Chapter 1

Z' Physics and Supersymmetry

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We review the status of heavy neutral gauge bosons, Z', with emphasis on constraints that arise in supersymmetric models, especially those motivated from superstring compactifications. After elaborating on the status and (lack of) predictive power for general models with an additional Z', we concentrate on motivations and successes for Z' physics in supersymmetric theories in general and in a class of superstring models in particular. We review phenomenologically viable scenarios and their implications with the Z' mass in the electroweak or in the intermediate scale region.

1.1. Introduction

The existence of heavy neutral (Z') vector gauge bosons are a feature of many extensions of the standard model (SM). In particular, one (or more) additional $U(1)'$ gauge factors provide one of the simplest extensions of the SM. Additional Z' gauge bosons appear in grand unified theories (GUT's), superstring compactifications, alternative models of electroweak symmetry breaking, in models involving an (almost) hidden dark sector, and other classes of models.[1]

However, for those models which do not incorporate constraints due to supersymmetry, supergravity, or superstring theory, the masses of additional gauge bosons are usually free parameters which can range from the electroweak scale $\mathcal{O}(1\text{ TeV})$ to the Planck scale M_{Pl} [a]. In addition, models with extended gauge symmetry generically contain exotic particles, e.g., new heavy quarks or leptons which are non-chiral under $SU(2)_L$, or new SM singlets, with masses that are tied to those of the new Z's, but are otherwise unconstrained. Thus, such models lack predictive power for Z' physics, and much of the phenomenological work in this context is of the "searching under the lamp-post" variety. In particular, there is no strong motivation to think that an extra Z' would actually be light enough to be observed at future colliders. Even within ordinary GUT's, there is no robust prediction for the mass of a Z'. (There *are*, however, concrete predictions for the relative couplings of the ordinary and exotic particles to the Z' in each ordinary or supersymmetric GUT.)

On the other hand $N = 1$ supersymmetric models typically provide more constraints. First, the scalar potential is determined by the superpotential, Kähler potential, D-terms, and soft supersymmetry breaking terms, and is generally more restrictive. In particular, the $U(1)'$ D-term, which is typically of the order of $M_{Z'}^2$, breaks supersymmetry, so the $U(1)'$ breaking scale should usually not be much larger than the electroweak scale, i.e., no more than a few TeV.[4,5] (Exceptions involving flat or almost flat directions are mentioned below.) Secondly, superstring models often imply constraints on the superpotential, such as the absence of mass terms and the existence of large (order one) Yukawa couplings, which can determine the mechanism and scale of $U(1)'$ breaking.

There are two promising classes of theoretical structures in which the minimal supersymmetric standard model (MSSM) and its extensions are likely to be embedded. One are superstring models which compactify directly to a gauge group consisting of the SM and possibly additional $U(1)'$ factors.[6–10] Some of the superstring models are based on $E_6 \times E_8$ Calabi-Yau compactifications of the heterotic string, in which E_6 is already broken at the string scale, e.g., to the SM gauge group and an additional $U(1)'$ factor, via the Wilson line (Hosotani) mechanism. Such Z' models, primarily employing the quantum numbers associated with a particular E_6 breaking pattern, were addressed in.[11–13] The Z' phenomenology of superstring models with a true GUT symmetry at the string scale has not been explored. Most of the recent work on supersymmetric Z's has been

[a]Major exceptions are alternative models of electroweak symmetry breaking,[2] which often involve new gauge symmetries broken at the TeV scale, and models connecting to a hidden dark matter sector by a light (MeV-GeV) weakly-coupled Z'.[3] Neither class will be discussed in detail here.

from the point of view of the first type, non-GUT models, and it will be emphasized in this contribution.

In the models studied in[6–10,12] the $U(1)'$ breaking is radiative. This is analogous to radiative electroweak breaking, in which the (running) Higgs mass-squared terms are positive at the Planck scale, but one of them is driven negative at a low or intermediate scale by the large Yukawa coupling associated with the top quark. Similarly, in radiative $U(1)'$ breaking one or more SM scalars that carry $U(1)'$ charges have positive mass-squared terms at the Planck scale. However, if these scalars have large Yukawa couplings to exotic multiplets or to Higgs doublets their mass-squares can be driven negative at lower scales so that the scalar develops a vacuum expectation value and breaks the $U(1)'$ symmetry. Typically, the initial (Planck scale) values of the Higgs and SM scalar mass-squares are comparable and given by the scale of soft supersymmetry breaking. In a class of models in which the magnitudes of the Yukawa couplings in the superpotential are motivated to be of $\mathcal{O}(1)$, the radiative breaking can occur, and it depends on the exotic particle content and on the boundary conditions for the soft supersymmetry breaking terms at the large scale. The symmetry breaking usually takes place at the electroweak scale,[6–8,10,12] so that the Z' mass is comparable to the ordinary Z and to the scale of supersymmetry breaking, and is typically less than a few TeV.[7,8,10] However, the breaking can instead occur at an intermediate scale[6,7,9,14] if the minimum occurs along an F- and D-flat direction [b]. Secluded sector models,[15] in which the flatness of the symmetry breaking direction is lifted by a small F term, interpolate between these cases, and allow $M_{Z'}$ in the multi-TeV range.

A class of superstring compactifications, based on free fermionic constructions[16–20] [c], contains all of these ingredients, including the general particle content and gauge group of the MSSM, and in general additional non-anomalous $U(1)'$ gauge symmetry factors and vector pairs of exotic chiral supermultiplets [d]. In this class of models there are no bilinear (mass) terms in the superpotential, and the non-vanishing trilinear (Yukawa) terms are of order one. These conditions usually suffice to require and allow ra-

[b] The actual minimum is typically shifted slightly away from the D-flat direction by soft supersymmetry breaking terms, leading to finite shifts in the sparticle and Higgs masses of order of the soft breaking, even for a large $U(1)'$ breaking scale.

[c] Certain models based on orbifold constructions with Wilson lines[21] also possess the gauge structure and the particle content of the MSSM.

