Superheavy Supersymmetry

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Abstract

One way to suppress flavor changing neutral currents or CP violating processes in supersymmetry is to make at least some of the first two generations’ scalars superheavy (above $\sim 20$ TeV). We summarize the motivations and challenges, theoretically and phenomenologically, for superheavy supersymmetry. We then argue for more viable alternatives on the superheavy theme and are led to models where the heavy spectrum follows a pattern of masses similar to what arises from gauge-mediation or with a “hybrid” spectrum of light and heavy masses based on each particle’s transformation under a global SU(5). In the end, despite the differences between the competing ideas, a self-consistent natural theory with superheavy masses seems to prefer low-energy supersymmetry breaking with possible correlations among the light sparticle masses. The resulting light gravitino and its coupling to matter could also impact the discovery capabilities and analyses of these models at Tevatron Run II. In addition, we comment on how the presence of superheavy states may influence the light spectrum, and how this may help efforts to distinguish between theories post-discovery.

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In the vast space of all viable physics theories, supersymmetry (SUSY) is not a point. Any theory can be “supersymmetrized” almost trivially, and the infinite array of choices for spontaneous SUSY breaking just increases the scope of possibilities in the real world. One thing that appears necessary, if SUSY has anything to do with nature, is superpartners for the standard model particles that we already know about: leptons, neutrinos, quarks, and gauge bosons. These superpartners must feel SUSY breaking and a priori can have arbitrary masses as a result.

Phenomenologically, the masses cannot be arbitrary. There are several measurements that have been performed that effectively limit what the SUSY masses can be. First, there are direct limits on $Z \to \text{SUSY}$, for example, that essentially require all superpartners to be above $m_Z/2$. Beyond this, collider physics limits become model dependent, and it is not easy to state results simply in terms of the mass of each particle. Second, comparing softly broken SUSY model calculations with flavor changing neutral current (FCNC) measurements implies that superpartner masses cannot be light and arbitrary. And finally, requiring that the $Z$ boson mass not result from a fine-tuned cancellation of big numbers requires some of the particles masses be near $m_Z$ (less than about 1 TeV, say).

Numerous explanations for how the above criteria can be satisfied have been considered. Universality of masses, alignment of flavor matrices, flavor symmetries, superheavy supersymmetry, etc., have all been incorporated to define a more or less phenomenologically viable explanation of a softly broken SUSY description of nature.

In this contribution, we would like to summarize some of the basic collider physics implications of superheavy supersymmetry (SHS) at the Tevatron. Our understanding is that analyses of all the specific processes that are mentioned here in principle are being pursued within other subgroups. Therefore, our goal in this submission is to succinctly explain what SHS is and how some of the observables being studied within other contexts could be crucial to SHS. We also hope that by enumerating some of the variations of this approach that this contribution could help us anticipate and interpret results after discovery of SUSY, and help distinguish between theories. The idea we are discussing goes under several names including “decoupling supersymmetry”, “more minimal supersymmetry”, “effective supersymmetry”, “superheavy supersymmetry”, etc. The core principle is that very heavy superpartners do not contribute to low-energy FCNC or CP violating processes and therefore cannot cause problems. Furthermore, no fancy symmetries need be postulated to keep experimental predictions for them under control.

On the surface, it appears that decoupling superpartners is completely irrelevant for the
Tevatron. After all, Tevatron phenomenology is limited to what the Tevatron can produce. Superheavy superpartners, which we define to be above at least 20 TeV, are of course not within reach of a 2 TeV collider. However, not all sparticles need be superheavy to satisfy constraints. In fact, the third generation squarks and sleptons need not be superheavy to stay within the boundaries of experimental results on FCNC and CP violating phenomena. As an all important bonus, the third family squarks and sleptons are the only ones that contribute significantly at one loop to the Higgs potential mass parameters. By keeping the third generation sfermions light, we simultaneously can maintain a “natural” and viable lagrangian even after quantum corrections are taken into account.

