SUPERSYMMETRY

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A. Introduction: Supersymmetry is a generalization of the space-time symmetries of quantum field theory that transforms fermions into bosons and vice versa. It also provides a framework for the unification of particle physics and gravity, which takes place at an energy of order the Planck scale ($\approx 10^{19}$ GeV) [1–3]. However, supersymmetry is clearly not an exact symmetry of nature, and therefore must be broken. In theories of "low-energy" supersymmetry, the effective scale of supersymmetry breaking is tied to the electroweak scale [4–6]. In this way, it is hoped that supersymmetry will ultimately explain the origin of the large hierarchy between the W and Z masses and the Planck scale. At present, there are no unambiguous experimental results that require the existence of low-energy supersymmetry. However, if experimentation at future colliders uncovers evidence for supersymmetry, this would have a profound effect on the study of TeV-scale physics and the development of a more fundamental theory of mass and symmetry-breaking phenomena in particle physics.

B. Structure of the MSSM: The minimal supersymmetric extension of the Standard Model (MSSM) consists of taking the Standard Model and adding the corresponding supersymmetric partners [7]. In addition, the MSSM contains two hypercharge $Y = \pm 1$ Higgs doublets, which is the minimal structure for the Higgs sector of an anomaly-free supersymmetric extension of the Standard Model. The supersymmetric structure of the theory also requires (at least) two Higgs doublets to generate mass for both "up"-type and "down"-type quarks (and charged leptons) [8,9]. All renormalizable supersymmetric interactions consistent with (global) B–L conservation (B =baryon number and L =lepton number) are included. Finally, the most general soft-supersymmetry-breaking terms are added [10].

If supersymmetry is relevant for explaining the scale of electroweak interactions, then the mass parameters that occur in the soft-supersymmetry-breaking terms must be of order 1 TeV or below [11]. Some bounds on these parameters exist due to the absence of supersymmetric-particle production at current accelerators (see the Particle Listings following this note). Additional constraints arise from limits on the contributions of virtual supersymmetric particle exchange to a variety of Standard Model processes [12]. The impact of precision electroweak measurements at LEP and SLC on the MSSM parameter space is discussed briefly at the end of this note.

As a consequence of B–L invariance, the MSSM possesses a discrete R-parity invariance, where $R = (-1)^{3(B-L)+2S}$ for a particle of spin S [13]. Note that this formula implies that all the ordinary Standard Model particles have even R-parity, whereas the corresponding supersymmetric partners have odd R-parity. The conservation of R-parity in scattering and decay processes has a crucial impact on supersymmetric phenomenology. For example, starting from an initial state involving ordinary (R-even) particles, it follows that supersymmetric particles must be produced in pairs. In general, these particles are highly unstable and decay quickly into lighter states. However, R-parity invariance also implies that the lightest supersymmetric particle (LSP) is absolutely stable, and must eventually be produced at the end of a decay chain initiated by the decay of a heavy unstable supersymmetric particle.

In order to be consistent with cosmological constraints, the LSP is almost certainly electrically and color neutral [14]. Consequently, the LSP is weakly-interacting in ordinary matter, *i.e.* it behaves like a stable heavy neutrino and will escape detectors without being directly observed. Thus, the canonical signature for (R-parity conserving) supersymmetric theories is missing (transverse) energy, due to the escape of the LSP.

Some model builders attempt to relax the assumption of R-parity conservation. Models of this type must break B–L and are therefore strongly constrained by experiment [15]. Nevertheless, it is still important to allow for the possibility of R-parity violating processes in the search for supersymmetry. In such models, the LSP is unstable and supersymmetric particles can be singly produced and destroyed in association with B or L violation. These features lead to a phenomenology of broken-R-parity models that is very different from that of the MSSM.

