Post-LEP CMSSM Benchmarks for Supersymmetry

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We introduce a set of CMSSM benchmark scenarios that take into account the constraints from LEP, Tevatron, $b \to s\gamma$, $g_\mu - 2$ and cosmology. The benchmark points are chosen to span the range of different generic possibilities, including focus-point models, points where coannihilation effects on the relic density are important, and points with rapid relic annihilation via direct-channel Higgs poles, as well as points with smaller sparticle masses. We make initial estimates of the physics reaches of different accelerators, including the LHC, and e^+e^- colliders in the sub- and multi-TeV ranges. We stress the complementarity of hadron and lepton colliders, with the latter favoured for non-strongly-interacting particles and precision measurements.

1. Introduction

The completion of the LEP experimental programme has brought to an end an era of precise electroweak measurements and the search for new particles with masses $\lesssim$ 100 GeV. With the start of Tevatron Run II, the advent of the LHC and hopefully a linear e^+e^- collider, the experimental exploration of the TeV energy scale is beginning in earnest.

The best-motivated scenario for new physics beyond the Standard Model (SM) at the TeV energy scale is generally agreed to be Supersymmetry. Theoretically, it is compellingly elegant, offers the possibility of unifying fermionic matter particles with bosonic force particles, is the only framework thought to be capable of connecting gravity with the other interactions, and appears essential for the consistency of string theory. However, none of these fundamental arguments offer clear advice as to the energy scale at which supersymmetric particles might appear. Preserving the gauge hierarchy in a natural way, however, motivates supersymmetry at the TeV scale. Supersymmetry suggests the existence of a light Higgs boson, which is favoured indirectly by precision electroweak data. If a Higgs particle weighing less than about 130 GeV is discovered at the Tevatron, testing for the existence of supersymmetric particles and exploring their properties would become a prime focus of the experiments at the LHC.

As an aid to the comparative assessment of the prospects for detecting and measuring these sparticles at different accelerators, benchmark sets of supersymmetric parameters have often been found useful, since they provide a focus for concentrating the discussion [1, 2, 3]. Here we review a recently-proposed set of post-LEP benchmark points that take into account constraints derived from the direct searches for sparticles and Higgs bosons, the measurement of the $b \to s\gamma$ branching ratio, and the preferred cosmological density range, within the framework of the constrained MSSM (CMSSM) [4]. Some of our points have been adopted by the working groups at Snowmass 2001 in defining the benchmark 'Snowmass slopes' 1–4. Input parameters in the CMSSM are universal gaugino masses $m_{1/2}$, scalar masses m_0 (including those of the Higgs multiplets) and trilinear supersymmetry breaking parameters A_0 at the supersymmetric grand unification scale, together with $\tan\beta$ and the sign of μ. This framework has the merit of being sufficiently specific that the different phenomenological constraints can be combined meaningfully. On the other hand, it is just one of the phenomenological possibilities offered by supersymmetry, and others also merit study.

2. Constraints

Important constraints on the CMSSM parameter space are provided by direct sparticle searches at LEP and the Tevatron collider. Also important is the LEP limit on the Higgs mass m_H >114.1 GeV [5]. This holds in the Standard Model and, for the lightest Higgs boson h, in the general MSSM for

$\tan\beta \lesssim 8$ and for all $\tan\beta$ in the CMSSM cases of interest, at least as long as CP is conserved. This limit imposes important indirect constraints on the CMSSM parameters, principally $m_{1/2}$. Finally, the loop-mediated $b \to s\gamma$ transition is sensitive to chargino, squark and charged Higgs masses. The $b \to s\gamma$ measurement [6, 7] is currently compatible with the rate predicted in the SM, thus restricting the possible mass range of those superpartners. This constraint is more important for $\mu < 0$ but is also significant for $\mu > 0$ when $\tan\beta$ is large.

