Flavor- and *CP*-Violating Physics from New Supersymmetric Thresholds

Maxim Pospelov,[1,2] Adam Ritz,[2,3] and Yudi Santoso[1,2]
[1]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2J 2W9, Canada*
[2]*Department of Physics and Astronomy, University of Victoria, Victoria, BC, V8P 1A1, Canada*
[3]*Theoretical Division, Department of Physics, CERN, Geneva 23, CH-1211 Switzerland*
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Treating the minimal supersymmetric standard model as an effective theory, we study the implications of having dimension-five operators in the superpotential for flavor- and *CP*-violating processes, exploiting the linear decoupling of observable effects with respect to the new threshold scale Λ. We show that the assumption of weak-scale supersymmetry, when combined with the stringent limits on electric dipole moments and lepton-flavor-violating processes, provides sensitivity to Λ as high as 10^7–10^9 GeV (and up to 10^{17} GeV through the θ term), while the next generation of experiments could directly probe the high-energy scales suggested by neutrino physics.

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Weak-scale supersymmetry (SUSY) is a theoretical framework that helps to soften the so-called gauge hierarchy problem by removing the powerlike ultraviolet sensitivity of the dimensionful parameters in the Higgs potential. It also has other advantages, notably an improvement in gauge coupling unification and a natural dark matter candidate, which have made it the standard paradigm for physics beyond the standard model (SM). However, the simplest scenario—the minimal supersymmetric standard model (MSSM)—suffers from a number of well-known tuning problems, due in part to the large array of possible parameters responsible for soft SUSY breaking [1] and, consequently, the possibility of catastrophically large flavor- and *CP*-violating amplitudes. The absence of new flavor structures and order-one sources of *CP* violation in the soft-breaking sector, as evidenced, respectively, by the perfect accord of the observed K and B meson mixing and decay with the predictions of the SM [2] and the null results of electric dipole moment (EDM) searches [3–5], motivates continuing work on the specifics of SUSY breaking.

In the present Letter, we will instead ask: Given a solution to the flavor and *CP* problems in the soft-breaking sector, what sensitivity do we have to new high-scale sources of flavor and *CP* violation? Such effects would arise through SUSY-preserving higher-dimensional operators generated at a new threshold $\Lambda \gg M_W$. Such thresholds are indeed expected due to various completions of the MSSM, e.g., via mechanisms for SUSY breaking and mediation, the breaking of flavor symmetries, and moreover via the physics generating neutrino masses and mixings. Intermediate scales are also suggested by the axion solution to the strong *CP* problem, SUSY leptogenesis scenarios, and more entertainingly as a lowered grand unified theory/string scale arising from large compactification radii of extra dimensions. In contrast to nonuniversal or complex soft-breaking terms, the flavor- and *CP*-violating observables induced by such operators will scale as $(\Lambda m_{\rm SUSY})^{-1}$, and, thus, the constraints on nonminimal flavor or *CP* translate directly into sensitivity to Λ far above the scale of the superpartner masses $m_{\rm SUSY}$.

At dimension five, there are several well-known R-parity conserving operators associated with neutrino masses, H_uLH_uL, and baryon- and lepton-number violation, $UUDE$, $QQQL$ [6]. The constraints on proton decay put severe restrictions on the size of the latter baryon- and lepton-number-violating operators, $\Lambda_b > 10^{24}$ GeV, where $1/\Lambda_b$ is the overall normalization scale. The "superseesaw" operator H_uLH_uL is a welcome addition to the MSSM superpotential, as it generates Majorana masses and mixing for neutrinos, which imply $\Lambda_\nu \sim (10^{14}$–$10^{16})$ GeV. Note that, in the seesaw scenario, the actual scale of right-handed neutrinos, M_R, is lower than Λ_ν, since $\Lambda_\nu^{-1} = Y_\nu^2 M_R^{-1}$ with a small Y_ν, as is also favored by SUSY leptogenesis.

