Specific quasi-realistic superstring constructions often predict the existence of new TeV-scale physics which may be different in character from bottom-up motivated constructions. I describe examples of such beyond the MSSM physics, with special emphasis on heavy $Z'$ gauge bosons and associated exotic particles. Implications of an extra $U(1)'$ include a viable scenario for electroweak baryogenesis, a highly non-standard light Higgs sector, and $Z'$-mediated contributions to rare $B$ decays.

1. Beyond the MSSM

Even if supersymmetry holds, the MSSM may not be the full story. The MSSM stabilizes but does not explain the hierarchy between the electroweak and Planck scales, and it gives a plausible first step towards the incorporation of quantum gravity. However, the MSSM does not address the other problems of standard model (SM). Moreover, the $\mu$ problem (i.e., that the supersymmetric masses of the Higgs multiplets and their partners should be comparable to typical supersymmetry breaking scales) is introduced, and some versions have difficulty in avoiding new flavor changing effects and too large contributions to electric dipole moments.

One possibility is that the underlying new physics is at the Planck or a GUT scale, but even then there may be remnants surviving to the TeV scale. For example, specific string constructions often have extended gauge groups, especially $U(1)'$ factors, and associated exotic chiral supermultiplets. Such remnants might not solve or be directly motivated by bottom-up solutions to the problems of the SM or MSSM, but should instead be
2. Possible new TeV-scale physics motivated by string constructions

There have been a number of detailed investigations of concrete, semi-realistic superstring constructions, both heterotic (closed string) and intersecting brane (open string)\(^1\). Although it is unlikely that any fully realistic construction will be found soon, this program is useful for developing techniques and for suggesting new top-down motivated physics that may survive to the TeV scale. Specific constructions have led to such features as

- Direct compactification. The higher dimensional theory may break directly to the MSSM in four dimensions (possibly with an extended gauge sector) without going through a separate 4D GUT stage. This avoids the doublet-triplet problem and the need for large representations for GUT breaking and fermion/neutrino masses and mixings, that are hard to generate in some constructions.

- The minimal gauge unification of the MSSM is often lost, either because a non-standard unification is masked by higher Kač-Moody levels or exotic particle contributions to the runnings, or because of non-universal (moduli-dependent) boundary conditions. The observed unification may be due to (accidental?) compensation of such effects, or there may be new constructions in which these features are absent.

- There are often new chiral supermultiplets, including exotic quarks or leptons (i.e., with non-standard \(SU(2) \times U(1)\) quantum numbers); extra Higgs doublets; standard model singlets; and fractionally charged particles. There is often mixing between lepton and Higgs doublets (i.e., \((R_F)\)).

- In additional to the MSSM gauge group, there is often a quasi-hidden gauge group. It is not truly hidden, because there are typically a few states charged under the MSSM and hidden sectors. This may imply the existence of fractional electric charges if the group is not asymptotically free (AF); or charge confinement and light composites if it is AF\(^2\). There may also be gaugino condensation, leading to SUSY breaking and dilaton/moduli stabilization\(^3\).
• The Yukawa sector is very model dependent, and there may be different embeddings for the three families. Terms allowed by the symmetries of the 4D effective field theory are often forbidden by string selection rules, leading, e.g., to string-driven fermion textures. Allowed terms are often totally off diagonal in the fields, unlike many bottom-up phenomenological models for neutrino masses or extended Higgs sectors. There may be relations between quark and lepton Yukawas different than in simple GUTs.

• There are often extended gauge sectors. Some of the extra factors may be associated with a quasi-hidden sector. There are frequently additional (non-anomalous) extra $U(1)'$ factors which may survive to the TeV scale. Typically, the ordinary and hidden-sector states are both charged under the $U(1)'$, and there are often a number of SM singlets with $U(1)'$ charges. The $U(1)'$ couplings are often family-nonuniversal, leading to flavor changing neutral currents (FCNC) after flavor mixing.