In the MSSM, supersymmetry breaking is accomplished by including the soft-supersymmetry breaking terms mentioned earlier. These terms parametrize our ignorance of the fundamental mechanism of supersymmetry breaking. If this breaking occurs spontaneously, then (in the absence of supergravity) a massless Goldstone fermion called the *goldstino* ($\widetilde{G}$) must exist. The goldstino would then be the LSP and could play an important role in supersymmetric phenomenology [16]. In models that incorporate supergravity, this picture changes. If supergravity is spontaneously broken, the goldstino is absorbed ("eaten") by the *gravitino* ($g_{3/2}$), the spin-3/2 partner of the graviton [17]. By this super-Higgs mechanism, the gravitino acquires a mass ($m_{3/2}$). In many models, the gravitino mass is of order the electroweak-symmetry-breaking scale, while its couplings are gravitational in strength [1,18]. Such a gravitino would play no role in supersymmetric phenomenology at colliders.

The parameters of the MSSM are conveniently described by considering separately the supersymmetry-conserving sector and the supersymmetry-breaking sector. A careful discussion of the conventions used in defining the MSSM parameters can be found in Ref. 19. Among the parameters of the supersymmetry conserving sector are: (i) gauge couplings: g_s, g, and g', corresponding to the Standard Model gauge group SU(3)$\times$SU(2)$\times$U(1) respectively; (ii) Higgs-Yukawa couplings: λ_e, λ_u, and λ_d (which are 3×3 matrices in flavor space); and (iii) a supersymmetry-conserving Higgs mass parameter μ.

The supersymmetry-breaking sector contains the following set of parameters: (i) gaugino Majorana masses M_3, M_2 and M_1 associated with the SU(3), SU(2), and U(1) subgroups of the Standard Model; (ii) scalar mass matrices for the squarks and sleptons; (iii) Higgs-squark-squark trilinear interaction terms (the so-called "A-parameters") and corresponding terms involving the sleptons; and (iv) three scalar Higgs mass parameters—two diagonal and one off-diagonal mass terms for the two Higgs doublets. These three mass parameters can be re-expressed in terms of the two Higgs vacuum expectation values, v_1 and v_2, and one physical Higgs mass. Here, v_1 (v_2) is the vacuum expectation value of the Higgs field which couples exclusively to down-type (up-type) quarks and leptons. Note that $v_1^2 + v_2^2 = (246 \text{ GeV})^2$ is fixed by the W mass (or equivalently by the Fermi constant G_F), while the ratio

$$\tan\beta = v_2/v_1 \tag{1}$$

is a free parameter of the model.

The supersymmetric constraints imply that the MSSM Higgs sector is automatically CP-conserving (at tree-level). Thus, $\tan\beta$ is a real parameter (conventionally chosen to be positive), and the physical neutral Higgs scalars are CP-eigenstates. Nevertheless, the MSSM does contain a number of possible new sources of CP violation. For example, gaugino-mass parameters, the A-parameters, and μ may be complex. Some combination of these complex phases must be less than of order 10^{-2}–10^{-3} (for a supersymmetry-breaking scale of 100 GeV) to avoid generating electric dipole moments for the neutron, electron, and atoms in conflict with observed data [20]. However, these complex phases have little impact on the direct searches for supersymmetric particles, and are usually ignored in experimental analyses.

C. The Higgs sector of the MSSM: Before describing the supersymmetric-particle sector, let us consider the Higgs sector of the MSSM [21]. There are five physical Higgs particles in this model: a charged Higgs pair ($H^\pm$), two CP-even neutral Higgs bosons (denoted by H_1^0 and H_2^0 where $m_{H_1^0} \leq m_{H_2^0}$) and one CP-odd neutral Higgs boson (A^0). The properties of the Higgs sector are determined by the Higgs potential which is made up of quadratic terms [whose squared-mass coefficients were mentioned above Eq. (1)] and quartic interaction terms. The strengths of the interaction terms are directly related to the gauge couplings by supersymmetry (and are not affected at tree-level by supersymmetry-breaking). As a result, $\tan\beta$ [defined in Eq. (1)] and one Higgs mass determine: the Higgs spectrum, an angle α [which indicates the amount of mixing of the original $Y = \pm 1$ Higgs doublet states in the physical CP-even scalars], and the Higgs boson couplings.

