Higher dimensional operators in MSSM

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Outline

- Effective operators from new physics

  integrating out heavy states : - higher-dimensional

  - higher-derivative operators (hdo)

- SUSY hdo: - 2-derivative description

  - SUSY breaking

- Higher-dim + hdo in MSSM: - generation from heavy fields

  - classification of dim 5

  - physical consequences

Effective operators from new physics

- Low-energy physics is described by local interactions of dimension ≤ 4

  renormalizable QFT $\rightarrow$ predictive power

- However at energies lower than masses of heavy particles

  some interactions may look non-renormalizable

  e.g. four-fermion Fermi interactions

- Unknown new physics in the multi-TeV range parametrized by:

  local effective operators O_n^i of dim $(4+n)$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm Standard\ Model} + \sum_i \frac{c_n^i}{M^n} O_n^i \qquad E << M$$

M not far from the electroweak scale $\Rightarrow$

lowest-dim operators O_n^i can affect significantly the low energy physics

Integrating out heavy fields $\Rrightarrow$ two types of higher-dim effective operators

- with two (or less) derivatives

  from tree-level exchanges of massive states

$$|(\partial_\mu - Z'_\mu)H|^2 - \frac{M^2}{2} Z'_\mu Z'_\mu \quad \to \quad \frac{1}{M^2}(H^\dagger \partial_\mu H)^2$$

$$i\bar{\psi}\gamma^\mu D_\mu \psi - \frac{M^2}{2} Z'_\mu Z'_\mu \quad \to \quad \frac{1}{M^2}(\bar{\psi}\gamma_\mu \psi)^2$$

- higher-derivative operators (hdo) generated by:
  - mixing with heavy states
  - string theory DBI action, α'/loop corrections

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{\lambda_1\phi^4}{4} + \frac{1}{2}(\partial\chi)^2 + c(\partial\phi)(\partial\chi) - \frac{M^2\chi^2}{2} - \frac{\lambda_2\phi^2\chi^2}{2}$$

Integrate out the massive field $\chi \Rightarrow$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{\lambda_1\phi^4}{4} + \frac{c^2}{2}\Box\phi\frac{1}{M^2 + \Box + \lambda_2\phi^2}\Box\phi$$

$$\to \frac{c^2}{M^2}\left(\Box\phi\right)^2$$

SUSY hdo

General 2-derivative SUSY lagrangian: 3 functions of chiral superfields ϕ_i

1 real: Kähler potential K

2 analytic: superpotential W, gauge kinetic function f

$$\mathcal{L}_{susy} = \int d^4\theta\, K(\phi_i^\dagger e^V, \phi^i) + \int d^2\theta\, \left[W(\phi_i) \;+\; f_{ab}(\phi_i)\mathcal{W}^a\mathcal{W}^b \right] + \text{h.c.}$$

chiral gauge superfield $\mathcal{W} \sim \bar{D}^2 DV$

Higher-dimensional operators: encoded in power expansions

$$K \;=\; \phi_i^\dagger e^V \phi^i \;+\; \left(\frac{c^i_{jk}}{M} \phi_i^\dagger e^V \phi^j \phi^k + \text{h.c.} \right) + \cdots$$

$$W \;=\; \lambda_{ijk}\phi^i\phi^j\phi^k \;+\; \frac{c_{ijkl}}{M}\phi^i\phi^j\phi^k\phi^l + \cdots \qquad f_{ab}(\phi_i) = \delta_{ab} \;+\; \frac{f_{abi}}{M}\;\phi^i + \cdots$$

the first terms in the rhs are renormalizable

hdo operators

- hdo in the superpotential

$$(a)\quad \frac{\lambda_{ij}}{M}\int d^2\theta\, \Phi_i \Box \Phi_j \sim \frac{\lambda_{ij}}{M}\int d^4\theta\, \Phi_i D^2 \Phi_j$$

$\bar{D}^2 D^2$

- hdo in the Kähler potential

$$(b)\quad \frac{k_{ij}}{M^2}\int d^4\theta\, \Phi_i^\dagger \Box \Phi_j\ , \quad \frac{k_{ijk}}{M^2}\int d^4\theta\, \Phi_i^\dagger\ \Phi_j D^2 \Phi_k\ , \quad \cdots$$

In components: $\Phi = z\ +\ \sqrt{2}\theta\psi\ +\ \theta^2 F$

(a) contains $\psi\Box\psi$, $F\Box z$

(b) contains $|\Box z|^2$, $\bar{\psi}\partial\Box\psi$, $\bar{F}\Box F$

$\Rightarrow$ higher-derivative kinetic terms $\rightarrow$ propagating auxiliary fields