In short, the first-pass description of SHS is to say that, in absence of any alignment, special symmetry or other mechanism yielding flavor-horizontal degeneracy, all particles which are significantly coupled to the Higgs states should be light, and the rest heavy. The gluino does not by itself contribute to FCNC, nor does it couple directly to the Higgs bosons and so it could be heavy or light. However, the gauginos usually have a common origin, either in grand unified theories (GUTs), theories with gauge-mediated supersymmetry breaking (GMSB), or superstring theories, and so it is perhaps more likely that the gluino is relatively light with its other gaugino friends, the bino and the wino. Furthermore, the $H_d$ could be superheavy as well, but that is not as relevant for Tevatron phenomenology. Therefore, we can summarize the “Basic Superheavy Supersymmetry” (BSSH) spectrum:

**Superheavy** ($\gtrsim 20$ TeV): $\tilde{Q}_{1,2}$, $\tilde{u}_{1,2}$, $\tilde{d}_{1,2}$, $\tilde{L}_{1,2}$, $\tilde{e}_{1,2}$;

**Light** ($\lesssim 1$ TeV): $\tilde{Q}_3$, $\tilde{e}$, $\tilde{B}$, $\tilde{W}$, $H_u$, $\mu$ (higgsinos);

**Unconstrained** (either light or heavy): $\tilde{b}$, $\tilde{L}_3$, $\tilde{\tau}$, $\tilde{g}$, $H_d$.

Specific models of SUSY breaking will put the “unconstrained” fields in either the “superheavy” or “light” categories.

Any question about relative masses within each category above can not be answered within this framework. In fact, that is one of the theoretically pleasing aspect of this approach: no technical details about the spectrum need be assumed to have a viable theory. Another nice feature is that the mass pattern for the scalar partners across generations is somewhat opposite to that of the SM fermions. This might well inspire a profound connection between the physics of flavor and SUSY breaking. A possible theoretical explanation of such a large mass hierarchy in the scalar sector is that it could be a result of new gauge interactions carried by the first two generations only, and which could be, e.g., involved in a
dynamical breaking of SUSY. For Tevatron enthusiasts, it is a frustrating model, since we do not even know what phenomenology should be studied because things will change drastically depending on the relative ordering of states in the “light” category.

However, there are several features about the BSHS spectrum which are interesting not because of the phenomena that it predicts at the Tevatron, but rather for what it does not predict. For example, \( \tilde{q}_{1,2} \tilde{g} \) and \( \tilde{q}_{1,2} \tilde{q}_{1,2}' \) production is not expected at the Tevatron. This is a potentially large source of events in other scenarios, such as minimal supergravity (mSUGRA), but is not present here. A more predictive feature is the expectation of many bottom quarks and \( \tau \) leptons in the final state of SUSY production. For example, \( p\bar{p} \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \) will not be allowed to cascade decay through \( \tilde{e}_L \) for example, but may have hundred percent branching fractions to \( \tau \) final states. Therefore, while the “golden tri-lepton” signals are generally suppressed in these models, efforts to look for specific \( 3\tau \) final states are relatively more important to study in the context of SHS compared to other models. Furthermore, light \( \tilde{t} \) and \( \tilde{b} \) production either directly or from gluino (chargino, stop) decays is of added interest in the BSHS spectrum, and may lead to high multiplicity \( b \)-jet final states. In short, drawing production and decay diagrams for all possible permutations of the BSHS spectrum always yields high multiplicity \( \tau \) or \( b \)-jet final states. From the BSHS perspective, preparation and analysis for \( \tau \) and \( b \)-jet identification is of primary importance. For instance, while detection of selectrons and smuons would exclude BSHS, detection of many staus and no \( \tilde{e} \) or \( \tilde{\mu} \) would be a good hint for it (although one could think of other SUSY scenarios where the \( m_{\tilde{e}} - m_{\tilde{\mu}} \) splitting is rather large, due e.g. to large values of \( \tan \beta \)). An interesting place to look for violations of \( e - \tau \) universality is \( \tilde{\chi}_1^\pm \) or \( \tilde{\chi}_2^0 \) branching fractions, after gaugino-pair (\( \tilde{\chi}_1^+ \tilde{\chi}_1^- \) or \( \tilde{\chi}_1^0 \tilde{\chi}_0^2 \)) production.