[d] Related classes of models based on higher level Kač-Moody algebra constructions yield[19,22,23] GUT gauge symmetry with adjoint representations. These models have not yet been explored for Z' physics.

diative $U(1)'$ breaking, respectively.[7] Thus, supersymmetric models (with constraints on couplings from a class of superstring models) *have predictive power* for the masses of Z' and the accompanying exotic particles. In that sense they are superior to general models with extended gauge structures. For these reasons, we would like to advocate that within supersymmetry (and superstring theory constraints), perhaps the best motivated physics for future experiments, next to the Higgs and sparticle searches, are searches for Z' and the accompanying exotic particles. On the other hand, at present we have little theoretical control over the type of dynamically preferred superstring compactification, or of the soft supersymmetry breaking parameters, i.e., the origin of supersymmetry breaking in superstring models; it is therefore hard to make general predictions for the specific $U(1)'$ charges and other details of the models.

In supersymmetric models additional $U(1)'$s would have important theoretical implications. For example, an extra $U(1)'$ breaking at the electroweak scale in a supersymmetric extension of the SM could solve the μ problem,[24,25] by forbidding an elementary superpotential μ-term $W = \mu \hat{H}_1 \cdot \hat{H}_2$, but allowing a trilinear coupling $W = h_s \hat{S} \hat{H}_1 \cdot \hat{H}_2$, where $\hat{S}$ is a SM singlet. The VEV $\langle S \rangle$ not only breaks the $U(1)'$ gauge symmetry but induces an effective $\mu_{eff} = h_s \langle S \rangle$ which is typically at the electroweak or soft supersymmetry breaking scale.[6–8] This mechanism is similar to the NMSSM (or can be considered as one of a larger class of NMSSM-like models),[26] but because of the continuous $U(1)'$ symmetry it is automatically free of domain wall and induced tadpole effects. Other possible implications, to be briefly discussed in Sections 1.4 and 1.5, include the Higgs, scalar partner, chargino, and neutralino masses and couplings, and thus the properties of the lightest supersymmetric particle (LSP); mechanisms for the generation of small Dirac or Majorana neutrino masses (or both); possible flavor changing neutral currents (FCNC); the hierarchies of small masses for quarks and charged leptons; a possible role in the mediation of supersymmetry breaking; the production of superpartners at colliders; and the possibility of electroweak baryogenesis (EWBG).

This review is organized as follows. In Section 1.2 we describe representative Z' models, introduce notation, and summarize the experimental situation. In Section 1.3, we review the features of Z' models with or without supersymmetry and with or without GUT embedding. In Section 1.4 we discuss both the electroweak and the intermediate scale scenarios for $U(1)'$ symmetry breaking in detail. In Section 1.5 we briefly discuss other implications of a Z', especially at the electroweak-TeV scale.

1.2. Z' Physics

1.2.1. *Overview of Z' Models*

The most commonly studied Z' couplings are sequential, GUT, T_{3R} and $B-L$, string-motivated, and phenomenological.[1] In each case, the Z' couples to $g'Q$, with g' the $U(1)'$ gauge coupling and Q the charge. The sequential models have the same couplings to fermions as the SM Z, and are mainly introduced as a convenient reference model for describing experimental constraints.

In the GUT-motivated cases[e] $g' = \sqrt{5/3}\sin\theta_W G\lambda_g^{1/2}$, with $G \equiv \sqrt{g_L^2+g_Y^2} = g_L/\cos\theta_W$, where g_L, g_Y are the gauge couplings of $SU(2)_L$ and $U(1)_Y$, and λ_g depends on the symmetry breaking pattern.[27] If the GUT group breaks directly to $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$, then $\lambda_g = 1$. Standard GUT-type examples include: (i) Z_χ, which occurs in $SO_{10} \to SU(5) \times U(1)_\chi$; (ii) Z_ψ, from $E_6 \to SO_{10} \times U(1)_\psi$; (iii) $Z_\eta = \sqrt{3/8}Z_\chi - \sqrt{5/8}Z_\psi$, which occurs in Calabi-Yau compactifications of the heterotic string if E_6 breaks directly to a rank 5 group[28] via the Wilson line (Hosotani) mechanism; (iv) the general E_6 boson $Z(\theta_{E_6}) = \cos\theta_{E_6} Z_\chi + \sin\theta_{E_6} Z_\psi$, where $0 \le \theta_{E_6} < \pi$ is a mixing angle. The $U(1)'$ charges for other specific examples are given in.[1,29]

Another class of models is based on linear combinations of T_{3R} and $B-L$, where $T_{3R} = \frac{1}{2}$ (u_R, ν_R), $-\frac{1}{2}$ (d_R, e_R), and 0 (ψ_L). They are economical in that they are the unique family-universal $U(1)'$ extensions of the SM with nontrivial couplings that do not require any new fermions other than right-handed neutrinos to cancel anomalies.[30] An important subclass, Z_{LR}, occurs in left-right symmetric (LR) models,[31] which contain a right-handed charged boson as well as an additional neutral boson. The ratio $\kappa = g_R/g_L$ of the gauge couplings $g_{L,R}$ for $SU(2)_{L,R}$, respectively, parametrizes the whole class of models. $\kappa = 1$ corresponds to manifest or pseudo-manifest left-right symmetry. In this case $\lambda_g = 1$ by construction and $\kappa > 0.55$ for consistency.[32,33]

Superstring constructions that compactify directly to the SM often contain additional non-anomalous $U(1)'$ factors, some of which may survive to the TeV scale.[34,35] Heterotic constructions often descend through an underlying $SO(10)$ or E_6 in the higher-dimensional space, and may therefore lead to the T_{3R} and $B-L$ or the E_6-type charges. Additional or alternative

[e] The models in this class are often viewed as plausible examples of anomaly-free charge assignments for the ordinary and exotic particles, rather than as full grand unified theories, to avoid some of the difficulties mentioned in Section 1.3.2.

$U(1)'$ structures may emerge that do not have any GUT-type interpretation and therefore have very model dependent charges, as often occurs in free fermionic constructions, for example. Intersecting brane models often involve Q_{LR} because of an underlying Pati-Salam structure.[36] Other branes can lead to other types of $U(1)'$ charges. For example, the construction in[37] involves two extra Z' s, one coupling to Q_{LR} and the other only to the Higgs and the right-handed fermions.

