidence for collisionless cold dark matter, e.g., the ‘bullet cluster’ which has been shown by weak lensing to contain two lumps of dark matter that have passed through each other, while the associated gas clouds have collided, heated up and remained stuck in between \([8]\). On the other hand, there are problems for the cold dark matter paradigm provided, e.g., by dwarf spheroidal galaxies \([9]\), the abundances of satellites of the Milky Way, and the apparent absence of cusps in galactic centres. Are we barking up the wrong tree again?

4 Constraints on Supersymmetry

There are important direct constraints on supersymmetry due to the absence of sparticles at LEP and the Tevatron, and also indirect constraints from, e.g., the LEP lower limit of 114 GeV on the Higgs mass, the success of SM calculations of \( b \to s \gamma \), etc. One of the most important constraints is that imposed by the cold dark matter density, assuming it is largely composed of the lightest supersymmetric particle (LSP): \( 0.094 < \Omega_{\text{LSP}} h^2 < 0.124 \). There is still some debate about the interpretation of the BNL measurement of the anomalous magnetic moment of the muon \( (g-\mu-2) \), which now disagrees by 3.4 \( \sigma \) with a SM calculation based on low-energy \( e^+ e^- \) data \([10]\). Recent \( e^+ e^- \) data agree very well with earlier data, whereas preliminary new \( \tau \) decay data apparently disagree with previous data.

Presumably the LSP has no strong or electromagnetic interactions, otherwise it would bind to conventional matter and be detectable as anomalous heavy nuclei. Possible weakly-interacting candidates include the sneutrino (though this seems to be excluded by LEP and direct searches), the lightest neutralino \( \chi \) (a mixture of the spartners of the \( Z, H \) and \( \gamma \)), and the gravitino (which would be a nightmare for astrophysical detection, but a boon for colliders, as discussed later).

5 A Paradigm: the CMSSM with a neutralino LSP

For the rest of this talk, I focus on the minimal supersymmetric extension of the Standard Model (MSSM), including two Higgs doublets with coupling \( \mu \) and a ratio of v.e.v.s denoted by \( \tan \beta \). The MSSM has \textit{a priori} unknown supersymmetry-breaking parameters, scalar masses \( m_0 \), gaugino masses \( m_{1/2} \), trilinear soft couplings \( A_0 \), and a bilinear soft coupling \( B_0 \). Universality at the input GUT scale is often assumed, the constrained MSSM (CMSSM) framework with a single \( m_0 \), a single \( m_{1/2} \), and a single \( A_0 \). However, there is no necessity for the universality hypothesis in string theory. I emphasize that \textit{the CMSSM is not the same...}
7 Looking for Supersymmetry at the LHC

The classic supersymmetric signature is missing transverse energy carried away by dark matter particles. The Tevatron collider has already provided important limits on gluinos and squarks: \( m_{\tilde{g}} > 290 \) GeV and \( m_{\tilde{q}} > 375 \) GeV \cite{limits}
and has also provided important upper limits on trilepton final states as might arise from chargino and neutralino production \cite{limits}. Even with low initial luminosity, the LHC will immediately have sensitivity to gluino and squark masses far beyond the Tevatron limits. However, the missing-energy search will not be without backgrounds \cite{backgrounds}, it will be necessary to understand very well the ATLAS and CMS detectors.

A possible strategy for classic supersymmetry searches (and discovery?) at the LHC is \cite{strategy}:

(i) search for single lepton + missing-energy events, (ii) search for all combinations of dilepton + missing-energy events, (iii) search for trilepton + jet events, (iv) search for \( b\bar{b} \) + lepton events, (v) search for zero-lepton + missing-energy events, etc. In addition, there will be searches for the photons characteristic of gauge-mediated scenarios and the metastable particles that might appear in scenarios with a gravitino LSP. Fig. \ref{fig:limits} shows the sensitivity of the LHC to the gluino mass (both for five-\( \sigma \) discovery and 95 % exclusion) as a function of the integrated luminosity. For example, with 1 fb\(^{-1} \) the LHC might be able to discover a gluino weighing up to 1.7 TeV, or exclude a gluino weighing less than 2.1 TeV.