Example

$$\mathcal{L} = \int d^4\theta \left(\Phi^\dagger\Phi + \chi^\dagger\chi\right) + \int d^2\theta \left(m\Phi\chi + \frac{M}{2}\chi^2\right) + \text{h.c.}$$

Integrate out the heavy field χ :

$$\begin{aligned}\mathcal{L} &= \int d^4\theta \left[\left(1 + \frac{m^2}{M^2}\right)\Phi^\dagger\Phi + \frac{m^2}{M^4}\Phi^\dagger\Box\Phi + \cdots\right] \\ &- \int d^2\theta \left(\frac{m^2}{2M}\Phi^2 + \frac{m^2}{2M^3}\Phi\Box\Phi\right) + \text{h.c.}\end{aligned}$$

Reformulate SUSY theories with hdo in terms of two-derivatives:

- coupling to gravity much simpler $\longrightarrow$

  SUSY breaking via gravity easier to study

- coupling to a SUSY breaking sector

  can be studied by standard methods

- theories with hdo : ghost (super)fields

  is the theory sick ?

  no, if treated as effective at energies $E \ll M$

hdo in the superpotential

$$\mathcal{L} = \int d^4\theta\, \Phi^\dagger\Phi + \int d^2\theta \left(\pm\sqrt{\xi}\,\Phi\Box\Phi + \frac{m}{2}\Phi^2 + \frac{\lambda}{3}\Phi^3 \right) + \text{h.c.}$$

$\Rightarrow$ one particle + one ghost with masses:

$$m_1^2 \simeq m^2 \quad , \quad m_2^2 \simeq \frac{1}{4\xi} \leftarrow \text{of order the cutoff}$$

$$\mathcal{L} = \int d^4\theta \left[\Phi_1^\dagger\Phi_1 - \Phi_2^\dagger\Phi_2 \right] + \int d^2\theta \left[\tfrac{1}{2} m_{kp}\Phi_k\Phi_p + \tfrac{1}{3}\lambda_{kpl}\Phi_k\Phi_p\Phi_l \right] + \text{h.c.}$$

$$\begin{pmatrix} \Phi \\ \sqrt{\xi}\,\bar{D}^2\Phi^\dagger \end{pmatrix} = \begin{pmatrix} a_1 & a_2 \\ b_1 & b_2 \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

unitary matrix $\nearrow$

Can hdo trigger SUSY breaking?

scalar potential not positive definite:

$$V = \sum_{\text{particles}} |F_i|^2 - \sum_{\text{ghosts}} |F_j|^2$$

No if SUSY is unbroken in the absence of hdo

SUSY minima are stable   but V could vanish with SUSY broken

However S$\not{U}$SY may be trivial without hdo

decoupled in a non-interacting sector

Higher-dim + hdo in MSSM

Generation from heavy fields

- Higher-dim operators: via interactions with heavy (super)fields

Example: singlet coupled to higsses in MSSM

Strumia '99 ; Brignole-Casas-Espinosa-Navarro '03
Dine-Seiberg-Thomas '07

$$W = \lambda\sigma H_1 H_2 + M\sigma^2 \quad \to \quad W_{\rm eff} = \frac{\lambda^2}{M}\,(H_1 H_2)^2$$

$\Rightarrow$ can raise the Higgs mass in MSSM ?

- hdo operators: via mixing with heavy fields

MSSM: Higgs mixing with heavy doublets

$$\int d^4\theta \sum_{i=1,2}^{3,4} H_i^\dagger H_i + \left(c_1 H_1^\dagger H_3 + c_2 H_2^\dagger H_4 + \mathrm{h.c.} \right) + \int d^2\theta \, (\mu H_1 H_2 + M H_3 H_4) + \mathrm{h.c.}$$

$\mu << M$ neglecting gauge interactions :

$$\int d^4\theta \left(H_1^\dagger H_1 + H_2^\dagger H_2 + \frac{c_1^2}{M^2} H_1^\dagger \Box H_1 + \frac{c_2^2}{M^2} H_2^\dagger \Box H_2 \right)$$

$$+ \int d^2\theta \, (\mu H_1 H_2 + \frac{c_1 c_2}{M} H_1 \Box H_2) + \mathrm{h.c.}$$

dominant at low energy

$$\frac{1}{M} \int d^4\theta \left(H_2 e^{-V} D^2 e^V H_1 + \mathrm{h.c.} \right)$$

gauge interactions

Low-energy supersymmetry: main target of LHC

Quantum corrections in MSSM:

important to reconcile the tree-level relation $m_h \leq m_Z$

with the experimental limit $m_h \gtrsim 114$ GeV

Higher-dim / hdo operators: can also affect low-energy predictions

masses, couplings, interactions, ...