String constructions usually also involve anomalous $U(1)'$ symmetries,[38] which must be cancelled by a generalized Green-Schwarz mechanism. Heterotic constructions typically have one anomalous combination of $U(1)'$s. In the Type II string constructions with D-branes, the intersecting D-brane models[35] are particularly suited for the study of particle physics, since they provide a geometric origin of the gauge symmetry and the chiral spectrum. Note, however, that T-duality maps to Type I models with magnetized branes, and Type IIB constructions with D-branes at singularities yield analogous results. Specifically, a stack of N D-branes typically yields a gauge symmetry $U(N) \sim SU(N) \times U(1)$ where $U(1)$ is usually anomalous, with the anomaly cancelled via a generalized Green-Schwarz mechanism. The associated Z' typically acquires a string-scale mass due to Chern-Simons terms, a string realization of the Stückelberg mechanism.[39] However, a particular linear combination of multiple $U(1)'$s, associated with multiple stacks of intersecting D-branes, can in principle remain massless, provided specific conditions on the cycles wrapped by the D-branes are satisfied.[40] (For recent implementations of these constraints within bottom-up MSSM constructions with intersecting D-branes, see.[41]) Such massless Z's have to acquire masses at scales below the string scale, as studied in Section 1.4.

Another way to obtain massless Z's in compactifications with D-branes is by the brane-splitting mechanism, where a non-abelian gauge symmetry of a stack of D-branes is broken down to non-anomalous abelian factors after the splitting of a stack of D-branes to wrap different cycles in the same homology. For a detailed analysis of this symmetry breaking mechanism both from the string theory and the field theory perspective, see.[42]

As for anomalous Z's, effective trilinear vertices may be generated between the Z' and the SM gauge bosons.[43] If there are large extra dimensions the string scale and therefore the Z' mass may be very low, e.g., at the TeV scale, with anomalous decays into ZZ, WW, and $Z\gamma$.[44] An anomalous $U(1)'$ survives as a global symmetry on the perturbative low energy theory, restricting the possible couplings and having possible implications, e.g., for baryon or lepton number. There has been considerable recent work involving the nonperturbative generation of such otherwise forbidden couplings by string instanton effects in intersecting brane constructions,[45] with implications for Majorana or Dirac neutrino masses, top-Yukawa couplings, and the μ parameter.

There are many other types of Z' models, often motivated on phenomenological grounds.[1] For example, many authors have considered couplings based on the cancellation of anomalies, with various assumptions concerning the types of exotic particles that are allowed,[1,30,46] whether the minimal MSSM-type gauge coupling unification is maintained,[47] and other conditions. Other classes of models include:

- Those emerging from Little Higgs models; un-unified models; dynamical symmetry breaking models, e.g., with strong $t\bar{t}$ coupling; or other types of new TeV scale dynamics or symmetry breaking mechanisms.[2]
- Kaluza-Klein excitations of the SM gauge bosons in models with large and/or warped extra dimensions.
- Models in which the Z' is decoupled from some or all of the SM particles, such as leptophobic, fermiophobic or weak coupling models.[5] These may have a low scale or even massless Z'.
- Models in which the Z' couples to a hidden sector, e.g., associated with dark matter or supersymmetry breaking.[3] Such a Z' may (almost) decouple from the SM particles and serve as a weakly coupled "portal" to the hidden sector (with small mixings due to kinetic mixing, higher-dimensional operators, etc), or may couple to both sectors, e.g., to mediate supersymmetry breaking.
- Supersymmetric models with a secluded or intermediate scale Z', e.g., associated with (approximately) flat directions, small Dirac m_ν from higher-dimensional operators, etc.
- Models with family-nonuniversal couplings, leading to Z'-mediated FCNC.
- Stückelberg models,[39,48] which allow a Z' mass without spontaneous symmetry breaking.

1.2.2. *Mass and Kinetic Mixing*

The $Z - Z'$ mass matrix takes the form

$$M^2 = \begin{pmatrix} M_Z^2 & \gamma M_Z^2 \\ \gamma M_Z^2 & M_{Z'}^2 \end{pmatrix}, \tag{1.1}$$

where γ is determined within each model once the Higgs sector is specified. The physical (mass) eigenstates of mass $M_{1,2}$ are then

$$Z_1 = +Z\cos\phi + Z'\sin\phi, \qquad Z_2 = -Z\sin\phi + Z'\cos\phi, \tag{1.2}$$

where Z_1 is the known boson and $\tan 2\phi = 2\gamma M_Z^2/(M_{Z'}^2 - M_Z^2)$. The mass M_1 is shifted from the SM value M_Z by the mixing, so that $M_Z^2 - M_1^2 = \tan^2\phi(M_2^2 - M_Z^2)$. For $M_Z \ll M_{Z'}$ one has $M_2 \sim M_{Z'}$ and $\phi \sim \gamma M_1^2/M_2^2$.

There may also be a gauge invariant mixing of the $U(1)$ gauge boson kinetic energy terms.[49] Such terms are usually absent initially, but a (usually small) effect may be induced by loops,[49–52] e.g., from nondegenerate heavy particles, or in running couplings when $Tr(Q_Y Q) \neq 0$, with the trace restricted to the light degrees of freedom. This can occur in GUTs, for example, when multiplets are split into light and heavy sectors. Kinetic mixing can also be due to higher genus effects in superstring theory.[53] However, such effects are small for superstring vacua based on the free fermionic construction [f], on the order of at most a %. An important implication[g] of kinetic mixing is that the effective charge of a TeV-scale Z' at low energies may contain a component proportional to the ordinary weak hypercharge [h].

1.2.3. *Precision Electroweak and Collider Limits and Prospects*

Constraints can be placed on the existence of Z''s either indirectly from fits to high precision electroweak data in weak neutral current experiments, at the Z-pole (LEP and SLC), at LEP 2, and at a future International Linear Collider (ILC), or from direct searches at hadron colliders, i.e., the Tevatron and LHC. The results depend on the chiral couplings of the Z', on the relation between the Z' mass and the $Z - Z'$ mixing angle, and

[f]If one of the $U(1)$'s is associated with a large supersymmetry-breaking D-term in a "hidden" sector, the kinetic mixing could propagate this large scale to the observable sector.[53]

[g]The effects of kinetic mixing for a light or massless Z' are quite different. For example, kinetic mixing of a massless Z' with the photon could induce tiny effective electric charges for hidden sector particles coupled to the Z'.[49]

[h]The Z' may also contain a component of hypercharge in models which are not based on $U(1)_Y \times U(1)'$, such as the LR.

on whether there are open decay channels to superpartners and exotics.[54] The GUT based Z' models, described at the beginning of Section 1.2.1, are fairly representative, with lower limits on the Z' mass in the range 800-1200 GeV,[1,29] and the mixing restricted to $|\phi| <$ few $\times 10^{-3}$. The limits may be considerably weaker in nonstandard models, e.g., with reduced couplings to ordinary fermions.[3]