When one-loop radiative corrections are incorporated, additional parameters of the supersymmetric model enter via virtual loops. The impact of these corrections can be significant [22,23]. For example, at tree-level, the MSSM predicts $m_{H_1^0} \leq m_Z$ [8,9]. If true, this would imply that experiments to be performed at LEP-2 operating at its maximum energy and luminosity would rule out the MSSM if H_1^0 were not found. However, this Higgs mass bound can be violated when the radiative corrections are incorporated. For example, in Ref. 22, the following approximate upper bound was obtained for $m_{H_1^0}$ (assuming $m_{A^0} > m_Z$) in the limit of $m_Z \ll m_t \ll M_{\widetilde{t}}$ [where top-squark ($\widetilde{t}_L$–$\widetilde{t}_R$) mixing is neglected]

$$m^2_{H_1^0} \lesssim m_Z^2 + \frac{3g^2 m_Z^4}{16\pi^2 m_W^2} \times \left\{ \ln\left(\frac{M^2_{\widetilde{t}}}{m_t^2}\right)\left[\frac{2m_t^4 - m_t^2 m_Z^2}{m_Z^4}\right] + \frac{m_t^2}{3m_Z^2}\right\}. \tag{2}$$

More refined computations (which include the effects of top-squark mixing, renormalization group improvement, and the leading two-loop contributions) yield $m_{H_1^0} \lesssim 125$ GeV for $m_t =$ 175 GeV and a top-squark mass of $M_{\widetilde{t}} = 1$ TeV [24]. Clearly, the radiative corrections to the Higgs masses have a significant impact on the search for the Higgs bosons of the MSSM at LEP [25].

D. Supersymmetric-particle spectrum: Consider next the supersymmetric-particle sector of the MSSM. The supersymmetric partners of the gauge and Higgs bosons are fermions, whose names are obtained by appending "ino" at the end of the corresponding Standard Model particle name. The *gluino* is the color octet Majorana fermion partner of the gluon with mass $M_{\widetilde{g}} = |M_3|$. The supersymmetric partners of the electroweak gauge and Higgs bosons (the *gauginos* and *Higgsinos*) can mix. As a result, the physical mass eigenstates are model-dependent linear combinations of these states, called *charginos* and *neutralinos*, which are obtained by diagonalizing the corresponding mass matrices. The chargino-mass matrix depends on M_2, μ, $\tan\beta$ and m_W [26].

The corresponding chargino-mass eigenstates are denoted by $\widetilde{\chi}_1^+$ and $\widetilde{\chi}_2^+$, with masses

$$M^2_{\widetilde{\chi}_1^+,\widetilde{\chi}_2^+} = \tfrac{1}{2}\Bigg\{|\mu|^2 + |M_2|^2 + 2m_W^2 \mp \Bigg[\left(|\mu|^2 + |M_2|^2 + 2m_W^2\right)^2 - 4|\mu|^2|M_2|^2 - 4m_W^4\sin^2 2\beta + 8m_W^2\sin 2\beta\,\mathrm{Re}(\mu M_2)\Bigg]^{1/2}\Bigg\}\,, \quad (3)$$

where the states are ordered such that $M_{\widetilde{\chi}_1^+} \leq M_{\widetilde{\chi}_2^+}$. If CP-violating effects are ignored (in which case, M_2 and μ are real parameters), then one can choose a convention where $\tan\beta$ and M_2 are positive. (Note that the relative sign of M_2 and μ is meaningful. The sign of μ is convention-dependent; the reader is warned that both sign conventions appear in the literature.) The sign convention for μ implicit in Eq. (3) is used by the LEP collaborations [27] in their plots of exclusion contours in the M_2 *vs.* μ plane derived from the non-observation of $Z \to \widetilde{\chi}_1^+\widetilde{\chi}_1^-$. The neutralino mass matrix depends on M_1, M_2, μ, $\tan\beta$, m_Z, and the weak mixing angle θ_W [26]. The corresponding neutralino eigenstates are usually denoted by $\widetilde{\chi}_i^0$ $(i = 1, \ldots 4)$, according to the convention that $M_{\widetilde{\chi}_1^0} \leq M_{\widetilde{\chi}_2^0} \leq M_{\widetilde{\chi}_3^0} \leq M_{\widetilde{\chi}_4^0}$. If a chargino or neutralino eigenstate approximates a particular gaugino or Higgsino state, it may be convenient to use the corresponding nomenclature. For example, if M_1 and M_2 are small compared to m_Z (and μ), then the lightest neutralino $\widetilde{\chi}_1^0$ will be nearly a pure photino, $\widetilde{\gamma}$ (the supersymmetric partner of the photon).