$\rightarrow$ classification of dim-5 (R-parity conserving):

$$\mathcal{L} = \mathcal{L}_{MSSM} + \mathcal{L}^{(5)}$$

$$\mathcal{L}_{MSSM} = \int d^4\theta \left(\mathcal{Z}_1 H_1^\dagger e^V H_1 + \mathcal{Z}_2 H_2 e^{-V} H_2^\dagger \right) + \text{gauge} + \text{matter}$$
$$+ \int d^2\theta \left(Q \lambda_U U H_2 - Q \lambda_D D H_1 - L \lambda_E E H_1 + \mu H_1 H_2 \right) + \text{h.c.}$$

soft terms: $\mathcal{Z}_i(S, S^\dagger)$, $\lambda_{U,D,E}(S)$, $\mu(S)$ spurion $S \equiv m_S \theta^2$

$$\mathcal{L}^{(5)} = \frac{1}{M} \int d^2\theta \left[Q\, U\, T_Q\, Q\, D + Q\, U\, T_L\, L\, E + \lambda_H (H_1 H_2)^2 \right] + h.c.$$
$$+ \frac{1}{M} \int d^4\theta \Big[H_1^\dagger e^V Q\, Y_U\, U + Q\, Y_D\, D\, e^{-V} H_2^\dagger + L\, Y_E\, E\, e^{-V} H_2^\dagger$$
$$+ A\, D^\alpha \left(B\, H_2\, e^{-V} \right) D_\alpha \left(C\, e^V H_1 \right) + h.c. \Big]$$

$T_{Q,L}(S)$, $\lambda_H(S)$, $Y_{U,D,E}(S, S^\dagger)$, $A(S, S^\dagger)$, $B(S, S^\dagger)$, $C(S, S^\dagger)$

T, Y dangerous FCNC $\Rightarrow$ simple ansatz for their absence:

$$T_Q = t_Q(S)\, \lambda_U \otimes \lambda_D \qquad T_L = t_L(S)\, \lambda_U \otimes \lambda_E$$
$$\lambda_F(S) = (1 + A_F S)\lambda_F \qquad Y_F = y_F(S, S^\dagger)\, \lambda_F \qquad F : U, D, E$$

Field redefinitions $\Rightarrow$ remove redundancy

$$H_1 \;\rightarrow\; H_1 - \frac{1}{M}\,\overline{D}^2\left[\Delta_1 e^{-V} H_2^\dagger\right] + \frac{1}{M}\,Q\,\rho_U\,U \qquad \Delta_i(S,S^\dagger)\,,\;\rho_{U,D,E}(S)$$

$$H_2 \;\rightarrow\; H_2 - \frac{1}{M}\,\overline{D}^2\left[\Delta_2\, H_1^\dagger\, e^{V}\right] + \frac{1}{M}\,Q\,\rho_D\,D + \frac{1}{M}\,L\,\rho_E\,E$$

$$\Rightarrow\; T_Q,\; T_L,\; A,\; B,\; C = 0 \quad Y_F = y_F(S^\dagger)\,\lambda_F \quad F: U, D, E$$

$$\mathcal{L}_F^{(5)} \;\sim\; (\eta_1 + \eta_2 S)\,(H_1 H_2)^2$$

$$\mathcal{L}_D^{(5)} \;\sim\; (y_U + z_U S^\dagger)\,H_1^\dagger\, e^V\, Q\,\lambda_U\,U \;+\; (y_D + z_D S^\dagger)\,Q\,\lambda_D\,D\; e^{-V}\,H_2^\dagger$$

$$+\;(y_E + z_E S^\dagger)\,L\,\lambda_E\,E\; e^{-V}\,H_2^\dagger + \mathrm{h.c.}$$

Physical consequences: Higgs potential

Higgs mass & potential: not important effect

perturbativity of $\mathcal{L}^{(5)} \Rightarrow$ only η_2 can change the tree-level upper bound