There are two main problems with the BSHS spectrum. The heavy particles can generate a disastrously large hypercharge Fayet-Iliopoulos term proportional to \( g_1^2 \text{Tr}(Y m^2) \). In universal scalar mass scenarios these terms are proportional to \( \text{Tr}(Y) \) which is zero because of the gravity–gravity–U(1)\( _Y \) anomaly cancellation. In minimal GMSB scenarios \( m^2 \propto Y^2 + \cdots \), and so \( \text{Tr}(Y m^2) = \text{Tr}(Y^3) + \cdots \) vanishes because of the \( U(1)_Y \) and SU(N)–SU(N)–U(1)\( _Y \) anomaly cancellation. No such principle exists in the BSHS ansatz given above, and so the \( \text{Tr}(Y m^2) \) is generically a problem. Barring the possibility of miraculous cancellations, we can cure the “\( \text{Tr}(Y m^2) \)” problem by postulating that the superheavy masses follow a GMSB hierarchy, or that the superheavy states come in complete multiplets of SU(5), and the masses of all states within an SU(5) representation are degenerate or nearly degenerate. We will consider both possibilities in the following. These requirements may lower the
stock of “superheavy supersymmetry” ideas for some, or it may change how one perceives model building based on decoupling superpartners, but it has no direct effect on Tevatron phenomenology.

The superheavy states are inaccessible anyway, so how they arrange their masses in detail is of little consequence to us here. On the other hand, the generic pattern and theoretical principles beyond this arrangement may affect the light sector of the model as well, both directly and indirectly through higher-order mass corrections. Indeed, another more serious problem, which has direct consequence to Tevatron phenomenology is related to new two-loop logarithmic contributions to the light scalar masses in SHS [3]. For example, the relevant renormalization group equation has a term

$$\frac{d\tilde{m}^2_{\text{light,}f}}{d \ln Q} \propto \sum_i \alpha_i^2 C^f_i \tilde{m}^2_{\text{heavy}} + \cdots$$

(1)

where $C^f_i$ are Casimirs for $f$, $i$ labels the indices of the SM gauge groups, and $m^2_{\text{heavy}}$ is the characteristic superheavy mass scale. This renormalization group equation begins its running at the scale where SUSY breaking is communicated to the superpartners. In supergravity, this is the Planck scale, and so the shift in light superpartner masses is proportional to the right side of eq. [1] multiplied by a large logarithm, of order $\ln M_{\text{Planck}}/m_Z$. This term is so large that in order to keep, e.g., the top squark mass squared from going negative, it must have a mass greater than several TeV at the high scale [3]. (Similar problems occur for the other “light scalars” which could potentially put us in a charge or color breaking vacuum.) Even though the top squark mass can be tuned to be light at the $Z$ scale, the renormalization group effects of the heavy top-squark at the high scale feed into the Higgs sector and results in a fine-tuned Higgs potential. Since fine-tuning is a somewhat subjective criteria, this problem may not be fundamental.

A healing influence on the above two-loop malady is to make the SUSY breaking transmission scale much lower than the Planck scale. This reduces the logarithm and allows for a more natural Higgs potential without large cancellations. The most successful low-energy SUSY breaking idea is GMSB [2]. There, the relevant scale is not tied to gravity ($M_{\text{Planck}}$), but rather to the scale of dynamical SUSY breaking. Transmission of this breaking to superpartner masses can take place at scales as low as $\sim m_{\text{heavy}}$ in this scheme.

With some thought about the BSHS spectrum and the troubles that could arise theoretically from it, we seem to be converging on something that looks more or less like GMSB. In fact, we can think of the input parameters for our converging model to be the input
parameters of minimal GMSB [2], which are

\[ \Lambda, M, N_{\text{mess}}, \text{sign}(\mu), \tan \beta, \text{ and } \sqrt{F_0} \]

(2)

where \( \Lambda \) sets the overall mass scale of the superpartners, \( M \) is the messenger scale, \( N_{\text{mess}} \) characterizes the number of equivalent \( 5 + \bar{5} \) messenger representations, and \( \sqrt{F_0} \) determines the interactions of the goldstino with matter. Then we add to these parameters,

\[ a_{1,2} = \frac{\tilde{m}_{f_1,2}^2(M)}{\tilde{m}_{f_3}^2(M)} \]

(3)

where we define \( \tilde{m}_{f_3}^2(M) \) to be the minimal GMSB values of the sfermion masses at the messenger scale excluding D-terms (\( f = \tilde{Q}, \tilde{d}, \tilde{L}, \tilde{e} \)). The two \( a_{1,2} \) parameters with the parameters of eq. 2 completely specify a gauge-mediated inspired superheavy SUSY (GMSS) model. (Another similar parameter might be introduced for the Higgs \( H_d \) if this is heavy, but this is less relevant to Tevatron phenomenology). We suggest that analyses can use these input parameters to make experimental searches and studies of SHS. Adding some family dependent discrete symmetries on the superpartners and messengers would allow such a model to arise in a similar way as ordinary gauge-mediated models. Recall also that in gauge mediation the \( \text{Tr}(Y m^2) \) problem can be solved by the triple gauge anomaly rather than by the gravity-gauge anomaly requirement as would be the case if we had heavy sparticles come in degenerate remnants of \( \bar{5} \) and/or 10 representation, as a result of the presence of an approximate global SU(5) symmetry.