The LHC has a discovery potential to $\sim 4-5$ TeV through $pp \to Z' \to e^+e^-, \mu^+\mu^-, jj, \bar{b}b, \bar{t}t, e\mu, \tau^+\tau^-$, and should be able to make diagnostic studies of the Z' couplings up to $M_{Z'} \sim 2-2.5$ TeV. Possible probes include relative branching ratios; forward-backward asymmetries; rapidity distributions; lineshape variables; associated production of $Z'Z, Z'W, Z'\gamma$; rare (but enhanced) decays such as $Z' \to W\bar{f}_1 f_2$ involving a radiated W; and decays such as $Z' \to W^+W^-, Zh, 3Z$, or $W^\pm H^\mp$, in which the small mixing is compensated by the longitudinal W, Z enhancement. The ILC would perhaps have an even larger reach for Z' discovery or diagnostics associated with interference effects in cross sections and asymmetries. Reviews and recent references include.[1,55–62]

1.3. Z's–Theoretical Considerations

Z' models fall into different classes, depending on whether they are embedded into a GUT and whether supersymmetry is included.

1.3.1. *Z' Models in GUT's without Supersymmetry*

In a general class of models with extended gauge structure which do not incorporate constraints of supersymmetry, supergravity or superstring theory, the mass and couplings of additional gauge bosons are free parameters in general. However, one class of models of special interest is based on the GUT gauge structure.[63] At M_U the GUT gauge group is broken to a smaller one which includes the SM gauge group and may also include additional $U(1)'$ factors. As opposed to general models the gauge couplings of the additional Z' are now determined within each GUT model, and the quantum numbers of additional exotic particles are also fixed.[5] However, even within GUT models, there is *no robust prediction for the Z' mass and the mass of the accompanying exotic particles*; without fine-tuning of parameters their masses are likely to be at M_U, while with fine-tuning their masses can be anywhere between M_U and M_Z.

1.3.2. Z' Models in Supersymmetric GUT's

Supersymmetric GUT models possess the advantages of the ordinary GUT models, e.g., gauge coupling unification, and they may provide more constraints on the parameters of the theory. The GUT models with the MSSM below M_U have a gauge coupling unification[64] that is consistent with current experiments. Taking the observed α and weak angle $\sin^2\theta_W$ as inputs and extrapolating assuming the particle content of the MSSM, one finds[65] that the running $SU(2)_L$ and $U(1)_Y$ couplings meet at a scale $M_U \sim 3\times 10^{16}$ GeV. One can then predict $\alpha_s(M_Z) \sim 0.130 \pm 0.010$ for the strong coupling, which is roughly consistent with, but slightly above, most experimental determinations, ~ 0.12. To ensure correct electroweak symmetry breaking, fine-tuning of the superpotential parameters or a specific (higher-dimensional) Higgs representation, e.g., the "missing partner" mechanism,[66,67] is needed.

Within a symmetry breaking scheme in which the GUT group is broken down to the SM and additional $U(1)'$ factors, the success of gauge coupling unification can be ensured only for certain exotic particle spectra. This in general involves fine-tuning of parameters in the superpotential. For example, in the E_6 models each SM family can be embedded in a 27-plet of E_6, along with a right-handed neutrino, Higgs pair $H_{1,2}$, a SM singlet S (which can break the $U(1)'$), and an exotic pair of ($SU(2)$-singlet) D-type quarks, along with their superpartners.[13,63] However, maintaining the MSSM-type unification for the SM gauge couplings requires the addition of an extra $H_1 + H_1^*$ or $H_2 + H_2^*$ from an incomplete (and therefore fine-tuned) $27 + 27^*$.[10] The parameters should be further constrained to ensure additional symmetry breaking. In particular, the breaking of $U(1)'$ within the full GUT context may involve large Higgs representations and/or fine-tuning to ensure $M_{Z'} \ll M_U$ and D- and F-flatness up to $\mathcal{O}(M_{Z'})$. Further fine-tuning of the superpotential parameters would be needed to allow $M_{Z'} \gg M_Z$ [i]. A final and major difficulty is that, in many cases, if one does achieve a low $U(1)'$ breaking scale there will be exotic particles of comparable mass that can mediate unacceptably rapid proton decay unless the GUT relations relating their Yukawa couplings to those of the Higgs are broken.

Thus, in spite of the constraining structure of supersymmetric GUT models, the mass of Z' and the accompanying exotic particles again gener-

[i] A somewhat analogous analysis of the symmetry breaking pattern of supersymmetric $SO(10)$ to the left-right and then SM gauge group was addressed in.[68]

ically tends to be of order M_U. Other mass scales could be achieved by choosing specific Higgs chiral supermultiplets and adjusting the amount of fine-tuning for the superpotential parameters.

1.3.3. *Supersymmetric Z' Models without GUT Embedding*

Supersymmetric models with additional $U(1)'$ factors, but without GUT embedding, provide a promising class of models with more predictive power, and are a possible *minimal extension of the MSSM*. If mass parameters are absent in the superpotential, the soft supersymmetry breaking masses and the type of the SM singlets responsible for the $U(1)'$ breaking determine the mass scale of the Z' without additional (excessive) fine-tuning. Furthermore, the dangerous Yukawa couplings that can lead to rapid proton decay may be absent.

Such a class of models can be derived within certain classes of superstring compactifications. In these models the massless particle spectrum and couplings in the superpotential are calculable, and there are *no mass parameters in the superpotential*. Thus, supersymmetric Z' models with built in constraints on couplings from superstring models *provide a class of models with a predictive power* for Z' physics and that of the accompanying exotic particles.

In the following Section we review the properties of Z's based on that type of model. It is primarily based on Refs.[7–9] An important related analysis was given in[6] [j]. Earlier work, which addresses Z's in models with softly broken $N = 1$ supergravity with no direct connection to superstring models, but with Z' quantum numbers obtained from E_6 embeddings (i.e., with E_6 broken already at the string scale by the Wilson line (Hosotani) mechanism), was given in.[11] More recent analyses in this context appeared in.[12,70] Z's which arise from the (intersecting) D-brane models of Type II string theory and remain massless at the string scale would also have to obtain mass at the level of the effective theory, along the lines discussed in the next Section.