3. A heavy $Z'$?

Extra $U(1)'$ gauge symmetries are predicted by many string constructions, grand unified theories, models of dynamical symmetry breaking, and Little Higgs models. String constructions in particular often predict extra $Z'$s as well as numerous SM singlets that are charged under the $U(1)'$. Furthermore, radiative breaking of the electroweak symmetry (either in SUGRA or gauge mediated schemes) often yields $EW$ or TeV scale $Z'$ masses \(^5\) (unless the breaking is along a flat direction, leading to breaking at an intermediate scale \(^6\)). The breaking may be due to negative mass\(^2\) for a scalar $S$ charged under the $U(1)'$(driven by a large Yukawa coupling) or by an $A$ term.

Limits on a possible $Z'$ mass and the $Z - Z'$ mixing $\theta_{Z-Z'}$ from CDF \(^7\) and precision experiments \(^8\) are model dependent, but typically $M_{Z'} > 500 – 800$ GeV and $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$. Discovery should be possible up to $M_{Z'} \sim 5 – 8$ TeV at the LHC or a linear collider, while diagnostics via asymmetries, $y$ distributions, associated production, and rare decays should be possible up to to 1-2 TeV \(^9\).

\(^{a}\)However, GUTs require extra fine tuning for $M_{Z'} \ll M_{\text{GUT}}$ and may have problems with proton decay.
4. Implications of a $Z'$

A TeV scale $U(1)'$ can lead to significant differences from the MSSM. In particular, it leads to a solution to the $\mu$ problem \(^{10,11}\) (i.e., why the supersymmetric $\mu$ parameter in the superpotential, $W_\mu = \mu H_u H_d$ is comparable to the electroweak (supersymmetry breaking) scale). The $U(1)'$ symmetry usually forbids an elementary $\mu$ parameter, but allows a superpotential term $W = h S H_u H_d$, where $S$ is a SM singlet charged under the $U(1)'$. The expectation value $\langle S \rangle$ not only breaks the $U(1)'$, but also generates an effective $\mu_{\text{eff}} = h \langle S \rangle$. This is similar to the Next to Minimal Super-symmetric Standard Model (NMSSM) \(^{12}\), but avoids the NMSSM problems with cosmological domain walls \(^{13}\). The $U(1)'$ symmetry does not allow the superpotential term $W \sim \kappa S^3$, which is needed in the NMSSM, but its role is played by $D$ terms or superpotential terms involving several SM singlets (e.g., $\lambda S_1 S_2 S_3$). Many string constructions do not lead to terms like $S^3$, so the $U(1)'$ models can be considered a string-motivated implementation of the NMSSM.

Other implications of a $U(1)'$ include: (a) the existence of new chiral supermultiplets with exotic SM quantum numbers, needed to cancel anomalies \(^{14}\). These may be consistent with minimal gauge unification. (b) SM singlets charged under the $U(1)'$. (c) A non-standard sparticle spectrum \(^{15,16}\). (d) CP phase correlations \(^{17}\). (e) A TeV-scale $U(1)'$ may forbid a large Majorana mass for the right-handed neutrino and therefore a conventional seesaw. Possibilities then include small Dirac masses (from higher-dimensional operators \(^{18}\) or large extra dimensions), with implications for Big Bang Nucleosynthesis \(^{19}\) unless the breaking is such that the $\nu_R$ decouples \(^{20}\); and TeV-scale seesaws. In this talk, I will comment more on (f) nonstandard Higgs/neutralino spectra \(^{16,21}\), (g) electroweak baryogenesis \(^{22}\), and (h) possible tree level FCNC effects relevant to rare $B$ decays \(^{23,24}\).

5. A secluded sector model

One possibility is for the $U(1)'$ to be broken at the SUSY-breaking scale \(^{11}\), by the same field $S$ which generates the effective $\mu$ parameter. One can have either: $M_{Z'} \sim M_Z$, if it is leptophobic (small leptonic couplings); or $M_{Z'} \gtrsim 10 M_Z$ by modest tuning. Another possibility is to somewhat decouple the $Z'$ mass scale from $\mu$ by allowing several SM singlets. In secluded sector models \(^{16}\), the $Z'$ mass can be naturally large because it is associated with an approximately $F$ and $D$ flat direction, broken by a
small ($\sim 0.05$) Yukawa coupling $\lambda$. In the examples in $^{16}$, there are four SM singlets, $S, S_1, S_2, S_3$, and two doublets $H_1, H_2$. The superpotential is