The psychological disadvantage of this GMSS model is that it is overkill on the FCNC problem. Gauge mediation cures this problem by itself, and there might not be strong motivation to further consider mechanisms that suppress it. However, gauge mediation does not automatically solve the CP problem, and so the heavy first two generations may help ameliorate it to some degree. As an aside, the above discussion can be reinterpreted as a powerful motivation for GMSB. We started with no theory principles but rather only experimental constraints and with some basic reasoning were drawn naturally to gauge mediation. However, we know of no compelling theoretical reason why \( a_{1,2} \neq 1 \). We only know that if the heavy spectrum follows a minimal gauge-mediated hierarchy, then the “\( \text{Tr}(Y m^2) \)” problem can be solved. (However, it is possible to construct a more complex gauge-mediated model that does not satisfy \( \text{Tr}(Y m^2) = 0 \).) Gauge-mediation, of course, is not necessarily the only way to transmit low-energy SUSY breaking. From a phenomenological point of view, one should be open to a more general low-energy SUSY breaking framework.
It must be said that in some cases, even when SUSY breaking is transmitted at low scales as in GMSS, one still could have a hard time avoiding color- and charge-breaking vacua. Indeed, the contribution from the superheavy states in eq. 1 can still be large when loops from all the scalars of the first two generations add up.

As anticipated, another possibility to cure the “Tr($Ym^2$) problem” and the “two-loop problem” is with the hybrid multi-scale SUSY models (HMSSM) [4], using the “approximate global SU(5)” pattern:

**HMSSM-I:** The first two generations of the 10 representation of SU(5) ($\tilde{Q}_{1,2}$, $\tilde{u}^c_{1,2}$, $\tilde{e}^c_{1,2}$) are superheavy ($\tilde{m}_{10_{1,2}}$), while the rest of the sparticles are light and approximately degenerate.

**HMSSM-II:** In HMSSM-IIa all three generations of the $\bar{5}$ representation of SU(5) ($\tilde{d}^c_{1,2,3}$, $\tilde{L}_{1,2,3}$) are superheavy ($\tilde{m}_{\bar{5}_{1,2,3}}$), while the rest of the sparticles are light. In HMSSM-IIb just the first two generations of the $\bar{5}$ are superheavy ($\tilde{m}_{\bar{5}_{1,2}}$).

In these models, one attempts a solution of the FCNC problem by using a combination of some decoupling (superheavy scalars) and some degeneracy. A theoretical motivation for this could be that due to an approximate SU(5) global symmetry of the SUSY breaking dynamics, only some of the quark/leptons superfields with the same SU(3)⊗SU(2)⊗U(1) quantum numbers are involved in the SUSY breaking sector, carry an additional quantum number under a new “strong” horizontal gauge group and are superheavy. The other superfields instead couple only weakly (but in a flavor-blind way) to SUSY breaking and are light and about degenerate.

Actually, these “hybrid” models present many advantages compared to other SHS realizations. The reduced content of the superheavy sector considerably weakens the “two-loop” problem, since the negative contribution to the light scalar masses squared is less important. This is especially true for the HMSSM-II, and in particular the IIb version. Actually, it is in this case possible to raise the $m_{\text{heavy}}$ scale up to $\sim 40$ TeV, in a natural way. Most problems with FCNC phenomena come from $L - R$ operators, and since these operators remain suppressed, the hybrid models are phenomenologically viable and attractive versions of superheavy supersymmetry.

The resulting spectrum is different than GMSS and BSHS in that some of first two generation states are now allowed to be light. For example, in the HMSSM-I model, the $\tilde{L}$ sleptons can be light, and on-shell decays of winos into $L + \tilde{L}$ can allow the trilepton signal
$\tilde{\chi}^{\pm}_1 \tilde{\chi}^0_2 \rightarrow 3l$ to have near 100\% branching fraction. This is not possible in the BSHS spectrum. Also, it may be useful to study the total rate of jets plus missing energy and the kinematics of the events to discern that only $\tilde{d}^c, \tilde{s}^c$ and 3rd-generation squarks are light, and the remaining squarks are heavy. More detailed phenomenological studies might start from observing that in the “hybrid” case too, one still needs low-energy SUSY breaking to deal with the “two-loop problem”. Again, a GMSB-inspired spectrum for the light sector corrected by the (here reduced) presence of the heavy scalars seems relevant as a starting point. In this case, a parametrization along the lines described above for the GMSS would involve new additional parameters such as $\tilde{m}_{10,1}$ for the HMSSM-I or $\tilde{m}_{6,1,2(a)}$ for the HMSSM-IIa(,b), plus possibly an analogous parameter for $H_d$.