1.4. $U(1)'$ Symmetry Breaking Scenarios

In this section we describe two important $U(1)'$-breaking scenarios in some detail. These were originally discussed in the context of a class of superstring compactifications that are based on free fermionic construc-

[j]Some aspects of Z's in superstring models were also addressed in.[69]

tions[16–20,22,23] (see also the extended discussion in[5]). This class provides the necessary ingredients for radiative $U(1)'$ breaking, either at the electroweak or at an intermediate scale. The particle content and the gauge group structure contain, along with the MSSM, additional $U(1)'$ gauge symmetry factors. The massless particle spectrum and the superpotential couplings (which do not have mass terms) are calculable. Importantly, in this class of superstring models the trilinear (Yukawa) couplings in the superpotential are either absent or of order one. However, most of the considerations are valid for other classes of string models as well.

In the following we shall concentrate on phenomenological consequences of an additional non-anomalous $U(1)'$ symmetry. Potential additional phenomenological problems [k] will not be addressed.

For the sake of simplicity we consider only one additional $U(1)'$. The symmetry breaking of the additional $U(1)'$ must take place via the Higgs mechanism, in which the scalar components of chiral supermultiplets S_i which carry non-zero charges under the $U(1)'$ acquire non-zero VEV's and spontaneously break the symmetry. The low energy effective action, responsible for symmetry breaking, is specified by the superpotential, Kähler potential, D-terms, and soft supersymmetry breaking terms.

We focus on two symmetry breaking scenarios: *(i) electroweak scale breaking.*[8] When an additional $U(1)'$ is broken by a *single* SM singlet S, the mass scale of the $U(1)'$ breaking should be[7] in the electroweak range (and not larger than a few TeV). The $U(1)'$ breaking may be radiative due to the large (of order one) Yukawa couplings of S to exotic particles. The scale of the symmetry breaking is set by the soft supersymmetry breaking scale, in analogy to the radiative breaking of the electroweak symmetry due to the large top Yukawa coupling. The analysis was generalized[6,8] by including the coupling of the two SM Higgs doublets to the SM singlet S.

(ii) Intermediate scale breaking.[9] This scenario takes place[7] if there are couplings in the renormalizable superpotential of exotic particles to two or more mirror-like singlets S_i with opposite signs of their $U(1)'$ charges. In this case, the potential may have D- and F-flat directions, along which it consists only of the quadratic soft supersymmetry breaking mass terms. If there is a mechanism to drive a particular linear combination negative at $\mu_{RAD} \gg M_Z$, the $U(1)'$ breaking is at *an intermediate scale* of order μ_{RAD},

[k] For example: (i) there may be additional color triplets which could mediate a too fast proton decay; (ii) the mass spectrum of the ordinary fermions may not be realistic; and (iii) the light exotic particle spectrum may not be consistent with gauge coupling unification.

or in the case of dominant non-renormalizable terms in the superpotential the $U(1)'$ takes place at an intermediate scale governed by these terms.

We will also comment briefly on the secluded models,[15] which are somewhat intermediate between cases (i) and (ii).

1.4.1. *Electroweak Scale Breaking*

The superpotential in this model is of the form:

$$W = h_s \hat{S} \hat{H}_1 \cdot \hat{H}_2 + h_Q \hat{U}_3^c \hat{Q}_3 \cdot \hat{H}_2, \tag{1.3}$$

where the Higgs doublet superfield $\hat{H}_2$ has only a Yukawa coupling to a single (third) quark family [1]. For simplicity, the Kähler potential is written in a canonical form, providing canonical kinetic energy terms for the matter superfields. Supersymmetry breaking is parametrized with the most general soft mass parameters, with $m^2_{1,2,S,Q,U}$ corresponding to the soft mass-squared terms of the scalar fields H_1, H_2, S, Q_3, U_3^c, respectively, and A and A_Q are the soft mass parameters associated with the first and the second trilinear terms in the superpotential (1.3).

Gauge symmetry breaking is now driven by the VEV's of the doublets H_1, H_2 and the singlet S, obtained by minimizing the Higgs potential. By an appropriate choice of the global phases of the fields, one can choose the VEV's such that $\langle H^0_{1,2} \rangle = v_{1,2}/\sqrt{2}$ and $\langle S \rangle = s/\sqrt{2}$ are positive in the true minimum. Whether the obtained local minimum of the potential is acceptable will depend on the location and depth of the other possible minima and of the barrier height and width between the minima.[72]

A nonzero value (in the electroweak range) for s renders the first term of the superpotential (1.3) into an effective μ-parameter, i.e., $\mu \hat{H}_1 \hat{H}_2$, with $\mu \equiv h_s s/\sqrt{2}$ in the electroweak range, thus providing an elegant solution to the μ problem.

The $Z - Z'$ mass-squared matrix is given by (1.1), where

$$M_Z^2 = \frac{1}{4} G^2 (v_1^2 + v_2^2), \qquad M_{Z'}^2 = {g'}^2 (v_1^2 Q_1^2 + v_2^2 Q_2^2 + s^2 Q_S^2), \tag{1.4}$$

$$\gamma = \frac{2g'}{G} \frac{(v_1^2 Q_1 - v_2^2 Q_2)}{v_1^2 + v_2^2}. \tag{1.5}$$

Here g' is the gauge coupling for $U(1)'$, $G = \sqrt{g_L^2 + g_Y^2}$, and $Q_{1,2}$ and Q_S are the $U(1)'$ charges for the $\hat{H}_{1,2}$ and $\hat{S}$ superfields.

[1] The masses of other quarks and leptons are obtained in this class of models through non-renormalizable terms.[71] The fermion masses obtained in this way may not be realistic.

Electroweak Scale Conditions

This symmetry breaking scenario can be classified in three different categories according to the value of the singlet s VEV:

$s = 0$. In this case the breaking is driven only by the two Higgs doublets (this would be the typical case if the soft mass of the singlet remains positive). The Z' boson would generically acquire mass of the same order as the Z, and some particles (Higgses, charginos and neutralinos) would tend to be dangerously light [m]. There is a possibility of a small $Z - Z'$ mixing due to cancellations, and by considerable fine-tuning one may be able to arrange the parameters to barely satisfy experimental constraints.

