High Energy Physics Thresholds in Weak-Scale Supersymmetry Models

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on the works with:

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- Weak Scale SUSY
- Dimension 5 operators in the MSSM
- The effects of high energy thresholds
- Experimental constraints
- Conclusion

Weak Scale SUSY

- Motivation: to maintain the SUSY solution to the gauge hierarchy problem while get along with the phenomenological requirement that SUSY must be broken.
- Big Q: We do not know the real SUSY breaking mechanism.
- MSSM: the minimal supersymmetric models with no extra gauge nor exotic particles other that required by SUSY. Supersymmetry is softly broken with soft masses   O(1 TeV).
- Constraints: flavor changing and CP constraint.
- Practical approach: Assume there is no tree level flavor changing and CP-phase in the soft-breaking sector, and real superpotential.
- Idea: Even with low scale SUSY complies with the constraints above , there could still be effects from (supersymmetric) new physics at higher energy scales.

The MSSM

- Assume Standard Model gauge,

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

- Chiral superfields:

Superfield	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	P_M
Q	$\mathbf{3}$	$\mathbf{2}$	1/6	-1
U	$\overline{\mathbf{3}}$	$\mathbf{1}$	-2/3	-1
D	$\overline{\mathbf{3}}$	$\mathbf{1}$	1/3	-1
L	$\mathbf{1}$	$\mathbf{2}$	-1/2	-1
E	$\mathbf{1}$	$\mathbf{1}$	1	-1
H_u	$\mathbf{1}$	$\mathbf{2}$	1/2	+1
H_d	$\mathbf{1}$	$\mathbf{2}$	-1/2	+1

- Assume that R-parity is conserved, and there is no singlets.
- Superpotential:

$$\begin{aligned} \mathcal{W}_{\rm MSSM} = & \; UY_uQH_u - DY_dQH_d \\ & -EY_eLH_d + \mu H_uH_d \end{aligned}$$

Dimension 5 Operators

- Gauge invariant, R-parity conserving, dimension 5 operators in MSSM:

$$\begin{aligned}\mathcal{W}^{(5)} &= QUQD + QULE + H_u H_d H_u H_d \\ &\quad + H_u L H_u L + UUDE + QQQL\end{aligned}$$

- Some operators violate baryon and lepton numbers directly.

- We would like to study

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

Note:

Dimension 5 operator in the Kähler terms.

$$K^{(5)} = c_u Q U H_d^\dagger + c_d Q D H_u^\dagger + c_e L E H_u^\dagger$$

can be absorbed into the superpotential, e.g. the equation of motion for $H_u^\dagger$ reads

$$\bar{\mathrm{D}}\bar{\mathrm{D}} H_u^\dagger = -\mu H_d + Y_u Q U,$$

so

$$\int d^4\theta c_e L E H_u^\dagger = \int d^2\theta c_e L E \bar{\mathrm{D}}\bar{\mathrm{D}} H_u^\dagger$$