It is common practice in the literature to reduce the supersymmetric parameter freedom by requiring that all three gaugino-mass parameters are equal at some grand unification scale. Then, at the electroweak scale, the gaugino-mass parameters can be expressed in terms of one of them (say, M_2). The other two gaugino-mass parameters are given by

$$M_3 = (g_s^2/g^2)M_2\ , \qquad M_1 = (5g'^2/3g^2)M_2\ . \quad (4)$$

Having made this assumption, the chargino and neutralino masses and mixing angles depend only on three unknown parameters: the gluino mass, μ, and $\tan\beta$. However, the assumption of gaugino-mass unification could prove false and must eventually be tested experimentally.

The supersymmetric partners of the quarks and leptons are spin-zero bosons: the *squarks*, charged *sleptons*, and *sneutrinos*. For a given fermion f, there are two supersymmetric partners $\widetilde{f}_L$ and $\widetilde{f}_R$ which are scalar partners of the corresponding left and right-handed fermion. (There is no $\widetilde{\nu}_R$.) However, in general, $\widetilde{f}_L$ and $\widetilde{f}_R$ are not mass-eigenstates since there is $\widetilde{f}_L$-$\widetilde{f}_R$ mixing which is proportional in strength to the corresponding element of the scalar mass-squared matrix [28]:

$$M^2_{LR} = \begin{cases} m_d(A_d - \mu\tan\beta), & \text{for “down”-type } f \\ m_u(A_u - \mu\cot\beta), & \text{for “up”-type } f, \end{cases} \tag{5}$$

where m_d (m_u) is the mass of the appropriate "down" ("up") type quark or lepton. Here, A_d and A_u are (unknown) soft-supersymmetry-breaking A–parameters and μ and $\tan\beta$ have been defined earlier. The signs of the A parameters are also convention-dependent; see Ref. 19. Due to the appearance of the *fermion* mass in Eq. (5), one expects M_{LR} to be small compared to the diagonal squark and slepton masses, with the possible exception of the top-squark, since m_t is large, and the bottom-squark and tau-slepton if $\tan\beta \gg 1$.

The (diagonal) L- and R-type squark and slepton masses are given by [2]

$$M^2_{\widetilde{u}_L} = M^2_{\widetilde{Q}} + m^2_u + m^2_Z\cos 2\beta(\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W) \tag{6}$$

$$M^2_{\widetilde{u}_R} = M^2_{\widetilde{U}} + m^2_u + \tfrac{2}{3}m^2_Z\cos 2\beta\sin^2\theta_W \tag{7}$$

$$M^2_{\widetilde{d}_L} = M^2_{\widetilde{Q}} + m^2_d - m^2_Z\cos 2\beta(\tfrac{1}{2} - \tfrac{1}{3}\sin^2\theta_W) \tag{8}$$

$$M^2_{\widetilde{d}_R} = M^2_{\widetilde{D}} + m^2_d - \tfrac{1}{3}m^2_Z\cos 2\beta\sin^2\theta_W \tag{9}$$

$$M^2_{\widetilde{\nu}} = M^2_{\widetilde{L}} + \tfrac{1}{2}m^2_Z\cos 2\beta \tag{10}$$

$$M^2_{\widetilde{e}_L} = M^2_{\widetilde{L}} + m^2_e - m^2_Z\cos 2\beta(\tfrac{1}{2} - \sin^2\theta_W) \tag{11}$$

$$M^2_{\widetilde{e}_R} = M^2_{\widetilde{E}} + m^2_e - m^2_Z\cos 2\beta\sin^2\theta_W\,. \tag{12}$$

The soft-supersymmetry-breaking parameters: $M_{\widetilde{Q}}$, $M_{\widetilde{U}}$, $M_{\widetilde{D}}$, $M_{\widetilde{L}}$, and $M_{\widetilde{E}}$ are unknown parameters. In the equations above, the notation of first generation fermions has been used and generational indices have been suppressed. Further complications such as intergenerational mixing are possible, although there are some constraints from the nonobservation of flavor-changing neutral currents (FCNC) [29].