$$W = h S H_1 H_2 + \lambda S_1 S_2 S_3,$$

where the first term is associated with $\mu$ and the second with the approximate flat direction. The off-diagonal nature is motivated by string constructions. The potential is then $V = V_F + V_D + V_{soft}$, where

$$V_F = h^2 \left( |H_1|^2 |H_2|^2 + |S|^2 |H_1|^2 + |S|^2 |H_2|^2 \right) + \lambda^2 \left( |S_1|^2 |S_2|^2 + |S_2|^2 |S_3|^2 + |S_3|^2 |S_1|^2 \right)$$

$$V_D = \frac{G^2}{8} \left( |H_2|^2 - |H_1|^2 \right)^2 + \frac{1}{2} g'_{2\nu} \left( Q_S |S|^2 + Q_{H_1} |H_1|^2 + Q_{H_2} |H_2|^2 + \sum_{i=1}^{3} Q_S |S_i|^2 \right)^2$$

where $G^2 = g_1^2 + g_2^2$, and

$$V_{soft} = m_{H_1}^2 |H_1|^2 + m_{H_2}^2 |H_2|^2 + m_S^2 |S|^2 + \sum_{i=1}^{3} m_{S_i}^2 |S_i|^2 - (A_h h S H_1 H_2 + A_\lambda \lambda S_1 S_2 S_3 + \text{H.C.}) + (m_{S_1}^2 S S_1 + m_{S_2}^2 S S_2 + m_{S_3}^2 S_{S_3} S_{S_3} + \text{H.C.})$$

For small $\lambda$ one finds $\langle S_i \rangle \sim m_{S_i} / \lambda$, with the $U(1)'$ breaking along the $D$-flat direction $D(U(1)') \sim 0$, with smaller $\langle S \rangle$ and $\langle H_i \rangle$. Ensuring the correct minimum requires that the EW breaking is dominated by a large $A_h h$ term rather than soft mass-squares, implying $\tan \beta \sim 1, \langle S \rangle \sim \langle H_i \rangle$. This leads to large doublet-singlet mixing in the Higgs and neutralino sectors, and that the $(S, H_{u,d})$ and $S_i$ sectors are nearly decoupled. The $m_{S_i}^2$ terms break two unwanted global $U(1)$ symmetries, while the $m_{S_1 S_3}^2$ term allows tree-level CP violation in the scalar sector, with negligible contribution to electric dipole moments.

6. Nonstandard Higgs and neutralino sector

The extra $U(1)'$ and the SM singlets in the secluded sector models imply a rich Higgs and neutralino spectrum $^{16,21}$. In particular, the tendency for $\tan \beta \sim 1, \langle S \rangle \sim \langle H_i \rangle$ for the model in Section 5 leads to significant doublet-singlet mixing and therefore properties very different from the MSSM. That model involves nine neutralinos, with masses ranging from very light ($\ll 100$...
GeV) to several TeV. Four are mainly in the secluded sector \((U(1)')\) gauginos and \(S_i\) Higgsinos), while five mainly overlap the SM sector (SM gauginos and \(S, H_u, d\) Higgsinos).

Similarly, the neutral Higgs sector involves 6 scalars and 4 pseudoscalars (which will mix with each other if one includes tree level CP breaking associated with the \(m_{S_1S_2}^2\) term in \(V_{soft}\)). These typically separate into two sectors, one mainly decoupled (i.e., secluded). In principle, the lightest Higgs scalar can be considerably heavier than in the MSSM because of new \(F\) and \(D\) terms,

\[
M_h^2 \leq h^2 v^2 + (M_Z^2 - h^2 v^2) \cos^2 2\beta \\
+ 2g_2^2 v^2 (Q_{H_2} \cos^2 \beta + \sin^2 \beta Q_{H_1})^2 + \frac{3 \cos^2 \beta m_t^4}{2 v^2 \pi^2} \log \frac{m_t m_{\tilde{t}1}}{m_{\tilde{t}2}^2},
\]

allowing masses up to 185 GeV with all couplings perturbative to \(M_P\). Frequently, however, there are (nondecoupled) scalars and pseudoscalars that are below the usual LEP SM and MSSM exclusion limits\(^{25}\) (or which are in parameter regions that are not theoretically possible in the MSSM). These may have reduced couplings and therefore be allowed experimentally because of the doublet-singlet mixing\(^{21}\). Examples are shown in Figure 1.