The cosmological constraints on the CMSSM are set by requiring that the supersymmetric relic density $\rho_\chi = \Omega_\chi \rho_{\text{critical}}$ falls within the preferred range $0.1 < \Omega_\chi h^2 < 0.3$. The upper limit is rigorous, since astrophysics and cosmology tell us that the total matter density $\Omega_m \lesssim 0.4$, and the Hubble expansion rate $h \sim 1/\sqrt{2}$ to within about 10% (in units of 100 km/s/Mpc). On the other hand, the lower limit is optional, since there could be additional important contributions, other than sparticles, to the overall matter density. There are generic regions of the CMSSM parameter space where the relic density falls within the preferred range. Since the relic density typically increases with the relic mass, one might expect an upper limit on the mass of the lightest superparticle (LSP) $m_\chi \lesssim 1$ TeV. However, there are various ways in which this generic upper bound on m_χ can be evaded. For example, the relic density may be suppressed by coannihilation [8, 9, 10, 11, 12, 13, 14, 15, 16] and the allowed CMSSM region may acquire a 'tail' extending to large m_χ, as in the case where the next-to-lightest superpartner (NLSP) is the lighter stau, $\tilde{\tau}_1$, and $m_{\tilde{\tau}_1} \sim m_\chi$ [11, 12, 13, 16]. Another mechanism is rapid annihilation via a direct-channel pole when $m_\chi \sim \frac{1}{2} m_{Higgs,Z}$ [15, 17]. This may yield a 'funnel' extending to large $m_{1/2}$ and m_0 at large $\tan\beta$. Another allowed region at large m_0 is the 'focus-point' region [18, 19, 20], where the LSP has a sizable higgsino component, enhancing its annihilation.

These filaments extending the preferred CMSSM parameter space are clearly unconventional, but they cannot be excluded, and we think it important to investigate the sensitivity of future planned and proposed colliders to their phenomenology.

3. Proposed Benchmarks

The above constraints and limits define allowed regions in the $(m_{1/2}, m_0)$ plane which are qualitatively illustrated in Figure 1a. Electroweak symmetry breaking (EWSB) is not possible in the top left corner, and the LSP would be charged in the bottom right region. The experimental constraints on m_h and $b \to s\gamma$ exert pressures from the left, depending on the exact value of $\tan\beta$ and the sign of μ. In the remaining unshaded areas to the right the relic density is too large and the Universe is overclosed. We observe a central ('bulk') allowed region. The three filaments extending away from it are (from top to bottom) the 'focus-point' region, the rapid-annihilation 'funnel' and the coannihilation region.

In Figure 1b we show the corresponding allowed regions in the $(\tan\beta, m_0)$ plane. The absence of EWSB excludes the areas at the top and to the right (where $\mu^2 < 0$ and $m_A^2 < 0$, correspondingly). The m_h constraint is effective at low $\tan\beta$, while the bottom area is ruled out because the LSP is charged. The $b \to s\gamma$ constraint is maximally sensitive for large $\tan\beta$ and light superpartners, i.e., in the lower right corner. Finally, the relic density is too large in the remaining unshaded area in the middle. One can still recognize three distinct areas inside the allowed region: the 'focus point' branch at the top, the vertical band on the right, due to the rapid annihilation 'funnel', and the horizontal band at the bottom, comprising the 'bulk' and 'coannihilation' regions.

Within these allowed domains of CMSSM parameter space, thirteen benchmark points have been proposed, as sets of $m_{1/2}$, m_0, $\tan\beta$ and $sgn(\mu)$ values defining the entire spectrum of sparticles. These are given in Table I, while the details of the corresponding spectra are to be found in [4]. In order to reduce the number of free parameters and in the absence of clear guidance from experimental and theory constraints, for simplicity we have set $A_0 = 0$. Small nonzero values of A_0 have very little impact on phenomenology, because of the fixed point structure of the A-term renormalization-group equations. In order to obtain sufficiently distinct spectra, one must consider rather large values of A_0. The inputs listed in the Table have been used with the `SSARD` programme to calculate the last three lines. For the convenience of experimental simulations, in [4] we have also provided inputs for `ISASUGRA 7.51` which reproduce the relevant features of the benchmark spectra as closely as possible.

The recent precise measurement [21] of the anomalous magnetic moment of the muon, $g_\mu - 2$, which is in apparent disagreement with the SM at the $\simeq 2.5\sigma$ level, can also be used to derive