$s \sim v_{1,2}$. This case would naturally give $M_{Z'} \gtrsim M_Z$ (if $g'Q_{1,2}$ is not too small) and the effective μ-parameter may be small. Thus, some sparticles may be expected to be light. One requires $Q_1 = Q_2$ to have negligible $Z - Z'$ mixing [n]. A particularly interesting example is the "Large Trilinear Coupling Scenario", in which a large trilinear soft supersymmetry breaking term dominates the symmetry breaking pattern, and relative signs and the magnitudes of the soft mass-squared terms are not important since they contribute negligibly to the location of the minimum. The three Higgs fields assume approximately equal VEV's: $v_1 \sim v_2 \sim s \sim 174$ GeV. In this scenario, the electroweak phase transition may be first order, with potentially interesting cosmological implications.

$s \gg v_{1,2}$. Unless $g'Q_S$ is large, $M_{Z'} \gg M_Z$ requires $s \gg v_{1,2}$ and the effective μ-parameter is naturally large. In this case the breaking of the $U(1)'$ is triggered effectively by the running of the soft mass-squared term m_S^2 towards negative values in the infrared, yielding $s^2 \simeq -(2m_S^2)/(g'^2 Q_S^2)$ and $M_{Z'}^2 \sim -2m_S^2$, with m_S^2 evaluated at s. The presence of this large singlet VEV influences $SU(2)_L \times U(1)_Y$ breaking already at tree level. The hierarchy $M_{Z'} \gg M_Z$ results from a cancellation of different mass terms of order $M_{Z'}$; the fine-tuning involved is roughly given by $M_{Z'}/M_Z$. The $Z - Z'$ mixing is suppressed by the large Z' mass (in addition to any accidental cancellation for particular choices of charges). Excessive fine-tuning would be needed for $M_{Z'} \gg 1$ TeV. More details are given in[8] (see

[m] In the $Q_1 + Q_2 = 0$ (which allows an elementary μ-parameter) or large $\tan\beta = v_2/v_1 \gg 1$ cases one of the neutral gauge bosons becomes massless.[73] This does not provide a viable hierarchy since the $W^\pm$ mass is non-zero and related to $v_{1,2}$ and G in the usual way.

[n] Such models are allowed for, e.g., leptophobic couplings.

also[6,70]).

String Scale Conditions

A detailed discussion of the relation of the electroweak scale parameters to the boundary conditions at M_{string} is given in[5,8,10] (see also[6,7,12]), assuming that the non-zero Yukawa couplings are given by $h_s = h_Q = \sqrt{2}g_U$ at M_{string}, as determined in a class of superstring models. It was shown that the symmetry breaking scenarios described above can be obtained, but that one requires either nonuniversal soft breaking terms at M_{string}, or additional exotic particles, e.g., additional $SU(3)_C$ triplets $\hat{D}_{1,2}$, which couple to $\hat{S}$ in the superpotential.

The Spectra of Other Particles

The spectrum of physical Higgses after symmetry breaking consists of three neutral CP even scalars (h_i^0, $i = 1, 2, 3$), one CP odd pseudoscalar (A^0) and a pair of charged Higgses ($H^\pm$), i.e., it has one scalar more than in the MSSM (for a detailed analysis see,[8,74,75] for an earlier discussion see[4,11]). In the neutralino sector, there is an extra $U(1)'$ zino and the higgsino $\tilde{S}$ as well as the four MSSM neutralinos. In these models the LSP is usually mostly $\tilde{B}$. For large gaugino masses, however, the lightest neutralino is the singlino $\tilde{S}$, whose mass is of the order of M_Z. It provides a viable dark matter candidate.[76,77]

Masses for the squarks and sleptons can be obtained directly from the MSSM formulae by setting $\mu \equiv h_s s/\sqrt{2}$ and adding the pertinent D-term diagonal contributions from the $U(1)'$.[4,78] This extra term can produce significant mass deviations with respect to the minimal model and plays an important role in the connection between parameters at the electroweak and string scales.

1.4.2. *Intermediate Scale Breaking*

A mechanism to generate intermediate scale $U(1)'$ breaking in supersymmetric theories utilizes the D-flat directions,[14] which are in general present in the case of two or more SM singlets with opposite signs of the $U(1)'$ charges. For simplicity, consider *two* chiral multiplets $\hat{S}_{1,2}$ that are singlets under the SM gauge group, with the $U(1)'$ charges Q_{1S} and Q_{2S}, respectively. If these charges have opposite signs ($Q_{1S}Q_{2S} < 0$), there is a D-flat direction:

$$Q_{1S}\langle S_1\rangle^2 + Q_{2S}\langle S_2\rangle^2 = 0. \tag{1.6}$$

In the absence of the self-coupling of $\hat{S}_1$ and $\hat{S}_2$ in the superpotential there is an F-flat direction in the $S_{1,2}$ scalar field space as well. Then the only contribution to the scalar potential along this D- and F-flat direction is due to the soft mass-squared terms $m^2_{1S}|S_1|^2 + m^2_{2S}|S_2|^2$. For the (real) component along the flat direction $s \equiv (\sqrt{2|Q_{2S}|}\mathrm{Re}S_1 + \sqrt{2|Q_{1S}|}\mathrm{Re}S_2)/\sqrt{|Q_{1S}| + |Q_{2S}|}$ the potential is simply

$$V(s) = \frac{1}{2}m^2 s^2, \qquad m^2 \equiv \frac{|Q_{2S}|m^2_{1S} + |Q_{1S}|m^2_{2S}}{|Q_{1S}| + |Q_{2S}|}, \tag{1.7}$$

where $m^2_{1S,2S}$ are respectively the $S_{1,2}$ soft mass-squared terms. m^2 is evaluated at the scale s. For m^2 positive at the string scale it can be driven to negative values at the electroweak scale if $\hat{S}_1$ and/or $\hat{S}_2$ have a large Yukawa coupling to other fields, which is in general the case for this class of superstring models. In this case, $V(s)$ develops a minimum along the flat direction and s acquires a VEV[o].

From the minimization condition for (1.7) the VEV $\langle s\rangle$ occurs very close to the scale μ_{RAD} at which m^2 crosses zero. This scale is fixed by the RGE evolution of parameters from M_{string} down to the electroweak scale and lies in general at an intermediate scale. It can be achieved with universal boundary conditions at M_{string} as long as there is a large Yukawa coupling of SM singlets to other matter. The precise value depends on the type of couplings of $\hat{S}_{1,2}$ and the particle content of the model. Examples with μ_{RAD} in the range 10^{15} GeV – 10^4 GeV are discussed in detail in[9] (see also[6,7]).