In what follows, we analyze in detail the remaining operators allowed in the R-parity conserving MSSM at dimension-five level [6]. We write the superpotential as

$$\mathcal{W} = \mathcal{W}_{\rm MSSM} + \frac{y_h}{\Lambda_h} H_d H_u H_d H_u + \frac{Y^{qe}_{ijkl}}{\Lambda_{qe}}(U_i Q_j) E_k L_l + \frac{Y^{qq}_{ijkl}}{\Lambda_{qq}}(U_i Q_j)(D_k Q_l) + \frac{\tilde{Y}^{qq}_{ijkl}}{\Lambda_{qq}}(U_i t^A Q_j)(D_k t^A Q_l), \quad (1)$$

where y_h, Y_{qe}, Y_{qq}, and $\tilde{Y}_{qq}$ are dimensionless coefficients, the latter three being tensors in flavor space. The parentheses in (1) denote a contraction of color indices. Note that, since we will consider only supersymmetric thresholds, the superfield equations of motion can be used to eliminate all dimension-five corrections to the Kähler potential, e.g., $K^{(5)} = c_u QUH_d^\dagger$, absorbing them in $\mathcal{W}^{(5)}$ and the Yukawa terms, and slightly modifying the soft-breaking sector. A renormalizable realization of (1) can easily be obtained, e.g., the MSSM extended by a singlet N (the NMSSM) or an extra pair of heavy Higgs bosons.

The full Lagrangian descending from (1) is rather cumbersome, and we will focus our attention here on those dimension-five operators which are of potential phenomenological interest, specifically those that involve two SM fermions and two sfermions. We then proceed to integrate out the sfermions to obtain operators composed from the SM fields (or, more precisely, those of a type II two-Higgs-boson doublet model). We will impose the requirements of flavor triviality and *CP* conservation in the soft-breaking sector. Thus, all dimension ≤ 4 coefficients in the Higgs potential, trilinear terms A_i, gaugino masses M_i, and the μ parameter, will be taken real. We will also make the simplifying assumption of universal sfermion masses, denoted $m_{\rm sq}$, $m_{\rm sl}$, which we will take, along with μ, M_i, to be somewhat larger than M_W. Deferring the full details [7], we quote the relevant results below:

Correction to the SM fermion masses.—The SM operators of lowest dimension that are of phenomenological interest are the fermion mass operators. From the diagrams in Fig. 1(a), we obtain the following corrections:

$$\delta(M_e)_{ij} = Y^{qe}_{klij}(M_u^{(0)})^*_{kl}\frac{3\ln(\Lambda_{qe}/m_{\rm sq})}{8\pi^2\Lambda_{qe}}(A_u^* + \mu\cot\beta),$$
$$\delta(M_d)_{ij} = K^{qq}_{klij}(M_u^{(0)})^*_{kl}\frac{\ln(\Lambda_{qq}/m_{\rm sq})}{4\pi^2\Lambda_{qq}}(A_u^* + \mu\cot\beta), \tag{2}$$

with a similar correction to M_u. The notation implies summation over the repeated flavor indices, and we have defined the combination $K^{qq} \equiv (Y^{qq} - 2\tilde{Y}^{qq}/3)$. $M^{(0)}_{e,d,u}$ denote unperturbed mass matrices arising from dimension-four terms in the superpotential. Note that the corrections proportional to A_u directly break SUSY, while those proportional to μ arise from corrections to the Kähler potential.

Dipole operators.—At dimension five, dipole operators first arise at two-loop order, as in Fig. 1(b). In the charged lepton sector, they result in

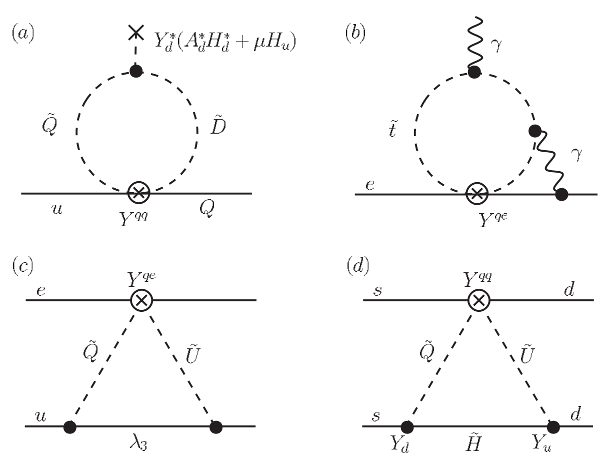

FIG. 1. Several representative loop corrections to: (a) SM fermion masses; (b) dipole amplitudes contributing to EDMs (cf. the supersymmetric Barr-Zee diagrams [18]), $\mu \to e\gamma$, $b \to s\gamma$, $(g-2)_\mu$; and (c),(d) dimension-six four-fermion operators. The crossed vertex descends from dimension-five terms in the superpotential (1).