$$= \int d^2\theta (-c_e \mu L E H_d + c_e Y_u Q U L E).$$

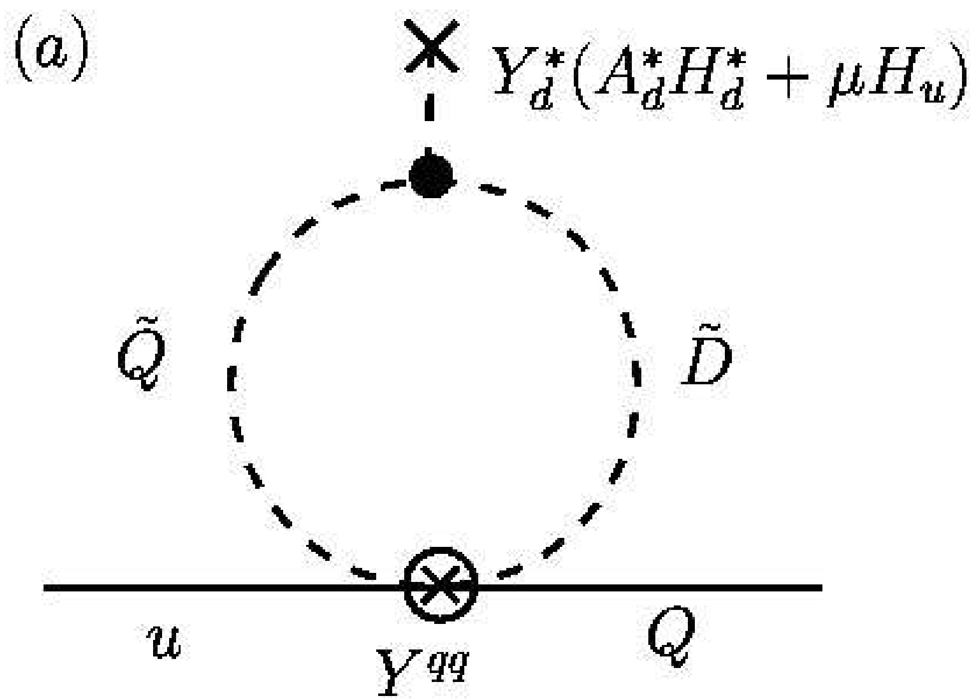
The effects of high energy thresholds

- SM fermion masses

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

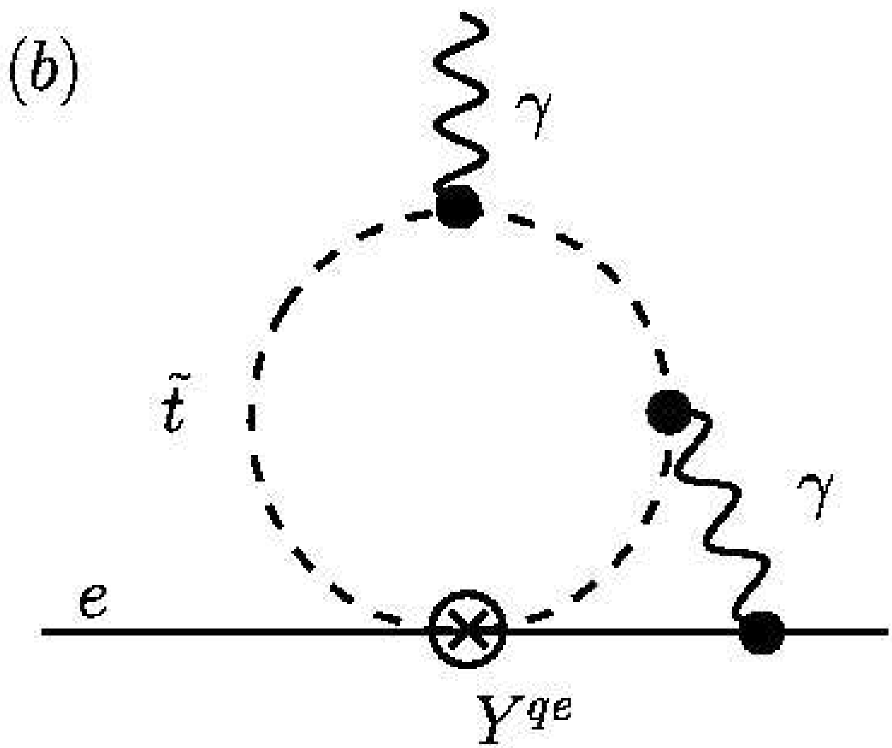
$$\delta(M_d)_{ij} = K^{qq}_{klij}(M_u^{(0)})^*_{kl}\,\frac{\ln(\Lambda_{qq}/m_{\rm sq})}{4\pi^2\Lambda_{qq}} \times(A_u^* + \mu\cot\beta),$$

where $K^{qq} \equiv Y^{qq} - 2\tilde{Y}^{qq}/3$.