6 What Might be the Scale of Supersymmetry?

Is there any preference for any particular range of particle masses within this allowed band? Fig. \ref{fig:scale} shows the \( \chi^2 \) distributions for global fits to precision electroweak and \( B \)-decay data, assuming \( \tan \beta = 10 \) (left) and \( \tan \beta = 50 \) (right) \cite{fits}. We see that relatively low values of \( m_{1/2} \sim 300,600 \) GeV are favoured, essentially by \( g_{\mu} - 2 \) (though there is also some support from \( m_W \)). Results from a more complete analysis of parameter space using a larger set of observables (with better graphics) are given in \cite{analysis}. There may be good reason to hope that supersymmetry might be detectable at the LHC with 1 fb\(^{-1} \) of integrated luminosity.

as minimal supergravity (mSUGRA), which imposes an relation on the gravitino mass: \( m_{3/2} = m_0 \), and the additional relation \( B_0 = A_0m_0 \).

Fig. \ref{fig:scale} is an example of the current constraints on the CMSSM \cite{cmssm}, assuming that the LSP is the lightest neutralino \( \chi \), showing the region excluded because the LSP is the charged stau (shaded brown), excluded by \( b \to s\gamma \) (shaded green), preferred by \( g_{\mu} - 2 \) (shaded pink) and by the cold dark matter density (shaded pale blue). The region allowed by these constraints extends to large \( m_{1/2} \) (and there is another allowed region at large \( m_0 \)), so sparticles may be quite heavy, as seen in Fig. \ref{fig:scale} \cite{analysis}. The red symbols are the full data sample, the blue symbols indicate models that could provide the astrophysical dark matter, the green symbols indicate models that are detectable at the LHC, and the yellow points are that are detectable directly in searches for dark matter scattering \cite{direct}.

Fig. 3. The \((m_{1/2}, m_0)\) plane in the CMSSM for \( \tan \beta = 10, \mu > 0 \) and \( A_0 = 0 \) \cite{cmssm}, incorporating the theoretical, experimental and cosmological constraints described in the text.

Fig. 4. The masses of the lightest and next-to-lightest visible supersymmetric particles in a sampling of CMSSM scenarios \cite{analysis}. Also indicated are the scenarios providing a suitable amount of cold dark matter (blue), those detectable at the LHC (green) and those where the astrophysical dark matter might be detected directly (yellow).
8 The LHC Reach and Linear Colliders

The results of the LHC search for gluinos will carry important implications for future linear colliders [5], as illustrated in Fig. 2. Specifically, concentrating on the coannihilation region and models with unification of gaugino masses at the GUT scale, such as the CMSSM, discovery with 1 fb$^{-1}$ would suggest that the $e^+e^- \rightarrow \chi\chi$ threshold lies below 650 GeV, whereas exclusion would exclude a threshold below 800 GeV. Well beyond the initial LHC luminosity, discovery of the gluino at the SLHC with a ‘year’ at a luminosity of 10$^{36}$ cm$^{-2}$s$^{-1}$ would tell us that the $e^+e^- \rightarrow \chi\chi$ threshold lies below about 1.3 TeV. The LHC will tell us what energy a linear collider will need to study supersymmetry.

As is well known, the ILC would be able to make accurate measurements of the masses and couplings of any sparticles within its kinematic reach [20], and these measurements would have invaluable synergies with LHC measurements, for example by probing models of supersymmetry breaking by testing unification ideas [20]. However, supersymmetry enthusiasts should be aware that not all scenarios with large cross sections at the LHC will necessarily be observable at the ILC [21]. A preliminary study of 242 such scenarios found that 158 or 65% have no observable signal at the ILC with 500 GeV, and further investigation shows that the unobservable percentage actually rises to 75%.