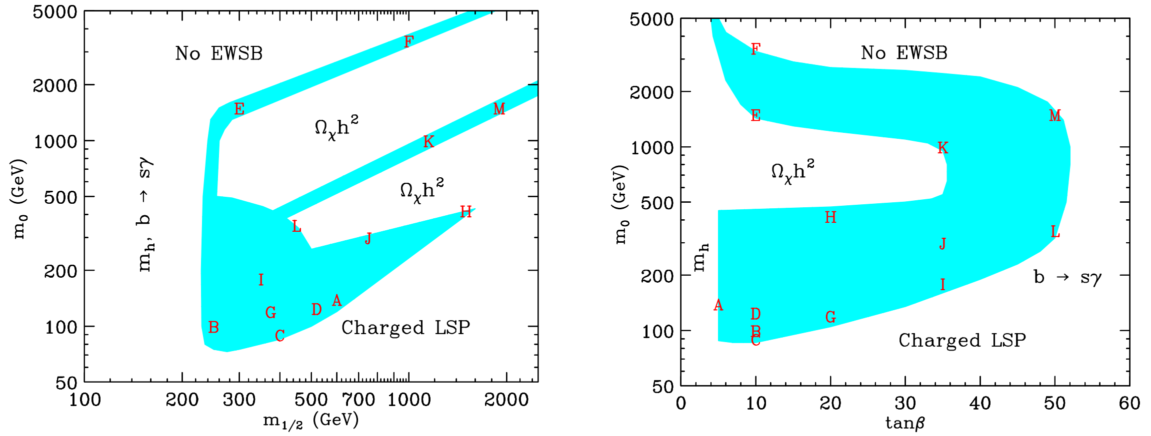

Figure 1: Locations of our proposed CMSSM benchmark points [4] in (a) the $(m_{1/2}, m_0)$ plane, and (b) the $(\tan\beta, m_0)$ plane. The shaded areas roughly indicate the various cosmologically preferred regions discussed in the text.

Table I The CMSSM parameters for the benchmark points proposed. In addition to the relic density $\Omega_\chi h^2$, the supersymmetric contribution to $a_\mu \equiv (g_\mu - 2)/2$ (in units of 10^{-10}), and the $b \to s\gamma$ decay branching ratio (in units of 10^{-4}) are given.

Model	A	B	C	D	E	F	G	H	I	J	K	L	M
$m_{1/2}$	600	250	400	525	300	1000	375	1500	350	750	1150	450	1900
m_0	140	100	90	125	1500	3450	120	419	180	300	1000	350	1500
$\tan\beta$	5	10	10	10	10	10	20	20	35	35	35	50	50
sign(μ)	+	+	+	−	+	+	+	+	+	+	−	+	+
$\Omega_\chi h^2$	0.26	0.18	0.14	0.19	0.31	0.17	0.16	0.29	0.16	0.20	0.19	0.21	0.17
δa_μ	2.8	28	13	-7.4	1.7	0.29	27	1.7	45	11	-3.3	31	2.1
$B_{s\gamma}$	3.54	2.80	3.48	4.07	3.40	3.32	3.10	3.28	2.55	3.21	3.78	2.71	3.24

constraints on the CMSSM parameters [22, 23, 24, 25, 26, 27, 28, 29]. It disfavours $\mu < 0$ and large values of m_0 and $m_{1/2}$ for $\mu > 0$. However, as the experimental accuracy is soon expected to be significantly improved and consensus on the calculation of hadronic contributions to $g_\mu - 2$ has yet be reached [1], we have chosen not to apply strictly this constraint in the definition of the benchmarks here. However, our choice of benchmark points has preferred somewhat those compatible with the present $g_\mu - 2$ measurement. Table I shows the supersymmetric contribution to $a_\mu \equiv (g_\mu - 2)/2$, the relic density, and the $B_{s\gamma} \equiv B(b \to s\gamma)$ for each benchmark point.

The proposed points were not chosen to provide an 'unbiased' statistical sampling of the CMSSM parameter space but rather are intended to illustrate different possibilities that are still allowed by the present constraints [4], highlighting their different experimental signatures. Five of the chosen points are in the 'bulk' region at small $m_{1/2}$ and m_0, four are spread along the coannihilation 'tail' at larger $m_{1/2}$ for various values of $\tan\beta$, two are in the 'focus-point' region at large m_0, and two are in rapid-annihilation 'funnels' at large $m_{1/2}$ and m_0. Furthermore, the proposed points range over the allowed values of $\tan\beta$ from 5 up to 35 and 50. Most of the points have $\mu > 0$, as favoured by $g_\mu - 2$, but there are also two points with $\mu < 0$.

4. Discussion

With time, some of the points we propose will become obsolete, for example because of Higgs or SUSY searches at the Tevatron or reductions in the error in $g_\mu - 2$. If there is no convincing

[1] We note, in particular, the current questioning of the sign of the light-by-light scattering contribution [30, 31].