$m_h \leq m_Z$ marginally when $m_A \simeq m_Z$

$$
\begin{aligned}
\mathcal{V}_{\rm Higgs} = \; & m_1^2|h_1|^2 + m_2^2|h_2|^2 + B\mu(h_1 h_2 + \text{h.c.}) + \frac{g^2}{8}\left(|h_1|^2 - |h_2|^2\right)^2 \\
& + \left(|h_1|^2 + |h_2|^2\right)\left(\eta_1 h_1 h_2 + \text{h.c.}\right) + \frac{1}{2}\left[\eta_2 (h_1 h_2)^2 + \text{h.c.}\right] \\
& + \left(|h_1|^2 - |h_2|^2\right)\left(\eta_3 h_1 h_2 + \text{h.c.}\right)
\end{aligned}
$$

$g^2 = g_2^2 + g_Y^2$ $\quad$ η_3: hdo operator (can be eliminated by field redefinitions)

$m_h^2 + m_H^2 = m_A^2 + m_Z^2 + 2\eta_1 v^2 \sin 2\beta + \eta_2 v^2$ $\quad$ $v_1 = v\cos\beta, v_2 = v\sin\beta$

large $\tan\beta$ expansion: $m_h^2 - m_Z^2 = \frac{4 m_A^2 v^2}{m_A^2 - m_Z^2} \frac{(\eta_1 - \eta_3)}{\tan\beta} + \cdots$

can be made positive but breaks perturbative expansion in $1/M$

requiring η-corrections to be smaller than MSSM mass matrix elements $\Rightarrow$

$\eta_{1,3}$ cannot change the tree-level bound $m_h \leq m_Z$

η_2 can change marginally:

$$\frac{m_h^2 - m_Z^2}{m_Z^2} \simeq \begin{cases} 16\% & \text{for} \quad m_A = m_Z \quad (m_h \leq 105 \text{ GeV}) \\ 0.002\% & \text{for} \quad m_A \simeq 1.5 m_Z \end{cases} \Rightarrow$$

quantum corrections are still needed for $m_h \gtrsim 114$ GeV

Physical consequences: New couplings from $\mathcal{L}_D^{(5)}$

z_F $\mathcal{O}(\frac{m_S}{M})$:

- 'wrong Higgs' Yukawas: $H_1 \leftrightarrow H_2^\dagger \Rightarrow$ Martin '99 ; Haber-Mason '07

  $\tan\beta$ enhancement of Higgs decays into bottom quarks

  also in MSSM at 1-loop integrating out 'heavy' squarks

  $\rightarrow$ double suppression: $\delta\lambda_b \sim \mathcal{O}(\frac{m_S^2}{M^2}) \times$ loop factor

  $m_b = \frac{v \cos\beta}{\sqrt{2}} (\lambda_b + \delta\lambda_b + \Delta\lambda_b \tan\beta)$ $\Delta\lambda_b : z_B$

- Higgs - sfermion quartic interactions $h_1^\dagger h_2^\dagger\,(\mathrm{squark})^2$

  suppressed by $(\text{Yukawa})^2$

If FCNC ansatz is relaxed for the 3rd generation $\Rightarrow$

- 'wrong Higgs' - gaugino - higgsino coupling $h_i - \tilde{h}_i - \tilde{g}$
- 'wrong Higgs' A-terms

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y_F:

- 4 pt contact interactions: $f - f - \tilde{f} - \tilde{f} \Rightarrow$

  squark production enhancement for the 3rd generation

$$\mathcal{A}_{qq\to\tilde{q}\tilde{q}} \sim \frac{g_3^2}{\sqrt{s}} + \frac{y_t y_b}{M}$$

MSSM contribution decreases with s while correction is constant

- higher point gauge interactions: $A - \tilde{h} - f - \tilde{f}$, $A^2 - h^\dagger - \tilde{h} - f - \tilde{f}$

  $\tilde{g} - \tilde{h} - \tilde{f} - \tilde{f}$, $\tilde{g} - h^\dagger - f - \tilde{f}$, $\cdots$

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  $\tilde{g} - \tilde{h} - \tilde{f} - \tilde{f}\,,\ \tilde{g} - h^\dagger - f - \tilde{f}\,, \cdots$

Conclusions

- Effective actions with higher-dim/hdo:

  appropriate tools to parametrize our ignorance about new physics

- hdo can be rewritten as standard two-derivatives

  ghosts artifact of the truncation in derivative expansion

- General analysis of their effects in MSSM $\Rightarrow$

  classification of dim 5 (R-parity conserving):

  - (spurion dependent) field redefinitions to remove redundancy
  - no significant effects to the Higgs mass
  - additional couplings can be important

  e.g. enhancement of squark production & Higgs decays into b-quarks

- Same method can be applied to other cases