$$\mathcal{L}_e = \frac{A_u + \mu\cot\beta}{\Lambda^{qe}m_{\rm sq}^2}\frac{e\alpha}{12\pi^3}(M_u)^*_{kl}Y^{qe}_{klij}\bar{E}_i(F\sigma)P_L E_j + ({\rm H.c.}), \tag{3}$$

where we treated *LR* squark mixing as a mass insertion and used $P_L = (1-\gamma_5)/2$ and $(F\sigma) = F_{\mu\nu}\sigma^{\mu\nu}$. In the quark sector, the corresponding results are more cumbersome due to a large number of possible diagrams.

Jumping an additional dimension, we now consider dimension-six four-fermion operators generated by various terms in (1). Two representative diagrams are shown in Figs. 1(c) and 1(d).

Semileptonic operators.—Integrating out gauginos and sfermions as in Fig. 1(c), we find the following semileptonic operators, sourced by $QULE$:

$$\mathcal{L}_{qe} = \frac{1}{\Lambda_{qe}m_{\rm SUSY}}\frac{\alpha_s}{3\pi}Y^{qe}_{ijkl}\bar{U}_iQ_j\bar{E}_kL_l + ({\rm H.c.}). \tag{4}$$

Here $m^{-1}_{\rm SUSY}$ denotes a combination of superpartner masses folded with a loop function F: $m^{-1}_{\rm SUSY} = M_3m_{\rm sq}^{-2}F(M_3^2/m_{\rm sl}^2)$, and $F(a) = 2\{[1 - a + a\ln(a)]/(1-a)^2\}$, with $F(1) = 1$ (see [8] for the unequal mass case). In (4) we have retained only the gluino-squark contribution, which is expected to dominate unless there are additional hierarchies between the masses of sleptons and squarks.

Four-quark operators.—Integrating out gluinos and squarks as in Fig. 1(c), we arrive at the following four-quark effective operators:

$$\mathcal{L}_{qq} = \frac{1}{\Lambda_{qq}m_{\rm SUSY}}\frac{\alpha_s}{12\pi}K^{qq}\Big[\frac{8}{3}(\bar{U}Q)(\bar{D}Q) + (\bar{U}t^AQ)\times(\bar{D}t^AQ)\Big] + ({\rm H.c.}), \tag{5}$$

where the summation over flavor is carried out exactly as in (1). The largest down-type $\Delta F = 2$ operator arises instead from Fig. 1(d),

$$\mathcal{L}_{dd} = \frac{1}{\Lambda_{qq}m_{\rm SUSY}}\frac{1}{16\pi^2}(Y_u^*)_{im}(Y_d^*)_{nj}K^{qq}_{ijkl}\Big[\frac{1}{3}(\bar{Q}_mD_n)\times(\bar{D}_kQ_l) - (\bar{Q}_mt^AD_n)(\bar{D}_kt^AQ_l)\Big] + ({\rm H.c.}), \tag{6}$$

which inevitably contains additional Yukawa suppression originating from the Higgsino-fermion-sfermion vertices. Here $m_{\rm SUSY}$ is a combination of SUSY masses as in (4) and (5) with M_3 replaced by μ.

We will now turn to the phenomenological consequences and the sensitivity to Λ^{qe} and Λ^{qq} in various experimental channels. Of course, one of the most important issues is the flavor structure of the new couplings constants Y^{qe}, Y^{qq}, and $\tilde{Y}^{qq}$. We will assume that these coefficients are of order one and *do not factorize*: $Y^{qe} \neq Y_uY_e$. With this assumption, we should first determine the natural scale for Λ such that the corrections to SM fermion masses do not exceed their measured values.