Competition with Non-Renormalizable Operators

The stabilization of the minimum along the D-flat direction can also be due to non-renormalizable terms in the superpotential, which lift the F-flat direction for sufficiently large s. If these terms are important below μ_{RAD}, they will determine $\langle s\rangle$. The relevant non-renormalizable terms are of the

[o]If m^2 remains positive at the electroweak scale, but, e.g., $m^2_{1S} < 0$, then one recovers the electroweak scale case with $\langle S_1\rangle \neq 0$ and $\langle S_2\rangle = 0$.

form [p]

$$W_{\rm NR} = \left(\frac{\alpha_K}{M_{Pl}}\right)^K \hat{S}^{3+K}, \tag{1.8}$$

where $\hat{S}$ is the effective chiral superfield (i.e., $W_{\rm NR}$ may actually involve the product of distinct superfields $\hat{S}_i$) with the (real) scalar component along the D-flat direction, $K = 1, 2, \cdots$, and M_{Pl} is the Planck scale.

Including the F-term from (1.8), the potential along s is

$$V(s) = \frac{1}{2}m^2 s^2 + \frac{1}{2(K+2)}\left(\frac{s^{2+K}}{M^K}\right)^2, \tag{1.9}$$

where $M \equiv C_K M_{Pl}/\alpha_K$, and C_K is a coefficient of order unity. The VEV of s is then [q]

$$\langle s \rangle = \left(|m| M^K\right)^{\frac{1}{K+1}} \sim (m_{soft} M^K)^{\frac{1}{K+1}}, \tag{1.10}$$

where $m_{soft} = \mathcal{O}(|m|) = \mathcal{O}(M_Z)$ is a typical soft supersymmetry breaking scale. m^2 is evaluated at the scale $\langle s \rangle$ and has to satisfy the necessary condition $m^2(\langle s \rangle) < 0$. If non-renormalizable terms are negligible below μ_{RAD}, no solution to (1.10) exists and $\langle s \rangle$ is fixed solely by the running m^2.

The coefficients α_K in (1.8) and thus M in (1.9) are in principle calculable, at least in the free fermionic models discussed above. Depending on the $U(1)'$ charges and world-sheet symmetries of the superstring models, not all values of K are allowed. It is expected that the world-sheet integrals that determine the couplings of non-renormalizable terms are such that M increases as K increases. For $K = 1$ one obtains (in a class of models): $M \sim 3 \times 10^{17}$ GeV, and for $K = 2$: $M \sim 7 \times 10^{17}$ GeV.

Higgs and Higgsino Mass Spectrum

The mass of the physical field s in the vacuum $\langle s \rangle$ is either $\sim m_{soft}/4\pi$ for pure radiative breaking, or $\sim m_{soft}$ in the case of stabilization by non-renormalizable terms. Thus, the potential is very flat, with possible important cosmological consequences. The physical excitations along the transverse direction have an intermediate mass scale. There remains one

[p] One can also have terms of the form $\alpha_K^K \hat{S}^{2+K}\hat{\Phi}/M_{Pl}^K$, where Φ is a SM singlet that does not acquire a VEV. These have similar implications as the terms in (1.8).

[q] For simplicity, soft-terms of the type $(AW_{\rm NR} + {\rm H.c.})$ with $A \sim m_{soft}$ are not included in (1.9). Such terms do not affect the order of magnitude estimates.

massless pseudoscalar, which can acquire a mass from a soft supersymmetry breaking term of the type $AW_{\rm NR}$ or from loop corrections.

The fermionic part of the $Z' - S_1 - S_2$ sector consists of three neutralinos $(\tilde{B}', \tilde{S}_1, \tilde{S}_2)$. One combination is light, with mass of order m_{soft} (if the minimum is fixed by non-renormalizable terms) or of order $m_{soft}/4\pi$ (obtained at one-loop order when the minimum is instead determined by the running of m^2). The two other neutralinos have intermediate scale masses.

Other fields that couple to $\hat{S}_{1,2}$ in the renormalizable superpotential acquire intermediate scale masses, and those that do not remain light.

μ-Parameter

The flat direction S can have a set of non-renormalizable couplings to MSSM states that offer a solution to the μ problem. The non-renormalizable μ-generating terms are of the form,

$$W_\mu \sim \hat{H}_1 \hat{H}_2 \hat{S} \left(\frac{\hat{S}}{M} \right)^P . \tag{1.11}$$

For breaking due to non-renormalizable terms, $K = P$ yields an effective μ-parameter $\mu \sim m_{soft}$, while for pure radiative breaking $\mu \sim \mu_{RAD}^{P+1}/M^P$, which depends crucially on the value of μ_{RAD}.

Fermion Masses

Non-renormalizable couplings can also yield mass hierarchies between family generations. Generational up, down, and electron mass terms appear, via

$$W_{u_i} \sim \hat{H}_2 \hat{Q}_i \hat{U}_i^c \left(\frac{\hat{S}}{M} \right)^{P'_{u_i}} ; W_{d_i} \sim \hat{H}_1 \hat{Q}_i \hat{D}_i^c \left(\frac{\hat{S}}{M} \right)^{P'_{d_i}} ; W_{e_i} \sim \hat{H}_1 \hat{L}_i \hat{E}_i^c \left(\frac{\hat{S}}{M} \right)^{P'_{e_i}} , \tag{1.12}$$

with i the family number. K and $P_i^{'}$ can be chosen to yield a realistic hierarchy for the first two generations.[9] Presumably the top mass is associated with a renormalizable coupling ($P'_{u_3} = 0$). The other third family masses do not fit as well; it is possible that m_b and m_τ are associated with some other mechanism, such as non-renormalizable operators involving the VEV of a different singlet.