E. Reducing the MSSM parameter freedom: One way to guarantee the absence of significant FCNC's mediated by virtual supersymmetric-particle exchange is to posit that the diagonal soft-supersymmetry-breaking scalar squared-masses are universal in flavor space at some energy scale (normally taken to be at or near the Planck scale) [5,30,31]. Renormalization group evolution is used to determine the low-energy values for the scalar mass parameters listed above. This assumption substantially reduces the MSSM parameter freedom. For example, supersymmetric grand unified models with universal scalar masses at the Planck scale typically give [32] $M_{\widetilde{L}} \approx M_{\widetilde{E}} < M_{\widetilde{Q}} \approx M_{\widetilde{U}} \approx M_{\widetilde{D}}$ with the squark masses somewhere between a factor of 1–3 larger than the slepton masses (neglecting generational distinctions). More specifically, the first two generations are thought to be nearly degenerate in mass, while $M_{\widetilde{Q}_3}$ and $M_{\widetilde{U}_3}$ are typically reduced by a factor of 1–3 from the other soft-supersymmetry-breaking masses because of renormalization effects due to the heavy top quark mass.

As a result, four flavors of squarks (with two squark eigenstates per flavor) and $\widetilde{b}_R$ will be nearly mass-degenerate and somewhat heavier than six flavors of nearly mass-degenerate sleptons (with two per flavor for the charged sleptons and one per flavor for the sneutrinos). On the other hand, the $\widetilde{b}_L$ mass and the diagonal $\widetilde{t}_L$ and $\widetilde{t}_R$ masses are reduced compared to the common squark mass of the first two generations. In addition, third generation squark masses and tau-slepton masses are sensitive to the strength of the respective $\widetilde{f}_L$–$\widetilde{f}_R$ mixing as discussed below Eq. (5).

Two additional theoretical frameworks are often introduced to reduce further the MSSM parameter freedom [1,2,33]. The first involves grand unified theories (GUTs) and the desert hypothesis (*i.e* no new physics between the TeV-scale and the GUT-scale). Perhaps one of the most compelling hints for low-energy supersymmetry is the unification of SU(3)×SU(2)×U(1) gauge couplings predicted by supersymmetric GUT models [5,34] (with the supersymmetry breaking scale of order 1 TeV or below). The unification, which takes place at an energy scale of order 10^{16} GeV, is quite robust (and depends weakly on the details of the GUT-scale theory). For example, a recent analysis [35] finds that supersymmetric GUT unification implies that $\alpha_s(m_Z) = 0.129 \pm 0.010$, not including threshold corrections due to GUT-scale particles (which could diminish the value of $\alpha_s(m_Z)$). This result is compatible with the world average of $\alpha_s(m_Z) = 0.118 \pm 0.003$ as quoted by the Particle Data Group. In contrast, gauge coupling unification in the simplest nonsupersymmetric GUT models fails by many standard deviations [36].

Grand unification can impose additional constraints through the unification of Higgs-fermion Yukawa couplings (λ_f). There is some evidence that $\lambda_b = \lambda_\tau$ leads to good low-energy phenomenology [37], and an intriguing possibility that in the MSSM (in the parameter regime where $\tan\beta \simeq m_t/m_b$) $\lambda_b = \lambda_\tau = \lambda_t$ may be phenomenologically viable [38]. However, such unification constraints are GUT-model dependent, and do not address the origin of the first and second generation fermion masses and the CKM mixing matrix. Finally, grand unification imposes constraints on the soft-supersymmetry-breaking parameters. For example, gaugino-mass unification leads to the relations given in Eq. (4). Diagonal squark and slepton soft-supersymmetry-breaking scalar masses may also be unified at the GUT scale (analogous to the unification of Higgs-fermion Yukawa couplings).