Particle masses and θ term.—Taking $(M_uA_u)_{kl} = (M_uA_u)_{33} \sim m_tA_t \sim 175 \times 300$ GeV in (2), and assuming a maximal $Y^{qe}_{3311} \sim O(1)$, we arrive at the estimate,

$$\Delta m_e \sim \frac{3 m_t A_t Y^{qe}_{3311} \ln(\Lambda^{qe}/m_{\rm sq})}{8\pi^2 \Lambda^{qe}} \sim 1\ {\rm MeV} \frac{10^7\ {\rm GeV}}{\Lambda^{qe}}. \quad (7)$$

Equation (7) clearly implies that the natural scale for new physics encoded in the semileptonic operators in the superpotential is $\Lambda^{qe} \sim 10^7$ GeV, while the corresponding scale in the quark sector is slightly lower.

A strikingly high naturalness scale emerges from consideration of the effective shift of $\bar{\theta}$ due to the mass corrections (2). Assuming uncorrelated phases between Y^{qq} and the eigenvalues of Y_u and Y_d, we find

$$\Delta\bar{\theta} \sim \frac{{\rm Im} m_d}{m_d} \sim \frac{{\rm Im} K^{qq}_{3311} m_t A_t \ln(\Lambda^{qq}/m_{\rm sq})}{4\pi^2 m_d \Lambda^{qq}} \sim \frac{10^7\ {\rm GeV}}{\Lambda^{qq}}. \quad (8)$$

Equation (8) translates directly to an extremely strong bound on Λ^{qq} in scenarios where $\bar{\theta} \simeq 0$ is engineered by hand, either by using discrete symmetries at high energies [9] or by imposing an approximate global $U(1)$ symmetry at tree level to ensure $m_u^{(0)} = 0$. In these cases, the experimental bound on the neutron EDM, $|d_n| < 6 \times 10^{-26} e$ cm [5] (soon to be updated [10]), combined with standard estimates for $d_n(\bar{\theta})$ [11] implies remarkable sensitivity to scales $\Lambda^{qq} \sim 10^{17}$ GeV. Future progress in EDM searches (for both neutrons and heavy atoms) can bring this up to the Planck scale and beyond. In contrast, no constraints from (8) ensue within the axion scenario.

Electric dipole moments from four-fermion operators.—EDMs of neutrons and heavy atoms and molecules are the primary probes for sources of flavor-neutral CP violation [11]. In addition to d_n, the strongest constraints on CP-violating parameters arise from the atomic EDMs of thallium, $|d_{\rm Tl}| < 9 \times 10^{-25} e$ cm [3], and mercury, $|d_{\rm Hg}| < 2 \times 10^{-28} e$ cm [4].

Assuming that $\bar{\theta}$ is removed by an appropriate symmetry, EDMs are mediated by higher-dimensional operators, and both (4) and (5) are capable of inducing atomic or nuclear EDMs if the overall coefficients contain an extra phase relative to the quark masses. Restricting Eq. (4) to the first generation, we find the following CP-odd operators (with real m_e, m_u):

$$\mathcal{L}_{CP} = -\frac{\alpha_s {\rm Im} Y^{qe}_{1111}}{6\pi \Lambda_{qe} m_{\rm SUSY}} [(\bar{u}u)\bar{e} i\gamma_5 e + (\bar{u} i\gamma_5 u)\bar{e}e]. \quad (9)$$

Accounting for QCD running from the SUSY scale to 1 GeV, and using the hadronic matrix elements over nucleon states $\langle N|(\bar{u}u + \bar{d}d)/2|N\rangle \simeq 4\bar{N}N$ and $\langle n|\bar{u} i\gamma_5 u|n\rangle \simeq -0.4(m_N/m_u)\bar{n} i\gamma_5 n$, we determine the induced corrections to the CP-odd electron-nucleon Lagrangian, $\mathcal{L} = C_S \bar{N}N\bar{e} i\gamma_5 e + C_P \bar{N} i\gamma_5 N \bar{e}e$,

$$C_S \sim \frac{2 \times 10^{-4}}{1\ {\rm GeV} \times \Lambda^{qe}}, \qquad C_P \sim \frac{4 \times 10^{-3}}{1\ {\rm GeV} \times \Lambda^{qe}}, \quad (10)$$

using maximal ${\rm Im} Y^{qe}$ and taking $m_{\rm SUSY} = 300$ GeV.