There may also be non-renormalizable Majorana and Dirac neutrino terms. They can produce small (non-seesaw) Dirac masses. It is also possible to have small Majorana masses, providing an interesting possibility for oscillations of the ordinary into sterile neutrinos.[79,80] A traditional seesaw can also be obtained, depending on the nature of the non-renormalizable operators.[9]

1.4.3. *Secluded Models*

In the weak scale model in (1.3) there is some tension between the electroweak scale and developing a large enough $M_{Z'}$. These can be decoupled without tuning when there are several S fields. For example, in the *secluded sector* model[15] there are four standard model singlets $S, S_{1,2,3}$ that are charged under a $U(1)'$, with

$$W = h_s \hat{S}\hat{H}_1 \cdot \hat{H}_2 + \lambda \hat{S}_1 \hat{S}_2 \hat{S}_3. \tag{1.13}$$

(Structures similar to this are often encountered in heterotic string constructions.) μ_{eff} is given by $h_s\langle S\rangle$, but all four VEVs contribute to $M_{Z'}$. The only couplings between the ordinary $(S, H_{1,2})$ and secluded $(S_{1,2,3})$ sectors are from the $U(1)'$ D term and the soft masses (special values of the $U(1)'$ charges, which allow soft mixing terms, are required to avoid unwanted additional global symmetries[81]). It is straightforward to choose the soft parameters so that there is a runaway (i.e., F- and D-flat) direction in the limit $\lambda \to 0$, for which the ordinary sector VEVs remain finite while the S_i VEVs become large. For λ finite but small, the flatness is lifted and the $\langle S_i\rangle$ and $M_{Z'}$ scale as $1/\lambda$. For example, one can find $M_{Z'}$ in the TeV range for $\lambda \sim 0.05 - 0.1$. Other implications of the secluded models are described in.[82]

1.5. Other Implications

The discovery of a TeV-scale Z' with electroweak-strength couplings would have implications far beyond the existence of a new vector particle. The role of a new $U(1)'$ gauge symmetry in solving the μ problem was already discussed in the Introduction, and a number of other implications in Section 1.4. Here, we list some of the other possibilities (see[1] for more complete references).

- TeV scale $U(1)'$ models generally involve an extended Higgs sector, requiring at least a SM singlet S to break the $U(1)'$ symmetry. New F and D-term contributions can relax the theoretical upper limit of ~ 130 GeV on the lightest Higgs scalar in the MSSM up to ~ 150

GeV, and smaller values of $\tan\beta$, e.g. ~ 1, become possible. Conversely, doublet-singlet mixing can allow a Higgs lighter than the direct SM and MSSM limits. Such mixing as well as the extended neutralino sector can lead to non-standard collider signatures.[75]

- $U(1)'$ models also have extended neutralino sectors,[77] involving at least the $\tilde{Z}'$ gaugino and the $\tilde{S}$ singlino, allowing non-standard couplings (e.g., light singlino-dominated), extended cascades, and modified possibilities for cold dark matter, $g_\mu - 2$, etc.
- Most family-universal $U(1)'$ models (with the exception of those involving T_{3R} and$B - L$) require new exotic fermions to cancel anomalies. These are usually non-chiral with respect to the SM (to avoid precision electroweak constraints) but chiral under the $U(1)'$. A typical example is a pair of $SU(2)$-singlet colored quarks $D_{L,R}$ with charge $-1/3$. Such exotics may decay by mixing, although that is often forbidden by R-parity. They may also decay by diquark or leptoquark couplings, or they be quasi-stable, decaying by higher-dimensional operators.[83,84]
- A heavy Z' may decay efficiently into sparticles, exotics, etc., constituting a "SUSY factory".[54,85]
- The $U(1)'$ charges may be family non-universal[r], leading to FCNC due to fermion mixings. The limits from K and μ decays and interactions are sufficiently strong that only the third family is likely to be non-universal.[87] Third family non-universality may lead to significant tree-level effects,[88] e.g., in $B_s - \bar{B}_s$ mixing or in charmless B_d decays, competing with SM loops, or with enhanced loops in the MSSM with large $\tan\beta$.
- A TeV-scale $U(1)'$ symmetry places new constraints on neutrino mass generation. Various versions allow or exclude Type I or II seesaws, extended seesaws, or small Dirac masses by higher-dimensional operators;[9,79,84,89] small Dirac masses by non-holomorphic soft terms;[90] and either Majorana (seesaw)[45] or small Dirac masses by string instantons.[91]
- Electroweak baryogenesis[92] is relatively easy to implement in $U(1)'$ (and other NMSSM-type) models because the cubic A term associated with the effective μ parameter can lead to a strongly first order electroweak phase transition,[93,94] and because of possible tree-level CP violation in the Higgs sector (which is not significantly con-

[r]This frequently occurs in string constructions.[34,35] For an E_6 GUT example, see.[86]

strained by EDMs).[94] However, the alternative leptogenesis model of baryogenesis, in which a lepton asymmetry is first created by the out of equilibrium decay of a heavy Majorana neutrino, and then converted to a baryon asymmetry by electroweak effects,[95] is forbidden by a light Z', at least in its simplest form, unless the heavy neutrino carries no $U(1)'$ charge.[96]

- Z' gauge bosons may couple only to an otherwise hidden sector associated with dark matter, etc., except for small effects associated, e.g., with kinetic mixing or higher-dimensional operators, thereby serving as a "portal" to that sector.[3] Examples include a massless Z';[49,97] a MeV-GeV "U-boson",[98] which is suggested by some dark matter models;[99] hidden valley models, which connect to a strongly coupled hidden sector;[100] and Stückelberg models.[48] Such models are not necessarily supersymmetric.
- Similarly, it often occurs in string constructions that a Z' couples to both the ordinary and "hidden" sectors. This allows the possibility of Z'-mediation of supersymmetry breaking,[101] in which a mass difference between the Z' and the associated gaugino is generated in the hidden sector and is communicated to the ordinary sector by loop effects. (See[102] for specific string realizations.) Scalar masses are generated at one loop and SM gaugino masses at two loops. If the latter are to be $\gtrsim 100$ GeV, then the scalar masses should be in the 100 TeV range for electroweak-size couplings, requiring a fine-tuning to obtain the electroweak scale (a mini form of split supersymmetry[103]). Alternatively, Z'-mediation can be combined with some other mediation mechanism for the SM gauginos to allow lower scalar masses. For example, the combination of Z' and anomaly mediation cures the problems of each and allows a realistic spectrum.[104] Other implications of a $U(1)'$ for supersymmetry breaking and mediation are reviewed in .[101]

1.6. Conclusions

Supersymmetric Z' models motivated from a class of superstring models provide a "minimal" extension of the MSSM. The electroweak breaking scenario yields phenomenologically acceptable symmetry breaking patterns which involve a certain but not excessive amount of fine-tuning. It predicts interesting new phenomena testable at future colliders. The intermediate scale scenario provides a framework in which intermediate scales can naturally occur, with implications for the μ-parameter and the fermion masses. There are also possibilities for other mass ranges, reduced couplings, etc. There are important possible implications for the Higgs, sparticle, exotic, and neutrino sectors; the μ problem; dark matter; baryogenesis; FCNC; and the mediation of supersymmetry breaking.

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