9 Supersymmetric Higgs Bosons

The LHC also has good prospects of discovering supersymmetric Higgs bosons, being able to cover entire generic ($m_A$, tan $\beta$) planes at least (but perhaps only) once. However, most points in the ($m_A$, tan $\beta$) planes corresponding to fixed values of $\mu$, $m_{1/2}$ and $m_0$ do not have a cold dark matter density within the range favoured by WMAP and other astrophysical and cosmological measurements [24].

10 Gravitino Dark Matter?

As already mentioned, it is possible that the LSP might be the gravitino [24], which would therefore pro-
Fig. 6. WMAP-compatible \((M_A, \tan \beta)\) planes for two NUHM benchmark surfaces, displaying (top) the 5-σ discovery contours for \(H/A \to \tau^+ \tau^-\) at the LHC with 60 or 30 fb\(^{-1}\) (depending on the \(\tau\) decay channels) and for \(H^\pm \to \tau^\pm \nu\) detection in the CMS detector when \(M_{H^\pm} > m_t\), and (bottom) the 1-, 2-, 3- and 5-σ contours (2-σ in bold) for SUSY-induced deviations from the SM value for the ratio \(BR(h \to \tau^+ \tau^-)/BR(h \to WW^*)\) at the LHC with 30 or 300 fb\(^{-1}\) [23].

Vide the dark matter (GDM), and this is a generic possibility even in minimal supergravity (mSUGRA), as shown in Fig. 7. After taking into account the LEP and \(b \to s\gamma\) constraints, there is a (pale blue) strip where the lightest neutralino is the LSP, a disallowed (brown) wedge where the LSP would be the lighter stau \(\tilde{\tau}_1\) [24], and another (yellow) wedge where the \(\tilde{\tau}_1\) is the next-to-lightest sparticle (NLSP) and metastable, but its decays do not upset the cosmological light-element abundances.

It is a feature of any GDM scenario with gravity-mediated supersymmetry breaking that the NLSP has
an uncertainty to locate the impact point on the cavern wall with walls [30]. The idea would be to use the muon system 1 could be dug out of the LHC experimental cavern. This would be useful if the $\tilde{\tau}_1$ lifetime is more than about $10^6$ s, but not if it is much shorter.

There is, however, an additional cosmological effect that needs to be taken into account. If the NLSP is charged (like the $\tilde{\tau}_1$), it may form bound states in the early Universe, which would have additional effects on the light-element abundances [25]. Under certain circumstances, these might even improve the agreement of theoretical calculations with the observed abundances of $^{6,7}\text{Li}$ [81]. However, this is possible only in very restricted regions of the GDM parameter space, in which the NLSP is relatively heavy (at least in the first examples studied).

11 Complexity of the CMSSM

Assuming universal soft supersymmetry-breaking parameters, as in the CMSSM, there are two new CP-violating phases beyond those in the SM, namely Arg $(m_{1/2}\mu)$ and Arg$(A_0\mu)$ [32]. At the loop level, these induce mixing between the CP-even and -odd neutral Higgs bosons of the CMSSM, so that $(h, H, A) \rightarrow (H_1, H_2, H_3)$ with indefinite CP. As seen in Fig. 9 the new CP-violating parameters affect the couplings of the MSSM Higgs bosons as well as their masses. The phases could in principle allow the lightest CMSSM Higgs boson to be lighter than in the usual limit in the MSSM with real parameters, but they are subject to important constraints imposed by upper limits on electric dipole moments. There are prospects for probing these phases at the LHC, in both the Higgs and sparticle sectors.