Comparing (10) to the limits on C_S and C_P deduced from the Tl and Hg EDM bounds [11], we obtain the following sensitivity:

$$\Lambda^{qe} \gtrsim 3 \times 10^8\ {\rm GeV} \quad \text{from Tl EDM}, \quad (11)$$

$$\Lambda^{qe} \gtrsim 1.5 \times 10^8\ {\rm GeV} \quad \text{from Hg EDM}, \quad (12)$$

$$\Lambda^{qq} \gtrsim 3 \times 10^7\ {\rm GeV} \quad \text{from Hg EDM}. \quad (13)$$

The last relation results from sensitivity to the CP-violating operators $(\bar{d} i\gamma_5 d)(\bar{u}u)$ from (5), leading to the Schiff nuclear moment and the Hg EDM. These are remarkably large scales and, indeed, not far below the scales suggested by neutrino physics. In fact, the next generation of atomic or molecular EDM experiments [12] may reach sensitivities sufficient to push Λ^{qe} into regions close to the suggested scale of right-handed neutrinos.

Semileptonic operators involving heavy quark superfields are, in turn, strongly constrained via two-loop corrections (3) to the dipole amplitudes. The bound on $d_{\rm Tl}$ implies $|d_e| \lesssim 1.6 \times 10^{-27} e$ cm, which for maximal ${\rm Im} Y^{qe}_{1133}$ implies:

$$\Lambda^{qe} \gtrsim 1.3 \times 10^8\ {\rm GeV}. \quad (14)$$

Results analogous to (3) apply for the quark EDMs and color EDMs, furnishing a similar sensitivity to Λ^{qq}.

Lepton-flavor violation.—Searches for lepton-flavor violation (LFV), such as $\mu \to e\gamma$ decay and $\mu \to e$ conversion in nuclei, have resulted in stringent upper bounds on the corresponding branching ratio ${\rm Br}(\mu \to e\gamma) < 1.2 \times 10^{-11}$ [13] and the rate of conversion normalized on capture rate $R(\mu \to e^- \text{ on Ti}) < 4.3 \times 10^{-12}$ [14], with further improvement anticipated. The latter bound implies a particularly high sensitivity to the semileptonic operators in (1). The conversion is mediated by $(\bar{u}u)\bar{e} i\gamma_5 \mu$ and $(\bar{u}u)\bar{e}\mu$ and involves the same matrix elements as C_S. Using bounds on such scalar operators derived elsewhere (see, e.g., [15]), we conclude that $\mu \to e$ conversion probes energy scales as high as

$$\Lambda^{qe} \gtrsim 1 \times 10^8\ {\rm GeV} \quad \text{from } \mu^- \to e^- \quad \text{on Ti}. \quad (15)$$

The constraint on $\mu \to e\gamma$ probes similar, but slightly lower, scales as it requires a two-loop diagram as in Fig. 1(b). Disregarding an $O(1)$ factor between (11) and (15), we conclude that searches for EDMs and LFV probe these extensions of the MSSM up to comparable energy scales of $\sim 10^8$ GeV.

Hadronic flavor constraints.—Often, the most constraining piece of experimental information comes from the contribution of new physics to the mixing of neutral mesons K and B. However, in the present case, there is necessarily a significant loop and Yukawa suppression arising from (6), and the sensitivity is correspondingly weakened. Taking $(\Delta m_K)_{\rm exp} \simeq 3.5 \times 10^{-6}$ eV [16], we find $\Lambda^{qq} \gtrsim (\tan\beta/50) \times 200$ GeV [7]. Δm_B exhibits a similar sensitivity, while ϵ_K is about 3 orders of magnitude more

TABLE I. Sensitivity to the threshold scale. The naturalness bound on $\mathrm{Im}(Y^{qq})$ does not apply to the axionic solution of the strong CP problem, the best sensitivity to $\mathrm{Im}(y_h)$ is achieved at maximal $\tan\beta$, and the Hg EDM constraint on $\mathrm{Im}(Y^{qq})$ applies when at least one pair of quarks belongs to the 1st generation.