### 7. Electroweak baryogenesis

Electroweak baryogenesis\(^{26}\) attempts to generate the observed baryon to entropy ratio \(n_B/s \sim 9 \times 10^{-11}\) by \(B\)-violating tunneling processes (sphalerons) at the time of the electroweak phase transition (EWPT). In the “off the wall” scenario\(^{27}\), nonequilibrium is provided the nucleation and expansion of bubbles of true vacuum during the EWPT. The CP violation is due to the asymmetric reflection of chiral fermions from the bubble wall back into the unbroken phase, where the sphaleron processes convert the chirality into a baryon and lepton asymmetry (with \(B-L\) conserved). The transition must be strongly first order to quickly turn off the sphalerons. Unfortunately, the SM is not strongly first order for the allowed Higgs masses, and the CP violation from the CKM matrix is too weak. In the MSSM there are new sources of CP violation, but the transition is not strong first order except for a small parameter range involving a light Higgs (< 120 GeV) and \(\tilde{t}\)\(^{26,28}\). The NMSSM allow a strong first order transition for a large \(A_h\) term \(hA_hSH_1H_2\)\(^{29}\), but either suffers cosmological domain wall problems or reintroduces the \(\mu\) problem.
Figure 1. Experimentally allowed scalar and pseudoscalar masses for typical parameters. $\xi_{\text{MSSM}}$ is the overlap of the state with the Higgs doublets.

The secluded sector $U(1)'$ model can easily account for the observed asymmetry within theoretical uncertainties, even for a large $\tilde{t}$ mass. There are actually two transitions. The first breaks $U(1)'$ and the second $SU(2) \times U(1)$. The large $A_h$ term needed for the model ensures that the second transition is strong first order. Finally, the tree-level CP breaking allowed in the SM singlet sector allows the CP violation in the bubble wall to be sufficiently large (most of the breaking is actually associated with the false (unbroken) vacuum), without generating significant new contributions to electric dipole moments.

8. FCNC and rare $B$ decays

The $U(1)'$ couplings are often family-nonuniversal in string constructions, leading to flavor changing neutral currents (FCNC) mediated by the $Z'$ (and the $Z$ from $Z - Z'$ mixing) after family mixing is turned on (because of GIM breaking). There may also be FCNC due to mixing of the ordinary and exotic fermions. The strength depends on the mixing matrices $V_{\psi L}$ and $V_{\psi R}$, $\psi = u, d, e, \nu$, for the chiral fermions, but only $V_{\text{CKM}} = V_{uL}V_{dL}^\dagger$
Figure 2. Predicted baryon to entropy ratio as a function of a CP violating phase $\gamma$ from the SM singlet sector for a particular set of input parameters. The asymmetry is within a factor of 2 (i.e., within theoretical uncertainties) of the observed value for $\gamma$ close to $\pi$.

and $V_{\text{MNS}} = V_{\nu_e} V_{e_L}^\dagger$ are known from experiment. Stringent limits from $K$ and $\mu$ decays imply that the first two families are universal. However, the third family could have different couplings, leading, for example, to effects in the forward-backward asymmetry for $Z$ decaying to $b\bar{b}$, or to FCNC effects in rare $B$ decays. The latter can be especially important for rare decays which only occur at the loop level in the standard model, such as $B \to \phi K$ or $\eta'/K$, for which there are possible anomalies. They could also lead to an enhanced rate for $B_s \to \mu^+\mu^-$ or $b \to s\mu^+\mu^-$ (as an alternative to the MSSM with large $\tan \beta$), without significantly modifying $b \to s\gamma$.

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