12 Supersymmetric Flavour Physics

The flavour and CP structure of any new physics at the TeV scale is tightly constrained by the continuing agreement of data from the B factories and the Tevatron with the predictions of the SM, e.g., their measurements of $b \rightarrow s\gamma$ and $B_u \rightarrow \tau\nu$, and their upper limits on $B_s \rightarrow mu^+ mu^-$. Improvements in these measurements and limits are places to look for supersymmetric flavour physics, and other opportunities may be provided by $K$ physics [54], for example in the search for violations of flavour universality in $K \rightarrow e\nu$ and $K \rightarrow \mu\nu$ decays [35], or in $K \rightarrow \pi\nu\nu$ decays. Charged leptons may also play roles in unravelling the supersymmetric flavour puzzle. For example, in supersymmetric extensions of the see-saw model for neutrino masses, the lepton-flavour-violating processes $\nu \rightarrow e\gamma$ and $\nu \rightarrow \mu(e)\gamma$ may occur at observable rates [36, 37, 38], as illustrated in Fig. 10.

![Fig. 7. Example of an mSUGRA $(m_{1/2}, m_0)$ plane with contours of tan $\beta$ superposed, for $\mu > 0$ and $A_0/m_0 = 2.0, B_0 = A_0 - m_0$ [22]. The regions excluded by LEP are indicated, as are excluded by $b \rightarrow s\gamma$ decay (medium green shading), and the region favoured by $g_\mu - 2$ is light (beige) shaded. The region favoured by WMAP in the neutralino LSP case has light (blue) shading, and the regions with $\chi$ shading), and the region favoured by $g_\mu - 2$ is light (beige) shaded. The region favoured by WMAP in the neutralino LSP case has light (blue) shading, and the regions with $\chi$ and $\chi^0$ contours of $\tan \beta$ are indicated, as are excluded by $g_\mu - 2$.](image-url)
of consistent compactifications of strings on manifolds in extra dimensions, and each of these has dozens or hundreds of topological cycles through which there may be topological fluxes taking any of dozens of values. Somewhere in this landscape of an enormous number of string vacua, it is suggested there may be one with a vacuum energy in the range indicated by the cosmology dark energy. The question then arises how the Universe chooses which of these vacua. One may also wonder whether, since nature apparently has the opportunity to choose a small vacuum energy, perhaps it also chooses a small value of $m_{W'}$, in which case there might be no need for supersymmetry to render the choice natural.

Indeed, ideas for models without supersymmetry (or even a Higgs boson) were also discussed here \[10\], and a unified discussion of alternatives has been presented. As illustrated in Fig. 11 there is a continuum of alternatives to the supersymmetric paradigm, ranging from little Higgs models to holographic pseudo-Nambu-Goldstone-boson Higgs models to Randall-Sundrum scenarios to Higgsless models to technicolour models and back again. The good news is that many

![Fig. 8](image1.png)

**Fig. 8.** The mass of a metastable stau could be measured quite accurately at the LHC \[29\], as exemplified in three benchmark scenarios \[30\].

![Fig. 9](image2.png)

**Fig. 9.** Numerical estimates of (a) the $H_{1,2}$- effective-potential and pole masses and (b) $\delta_{H_{1,2}}$ as functions of $\text{Arg}(A_{33})$, in a CP-violating scenario with $M_{\text{SUSY}} = 0.5$ TeV, $\text{Arg} (m_{1/2} \mu) = 0$ and $90^\circ$. In plot (a), the effective-potential mass $M_{\tilde{H}_1}$ ($M_{\tilde{H}_2}$) is indicated by a solid (dash-dotted) line for $\text{Arg} (m_{1/2} \mu) = 0$ ($90^\circ$), and its pole mass $\tilde{M}_{H_1}$ ($\tilde{M}_{H_2}$) by a dashed (dotted) line for $\text{Arg} (m_{1/2} \mu) = 0$ ($90^\circ$) \[33\].

13 Suggestions from String Theory?

The full enormity of the ambiguity in the string vacuum has sunk in only recently, with numbers $O(10^{500})$ being banded about \[39\]. This ambiguity arises because there are certainly millions and perhaps billions

![Fig. 10](image3.png)

**Fig. 10.** Correlation between $\text{BR}(\mu \rightarrow e \gamma)$ and $\text{BR}(\tau \rightarrow \mu \gamma)$ for different $m_{N_3}$, displaying the impact of $\theta_{13}$ with a scan over $\theta_i$ \[37\]. The horizontal and vertical dashed (dotted) lines denote the experimental bounds (future sensitivities).
(most? all?) of these scenarios can be tested at the LHC.