In order to further reduce the number of independent soft-supersymmetry-breaking parameters (with or without grand unification), an additional simplifying assumption is required. In the minimal supergravity theory, the soft-supersymmetry-breaking parameters are often taken to have the following simple form. Referring to the parameter list given above Eq. (1), the Planck-scale values of the soft-supersymmetry-breaking terms depend on the following minimal set of parameters: (i) a universal gaugino mass $m_{1/2}$; (ii) a universal diagonal scalar-mass parameter m_0 [whose consequences were described at the beginning of this section]; (iii) a universal A-parameter, A_0; and (iv) three scalar Higgs mass parameters—two common diagonal-squared masses given by $|\mu_0|^2 + m_0^2$ and an off-diagonal-squared mass given by $B_0\mu_0$ (which defines the Planck-scale supersymmetry-breaking parameter B_0), where μ_0 is the Planck-scale value of the μ-parameter.

As before, renormalization group evolution is used to compute the low-energy values of the supersymmetry-breaking parameters and determines the supersymmetric-particle spectrum. Moreover, in this approach, electroweak symmetry breaking is induced radiatively if one of the Higgs diagonal-squared masses is forced negative by the evolution. This occurs in models with a large Higgs-top quark Yukawa coupling (*i.e.* large m_t). As a result, the two Higgs vacuum expectation values (or equivalently, m_Z and $\tan\beta$) can be expressed as a function of the Planck-scale supergravity parameters. The simplest procedure [32] is to remove μ_0 and B_0 in favor of m_Z and $\tan\beta$ (the sign of μ_0 is not fixed in this process). In this case, the MSSM spectrum and its interactions are determined by m_0, A_0, $m_{1/2}$, $\tan\beta$, and the sign of μ_0 (in addition to the parameters of the Standard Model). However, the minimal approach above is probably too restrictive. Theoretical considerations suggest that the universality of Planck-scale soft-supersymmetry breaking parameters is not generic [39]. In the absence of a fundamental theory of supersymmetry breaking, further progress will require a detailed knowledge of the supersymmetric-particle spectrum in order to determine the nature of the Planck-scale parameters. Of course, any of the theoretical assumptions described in this section could be wrong and must eventually be tested experimentally.

F. The MSSM and precision of electroweak data: The MSSM (with or without constraints imposed from the theory near the Planck scale) provides a framework that can be tested by precision electroweak data. The level of accuracy of the measured Z decay observables at LEP and SLC is sufficient to test the structure of the one-loop radiative corrections of the electroweak model [40], and is thus potentially sensitive to the virtual effects of undiscovered particles. Combining the most recent LEP and SLC electroweak results [41] with the recent top-quark mass measurement at the Tevatron [42], a weak preference is found [41,43] for a light Higgs boson mass of order m_Z, which is consistent with the MSSM Higgs mass upper bound previously noted. Moreover, for Z decay observables, the effects of virtual supersymmetric-particle exchange are suppressed by a factor of $m_Z^2/M_{\rm SUSY}^2$, and therefore decouple in the limit of large supersymmetric-particle masses. It follows that for $M_{\rm SUSY}^2 \gg m_Z$ (in practice, it is sufficient to have all supersymmetric-particle masses above 200 GeV) the MSSM yields an equally good fit to the precision electroweak data as compared to the Standard Model fit.

On the other hand, there are a few tantalizing hints in the data for deviations from Standard Model predictions. Indeed, if $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ is confirmed to lie above its Standard Model prediction due to the presence of new physics, then a plausible candidate for the new physics would be the MSSM with some light supersymmetric particles (*e.g.* a light chargino and top-squark and/or a light CP-odd scalar, A^0) close in mass to their present LEP bounds [44,45]. Such a scenario would be tested by the search for supersymmetric particles at LEP-2 and the Tevatron.

G. Beyond the MSSM: Nonminimal versions of low-energy supersymmetry can also be constructed. These models add additional matter and/or gauge super-multiplets to the MSSM (at the TeV scale or below). Experimental and theoretical constraints place some restrictions on these approaches, although no comprehensive treatment has yet appeared in the literature.

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