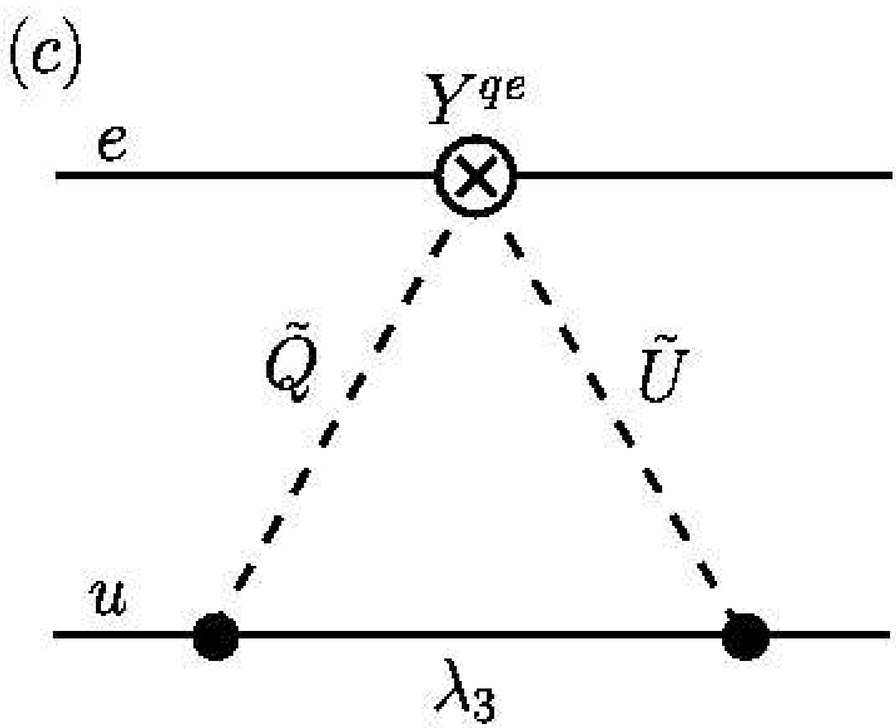
- Dipole operators

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



- Semileptonic operators

$$\mathcal{L}_{qe} = \frac{1}{\Lambda_{qe} m_{\rm susy}} \frac{\alpha_s}{3\pi} Y^{qe}_{ijkl} \bar{U}_i Q_j \bar{E}_k L_l + ({\rm h.c.})$$

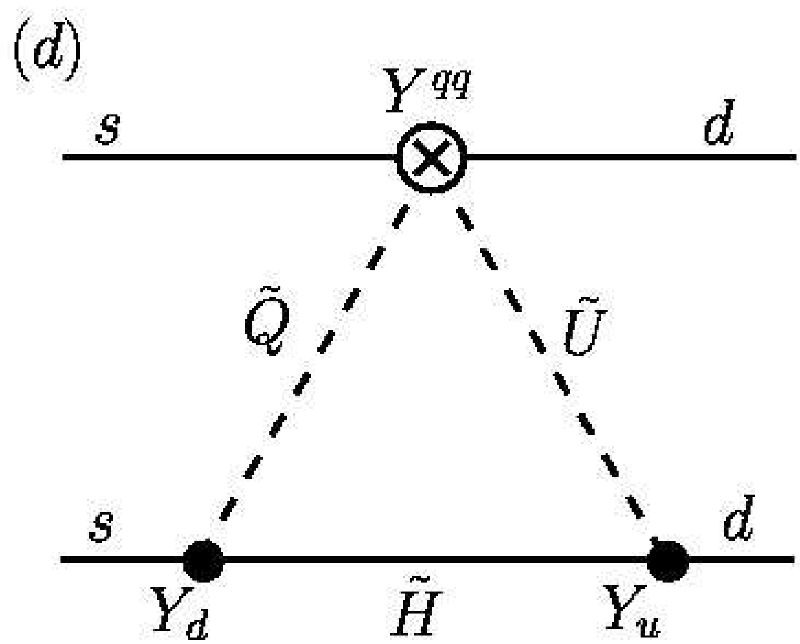


- Four-quark operators

$$\mathcal{L}_{qq} = \frac{1}{\Lambda_{qq} m_{\rm susy}} \frac{\alpha_s}{12\pi} \times K^{qq} \left[\frac{8}{3} (\bar{U} Q)(\bar{D} Q) + (\bar{U} t^A Q)(\bar{D} t^A Q) \right] + (\text{h.c.})$$

For $\Delta F = 2$:

$$\mathcal{L}_{dd} = \frac{1}{\Lambda_{qq} m_{\rm susy}} \frac{1}{16\pi^2} (Y_u^*)_{im} (Y_d^*)_{nj} K_{ijkl}^{qq} \times \left[\frac{1}{3} (\bar{Q}_m D_n)(\bar{D}_k Q_l) - (\bar{Q}_m t^A D_n)(\bar{D}_k t^A Q_l) \right] + (\text{h.c.})$$



Phenomenological Constraints

- Correction to electron mass

  Assume the massles couplings to be maximal $Y \sim O(1)$, for $A_t \sim 300$ GeV,

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

  Using naturalness we get $\Lambda^{qe} \gtrsim 10^7$ GeV.