An different question revived by the string landscape within the supersymmetric paradigm is whether we live in a metastable vacuum [41], a possibility discussed a long time ago as an exotic possibility in the framework of global supersymmetry [42]. If there are indeed myriads of consistent string vacua, it seems difficult to see why we should be living in the one that is energetically preferred.

The mainstream hope would be that string theory would add value to the MSSM by predicting the exact spectrum and grand unification, incorporating gauge and/or Yukawa unification and the see-saw mechanism and providing an explicit mechanism for breaking supersymmetry, e.g., via gaugino condensation [43]. One interesting variant of the conventional CMSSM scenario is the possibility of ‘mirage unification’, in which gaugino masses unify below the GUT scale as a result of mixed modulus and anomaly contributions to gaugino masses [44]:

\[
M_a = M_s (\rho + b_a g_a^2). \tag{1}
\]

Lowering the unification scale could have a dramatic effect on the phenomenology discussed previously in the CMSSM context. As seen in the top panel of Fig.12 the expected values of the sparticle masses change as the effective universality scale \( M_{in} \) is reduced and, as a consequence, the regions of parameter space favoured by cosmology may change significantly [45, 22], as seen in the lower panel of Fig.12. The LHC may soon tell us, in more ways than one, whether supersymmetry is a mirage!

**Fig. 11.** An illustration of the space of possible alternatives to supersymmetry at low energies [40].

**Fig. 12.** Evolution (top) of the gaugino mass parameters and the physical gluino mass as the effective ‘mirage’ unification scale \( M_{in} \) is reduced, and (below) an example of an \((m_{1/2}, m_0)\) plane with \( \tan \beta = 10 \) and \( A_0 = 0 \) and \( M_{in} = 10^{12.5} \) GeV, using the same notation as in Fig. 3. The region favoured by WMAP is very different from that in the CMSSM with GUT-scale universality.

**14 Conclusions**

LEP and the Tevatron have already advanced in the quests for supersymmetry and the Higgs boson, and these searches being continued by the Tevatron. In parallel, searches for supersymmetry have been underway in low-energy precision physics and in direct and indirect searches for dark matter, and will continue during the LHC era. However, the LHC will be the first accelerator to reveal to us directly what new physics exists at the electroweak scale. Without results from the LHC, starting around 2010, we will not know what major subsequent new accelerator investments would be optimal. One possibility, that would optimize the scientific return from immense investment that the community has made in the LHC, would be to improve its luminosity, perhaps by an order of magnitude. This would surely be interesting in many supersymmetric and other scenarios for physics beyond the SM. On a longer time-scale, there is general agreement that a linear e^+ e^- collider would be an ideal tool for studying in detail any new physics revealed by the LHC, provided it lies within the accessible energy range. Only time and the LHC will tell us whether the ILC will have sufficient energy, or whether physics will demand higher energy, as could be provided by CLIC.
References

1. F. Wilczek, arXiv:0708.4236 [hep-ph].
2. L. Evans, talk at this conference: see also http://lhc.web.cern.ch/lhc/
3. A. Duperrin, for the CDF and D0 Collaborations, arXiv:0710.3265 [hep-ex].
4. K. Jakobs, talk at this conference, see also:
5. A. Blondel, L. Camilleri, A. Ceccucci, J. Ellis, M. Lindroos, M. Mangano and G. Rolandi, Physics opportunities with future proton accelerators at CERN, arXiv:hep-ph/0609102.
6. C. Ruwiedel [ATLAS Collaboration], arXiv:0710.4954 [hep-ph].
7. J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. A. Olive and M. Srednicki, Nucl. Phys. B 238 (1984) 453.
8. M. Bradac et al., Astrophys. J. 652 (2006) 937 [arXiv:astro-ph/0608408].