Operator	Sensitivity to Λ (GeV)	Source
Y^{qe}_{3311}	$\sim 10^7$	Naturalness of m_e
$\mathrm{Im}(Y^{qq}_{3311})$	$\sim 10^{17}$	Naturalness of $\bar\theta$, d_n
$\mathrm{Im}(Y^{qe}_{ii11})$	10^7–10^9	Tl, Hg EDMs
Y^{qe}_{1112}, Y^{qe}_{1121}	10^7–10^8	$\mu \to e$ conversion
$\mathrm{Im}(Y^{qq})$	10^7–10^8	Hg EDM
$\mathrm{Im}(y_h)$	10^3–10^8	d_e from Tl EDM

sensitive but still well below the scales probed by EDMs and LFV. In contrast, it is clear that these observables provide much better sensitivity to SUSY dimension-six operators, which impose no additional suppression factors. Denoting the corresponding scale as Λ', we find $\Lambda' \gtrsim 8 \times 10^6$ GeV, while ϵ_K is sensitive to scales $\sim 10^8$ GeV.

Two-loop contributions to $b \to s\gamma$ [as in Fig. 1(b)] are not Yukawa suppressed and, with the current precision $\Delta\mathrm{Br}(B \to X_s\gamma) \sim 10^{-4}$ [16], are somewhat more sensitive. We find $\Lambda^{qq} \gtrsim 10^3$–$10^4$ GeV (for $Y^{qq}_{3233} \sim 1$), still well below the sensitivity in other channels.

Constraints on the Higgs operator.—The high sensitivity to $QULE$ and $QUQD$ arises primarily because they can flip the light fermion chirality without Yukawa suppression. It would then come as no surprise if $H_uH_dH_uH_d$ were to have little implication for CP- and flavor-violating observables; the operator will, of course, provide corrections to the sfermion and neutralino mass matrices and can induce CP-odd mixing between A and h, H, but these effects do not lead to high sensitivity to Λ_h.

Remarkably enough, it turns out that EDMs do exhibit a high sensitivity to $H_uH_dH_uH_d$ at large $\tan\beta$ through corrections to the Higgs potential and, in particular, the effective shift of the m_{12}^2 parameter

$$m_{12}^2 H_uH_d \to (m_{12}^2)_{\mathrm{eff}} H_uH_d \equiv \left(m_{12}^2 + \frac{\mu y_h v_{\mathrm{SM}}^2}{\Lambda_h}\right) H_uH_d. \quad (16)$$

Crucially, a complex phase in $(m_{12}^2)_{\mathrm{eff}}$, due to $\mathrm{Im}(y_h)$, is enhanced at large $\tan\beta$ because $m_{12}^2 \simeq m_A^2/\tan\beta$. The resulting phase affects the one-loop SUSY EDM diagrams (see, e.g., [17]):

$$d_e = \frac{e m_e \tan\beta}{16\pi^2 m_{\mathrm{SUSY}}^2}\left(\frac{5g_2^2}{24} + \frac{g_1^2}{24}\right)\sin\left[\mathrm{Arg}\frac{\mu M_2}{(m_{12}^2)_{\mathrm{eff}}}\right]. \quad (17)$$

Expanding to leading order in $1/\Lambda_h$, using (16), and imposing the present limit on d_e discussed earlier, one finds impressive sensitivity for large $\tan\beta$,

$$\Lambda_h \gtrsim 2 \times 10^7\ \mathrm{GeV}\left(\frac{\tan\beta}{50}\right)^2\left(\frac{300\ \mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)\left(\frac{300\ \mathrm{GeV}}{m_A}\right)^2. \quad (18)$$

In conclusion, we have examined new flavor- and CP-violating effects mediated by dimension-five superpotential operators and have shown that the sensitivity to these operators extends far beyond the weak scale (as summarized in Table I). The semileptonic operators that mediate flavor violation in the leptonic sector and/or break CP could be detectable even if the scale of new physics is as high as 10^9 GeV and well above the naturalness scale. Our results can be translated into constraints on CP and flavor violation in specific models leading to (1), e.g., the NMSSM or the MSSM with an extra pair of Higgs bosons. Moreover, the sensitivity quoted in (11) and (15) is robust, having a mild dependence on the SUSY threshold. Finally, since these effects decouple linearly, an increase in sensitivity by just 2 orders of magnitude would already start probing scales relevant for neutrino physics. Our results motivate further searches for EDMs and LFV in the SUSY framework even if the soft-breaking sector provides no new sources, as happens, e.g., in models with low scale SUSY breaking.

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