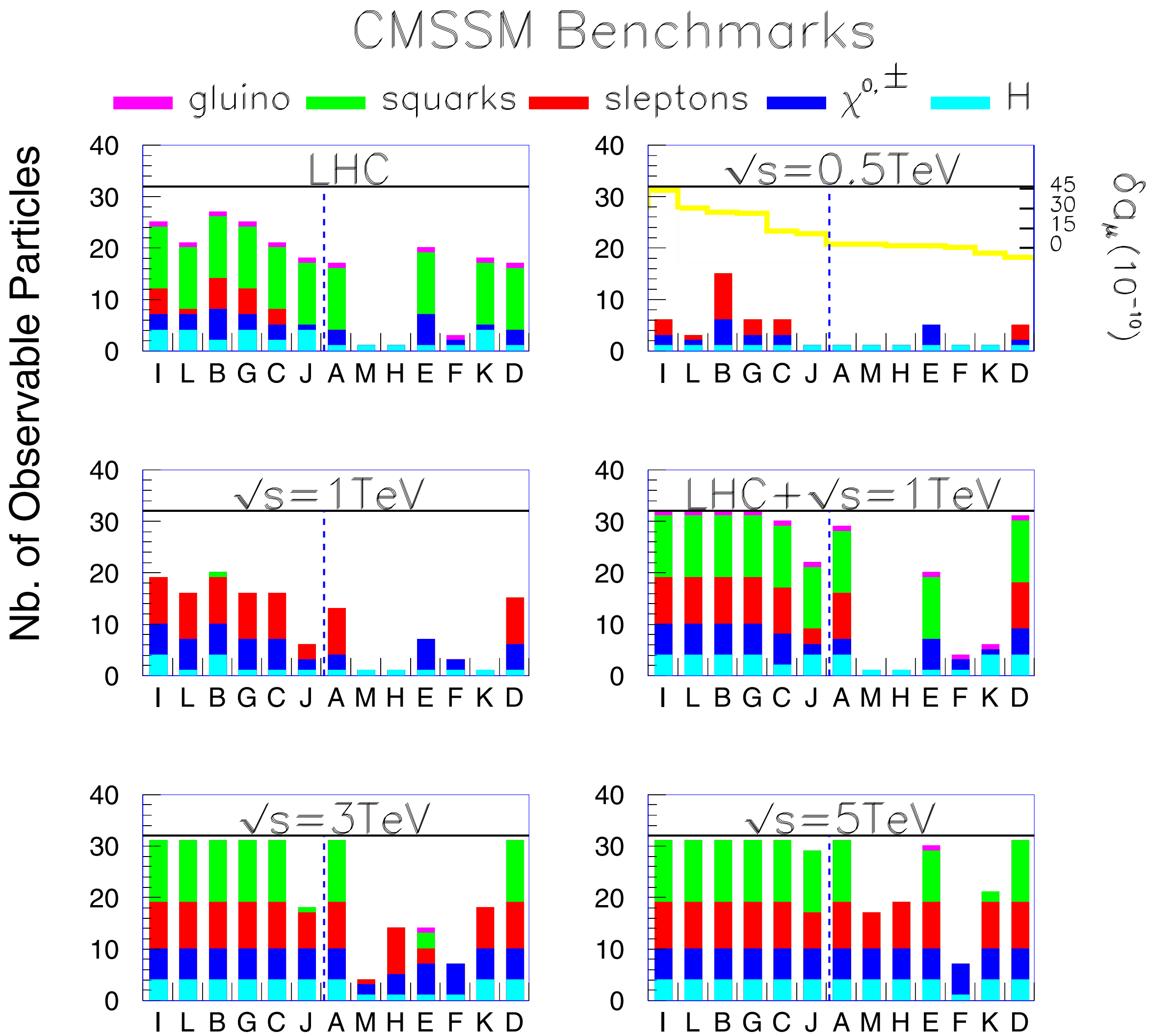

Figure 2: Summary of the prospective sensitivities of the LHC, linear colliders at different $\sqrt{s}$ energies and their combination in the proposed benchmark scenarios, which are ordered by their distance from the central value of $g_\mu - 2$, as indicated by the pale (yellow) line in the second panel. We see clearly the complementarity between an e^+e^- collider and the LHC in the TeV range of energies [4], with the former excelling for non-strongly-interacting particles, and the LHC for strongly-interacting sparticles and their cascade decays. CLIC provides unparallelled physics reach for non-strongly-interacting sparticles, extending beyond the TeV scale. We recall that mass and coupling measurements at e^+e^- colliders are usually much cleaner and more precise than at hadron–hadron colliders such as the LHC. Note, in particular, that it is not known how to distinguish the light squark flavours at the LHC.

indirect signal of new physics in low-energy experiments, the points in the coannihilation 'tail,' especially at its extreme tip, in the 'focus-point' region and in the rapid-annihilation 'funnels' will be more difficult to exclude or explore by direct detection. Some of these points might appear disfavoured by fine-tuning arguments, but they cannot be excluded. Taken together, the points proposed exemplify the range of different possible scenarios with which future colliders may be confronted, and should provide helpful aids for understanding better the complementarity of different accelerators in the TeV energy range.