  Suppose we have Dirac neutrino, without seesaw. Similar argument gives us

$$\Delta m_{\nu D} \sim 1\text{eV}\frac{10^6\text{GeV}}{\Lambda^{qe}}$$

  This leads to $\Lambda^{qe} \gtrsim 10^{12}$ GeV.

- Electric Dipole Moment

  Experimental bounds

$$|d_{\mathrm{Tl}}| < 9 \times 10^{-25}\, e\,\mathrm{cm}$$
$$|d_{\mathrm{Hg}}| < 2 \times 10^{-28}\, e\,\mathrm{cm}$$

  High energy correction

$$\mathcal{L}_{CP} = -\frac{\alpha_s \mathrm{Im} Y^{qe}_{1111}}{6\pi \Lambda_{qe} m_{\mathrm{susy}}} \times \left[(\bar{u}u)\bar{e}i\gamma_5 e + (\bar{u}i\gamma_5 u)\bar{e}e\right]$$

  For the nucleon, we write

$$\mathcal{L} = C_S \bar{N} N \bar{e} i\gamma_5 e + C_P \bar{N} i\gamma_5 N \bar{e} e$$

  and take $m_{susy} \sim 300$ GeV, we get

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

  yields

$$\begin{array}{lll} \Lambda^{qe} \gtrsim 3 \times 10^{8}\ \mathrm{GeV} & & \text{from Tl EDM} \\ \Lambda^{qe} \gtrsim 1.5 \times 10^{8}\ \mathrm{GeV} & & \text{from Hg EDM} \\ \Lambda^{qq} \gtrsim 3 \times 10^{7}\ \mathrm{GeV} & & \text{from Hg EDM} \end{array}$$

- θ term

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

Suppose $\bar{\theta}$ is tuned toward zero, combined with bound on neutron EDM, $|d_n| < 6 \times 10^{-26} e$ cm, trough $d_n(\bar{\theta})$ yields $\rightarrow \Lambda^{qq} \gtrsim 10^{17}$ GeV.

- Lepton flavor violation

$$BR(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$$
$$R(\mu \rightarrow e \text{ on Ti}) < 4.3 \times 10^{-12}$$

From $\mu^- \rightarrow e^-$ on Ti:

$$\Lambda^{qe} \gtrsim 1 \times 10^8 \text{GeV}$$

The $\mu \rightarrow e\gamma$ yields slightly lower.

- Hadronic flavor constraint

$$(\Delta m_K)_{\rm exp} \simeq 3.5 \times 10^{-6}{\rm eV}$$

yields

$$\Lambda^{qq} \gtrsim \frac{\tan\beta}{50} \times 200{\rm GeV}$$

These are suppressed by loop and Yukawa. Might need to look at dimension 6.

- Higgs sector

There is correction to the Higgs potential through the shift on m_{12}:

$$(m_{12}^2)_{\rm eff} H_u H_d \equiv \left(m_{12}^2 + \frac{\mu y_h v_{SM}^2}{\Lambda_h} \right) H_u H_d$$

which has phase effect on SUSY EDM

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

yields (for $m_{\rm susy}, m_A \sim 300$ GeV)

$$\Lambda_h \gtrsim 2 \times 10^7 \ {\rm GeV} \left(\frac{\tan\beta}{50} \right)^2$$

Summary

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

Conclusions

- We have studied the effects of dimension 5 operators in the MSSM scenario, focusing on the flavor changing and CP violation effects.
- We found that CP constraint can probe new physics above the MSSM as high as 10^9 GeV.
- It would be interesting to see how this constraints play in specific models.