Whether the spectrum is more minimal GMSB-like or is better described by the “hybrid models”, there is one feature in common. Due to the “two-loop problem”, SHS appears more natural with low-energy supersymmetry breaking, independent of how the SUSY breaking and transmission are accomplished (minimal gauge-mediation ideas or otherwise). This implies that the lightest superpartner is the gravitino rather than the neutralino, as e.g. in mSUGRA.

Depending on the details of SUSY breaking and the transmission of that breaking to superpartners (e.g., whether $\sqrt{F_0}$ in eq. $A$ is much larger or smaller than about 100 TeV), the next-to-lightest superpartner (NLSP) will either decay promptly in the detector, or decay with a long lifetime outside the detector. This may very well dominate the phenomenological implications of the model. Another important feature is the identity of the NLSP. It is well known that, e.g. in a GMSB-like spectrum, the best candidates are the $\tilde{\chi}^0_1$ and the lightest stau $\tilde{\tau}_1 \simeq \tilde{\tau}_R$. In SHS, a scenario with a neutralino NLSP, with associated decays such as $\tilde{\chi}^0_1 \rightarrow \gamma \tilde{G}$ possibly inside the detector, is still an important possibility. In this case, multiple high-$p_T$ photons are the tags to spectacular events. On the other hand, in the GMSS model and in the HMSSM models, the $\tilde{\tau}_R$ is always part of the light scalar sector. In addition, here the negative contributions from the heavy scalars to its mass will tend to lower it compared to the neutralino mass.

Further, in many realizations of SHS the big mass hierarchy between the Higgses $H_u$ and $H_d$ can trigger very large $O(m_{\text{heavy}}/M_Z)$ values of $\tan \beta$ (which might provide a reasonable explanation of the large $m_t/m_b$ ratio without fine-tuning). As a side result, after $L - R$ mixing, the $\tilde{\tau}_1$ mass might turn out to be even lighter relative to the other scalars and the neutralino than in GMSB models. Hence, we believe that the possibility of a $\tilde{\tau}_1$ NLSP in SHS deserves very serious consideration. If this is the case, the NLSP is charged and might
live beyond the detector if $\sqrt{F_0}$ is relatively large. Then stable charged particle tracks in the calorimeter will be tags to even more spectacular events [3]. Many of the results in the gauge-mediation literature will directly apply for discovery. After discovery, the particles that come along with the spectacular stable charged tracks (SCTs) or the high-$p_T$ photons can then be studied to find out with great confidence the light particle content of the theory, that could distinguish between the superheavy and the “traditional” models.

As an example of distinguishing phenomenology, we can define $R_{\ell^+\ell^-}$ to be

$$R_{\ell^+\ell^-} \equiv \sum_{\ell=e,\mu} \frac{\sigma[2 \text{ SCTs} + \ell^+\ell^-]}{\sigma[2 \text{ SCTs} + X]}.$$  \hspace{1cm} (4)

From total SUSY production in HMSSM-IIb one expects $R_{\ell^+\ell^-} < 1/10$ since $\tilde{e}$ and $\tilde{\mu}$ cannot participate in the decays. Most events will then have $X = \tau^+_{\text{hard}}\tau^-_{\text{hard}}$ accompanying the 2 SCTs. However, in minimal GMSB the $\tilde{e}$ and $\tilde{\mu}$ are present in the low-energy spectrum, and so $\tilde{\chi}^+ \rightarrow e^+\nu_e\tau^\pm_{\text{soft}}\tilde{\tau}^\mp$ may proceed with large branching fraction. Although a precise number depends mainly on the number of messenger representations and $\tan \beta$, $R_{\ell^+\ell^-}$ could be greater than 1/2 in GMSB. More generally, the unusually large $L-R$ mass hierarchies that are typical of “hybrid” models may allow identification of observables suitable for discerning superheavy supersymmetry from other more conventional forms of supersymmetry at the Tevatron.

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