The physics reaches of various TeV-scale colliders: the LHC, a 500-GeV to 1-TeV linear e^+e^- collider such as TESLA, the NLC or the JLC, and a 3- to 5-TeV linear e^+e^- collider such as CLIC have been estimated. The detectability criteria adopted for the LHC are discussed in detail in [4]. For e^+e^- colliders, the observability of each sparticle has been assessed on the basis of a required

0.1 fb for the product of production cross section × observable decay branching fraction [4]. A grand summary of the reaches of the various accelerators is presented graphically in Figure 2. The different levels of shading (colour) present the different types of sparticle: Higgses, charginos and neutralinos, sleptons, squarks and gluino. The first six points (I, L, B, G, C, J) are presently favoured: they are compatible within 2 σ with the present $g_\mu - 2$ measurement, and the fine tuning is relatively small for most of these points. Figure 2 summarises the discussion of [4], and exposes clearly the complementarity of hadron and electron machines. It is apparent that many alternative scenarios need to be kept in mind.

The LHC is expected to observe at least one CMSSM Higgs boson in all possible scenarios, and will in addition discover supersymmetry in most of the models studied. However, we do observe that the discovery of supersymmetry at the LHC is apparently not guaranteed, as exemplified by benchmarks H and M. It would be valuable to explore the extent to which precision measurements at the LHC could find indirect evidence for new physics in such scenarios. We have chosen points at different values of $\tan\beta$, five of which are at large values, which may assist the LHC experiments in assessing the implications of the underlying phenomenology in the trigger and reconstruction of events. Some points, such as B and those at high $\tan\beta$, have final states rich in τs, point H involves a heavy long-lived $\tilde{\tau}_1$, and the different mass hierarchies between squarks and the gluino affect the transverse energies and jet multiplicities of signal events. The CMS Collaboration has started an investigation of the B, C, E and G benchmarks, representative of these different scenarios, and analogous studies are foreseen by ATLAS. The need for high $\tan\beta$ points for LHC studies is dictated e.g. by the experimentally challenging $H \to \tau\tau$ decays, for a Higgs with a mass in the range of 300–500 GeV; this can be studied with points I and L.

An e^+e^- linear collider in the TeV range would in most cases bring important additional discoveries, exceptions being benchmarks H and M, and possibly E. Moreover, such a linear collider would also provide many high-precision measurements of the Higgs boson and supersymmetric particle masses and decay modes, that would play a pivotal role in first checking the CMSSM assumptions and subsequently pinning down its parameters. In particular point B is a prime candidate to be studied at such a collider.

In many of the scenarios proposed, the discovery and detailed measurements of the complete set of supersymmetric particles, and especially some of the heavy Higgses, gauginos and sleptons, will have to await the advent of a machine like CLIC. For some of the proposed points, CLIC may even need to run at an energy considerably higher than 3 TeV. Distinguishing the different squark flavours could be an interesting challenge for CLIC. The CLIC potential in mapping the sparticle properties is presently being studied for points C, E and H.

5. Prospects

Our preliminary observations need now to be confirmed by more detailed exploration of these benchmark scenarios. Moreover, we have not considered benchmarks for models with gauge-mediated [32, 33, 34], gaugino-mediated [35, 36] or anomaly-mediated [37, 38] supersymmetry breaking, or models with broken R parity. Studies of additional benchmarks in these and other models would represent interesting complements to this work. History reminds us that benchmarks have a limited shelf-life: at most one of them can be correct, and most probably none. In future, the CMSSM parameter space will be coming under increasing pressure from improved measurements of $g_\mu - 2$, assuming that the present theoretical understanding can also be improved, and $b \to s\gamma$, where the B factories will soon be dominating the measurements. We also anticipate significant improvement in the sensitivity of searches for supersymmetric dark matter [39]. This may stimulate the further redefinition of benchmarks for supersymmetry. However, we hope that the diversity of sparticle spectra and experimental signatures represented in these benchmarks will guarantee some general validity for the conclusions that can be obtained from their detailed study.

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