Higgs in MSSM with dim-5 and 6 operators

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1. Effective operators from new physics at the multi-TeV scale
2. MSSM: - classification of dim 5 operators

   - physical consequences
3. MSSM Higgs with dim 6 operators as well

- comparable to dim 5 at large tan β
- alleviate the MSSM fine-tuning

with E. Dudas, D. Ghilencea, P. Tziveloglou '08, '09 + in progress

Motivation

- New physics/heavy particles may exist above LHC energies
- Little hierarchy in MSSM $\quad \rightarrow \quad \sim 1\%$ fine tuning

  tension between LEPII bounds on the Higgs mass and SUSY particles
- Unknown new physics in the multi-TeV range parametrized by:

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

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

  M not far from the electroweak/TeV scale $\Rightarrow$

  lowest-dim operators O_n^i can affect significantly the low energy physics
- study MSSM + effective operators $\Rightarrow$ hints for new physics

Effective operators

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

- with two (or less) derivatives

  from tree-level exchanges of massive states

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

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

- 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 $\chi \Rrightarrow$

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

$$\rightarrow \frac{c^2}{M^2}\left(\Box\phi\right)^2 + \cdots$$

SUSY effective operators

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

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

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

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

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

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

⇒ can raise the Higgs mass in MSSM ?

• hdo operators: via mixing with heavy fields

MSSM Higgs mixing with heavy doublets

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

$\mu << M$ neglecting gauge interactions :

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

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

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

Classification of dim-5 (R-parity conserving): $MSSM_5 = \mathcal{L}_{MSSM} + \mathcal{L}^{(5)}$

Field redefinitions $\Rightarrow$ remove redundancy

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

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

$$\mathcal{L}^{(5)} = \frac{1}{M} \int d^2\theta \mathcal{L}_F^{(5)} + \frac{1}{M} \int d^4\theta \mathcal{L}_D^{(5)}$$ [12] [13]

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

$$\mathcal{L}_D^{(5)} \sim (y_U + z_U S^\dagger)\, H_1^\dagger\, e^V\, Q\, \lambda_U\, U + (y_D + z_D S^\dagger)\, Q\, \lambda_D\, D\; e^{-V}\, H_2^\dagger$$
$$+ (y_E + z_E S^\dagger)\, L\, \lambda_E\, E\; e^{-V}\, H_2^\dagger + \text{h.c.}$$

up to field redefinitions

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

'hard' SU$\not{}$SY terms $\sim z_F\ \mathcal{O}(\frac{m_S}{M})$:

- '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

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

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

  suppressed by (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

new SUSY couplings $\sim y_F$:

- 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: $A - \tilde{h} - f - \tilde{f}\,,\ A^2 - h^\dagger - \tilde{h} - f - \tilde{f}$

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

Physical consequences of $MSSM_5$: Higgs potential

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

$g^2 = g_2^2 + g_Y^2$ $\qquad \eta_1 \sim \mu/M$ $\qquad \eta_2 \sim m_S/M$ $\qquad$ [9]

- $\eta_{1,2} \Rightarrow$ quartic terms along the D-flat direction $|h_1| = |h_2|$
- potential stability $\Rightarrow \eta_2 \geq 4|\eta_1|$

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

only η_2 can change the tree-level bound $m_h \leq m_Z$ but marginally:

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

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

Relevance of dim-6 operators

1) Relaxing the condition on potential positivity: guaranteed by dim-6 ops

only one dim-6 along the D-flat direction induced by dim-5: $\propto \eta_1^2$ [9]

$$W = \eta_1 (H_1 H_2)^2 \longrightarrow V = \left| \frac{\partial W}{\partial H_i} \right|^2 \sim \eta_1^2 \, |H_1 H_2|^2 \left(|H_1|^2 + |H_2|^2 \right)$$

but 2nd minimum along the flat direction

stability of EW vacuum against tunelling $\Rightarrow$ new constraints on $\eta_{1,2}$ $\Rightarrow$

Blum-Delaunay-Hochberg '09

- tree-level mass Higgs bound can change above LEPII limit
- bigger parameter space for LSP being dark matter

Bernal-Blum-Nir-Losada '09

2) In the large $\tan\beta$ regime:

$$\delta_5 m_h^2 = \frac{4 m_A^2 v^2}{m_A^2 - m_Z^2} \frac{\eta_1}{\tan\beta} + \cdots \qquad \frac{1}{M \tan\beta} \sim \frac{1}{M^2} \qquad v_1 = v\cos\beta,\, v_2 = v\sin\beta$$

MSSM Higgs with dim-6 operators

dim-6 operators can have an independent scale from dim-5

Classification of all dim-6 contributing to the Higgs potential

(without $SU\!\!\!/SY$) $\Rightarrow$

large $\tan\beta$ expansion: $\delta_6 m_h^2 = f v^2 + \cdots$

constant receiving contributions from several operators

$f \sim f_0 \times \left(\mu^2/M^2,\ m_S^2/M^2,\ \mu m_S/M^2,\ v^2/M^2\right)$

$m_S = 1$ TeV, $M = 10$ TeV, $f_0 \sim 1 - 2.5$ for each operator

$\Rightarrow m_h \simeq 103 - 119$ GeV

$\Rightarrow$ MSSM with dim-5 and dim-6 operators:

possible resolution of the little hierarchy problem

Conclusions

- Effective actions with higher-dim/hdo:

  appropriate tools to parametrize our ignorance about new physics

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

  classification of dim 5 (R-parity conserving):

  - (spurion dependent) field redefinitions to remove redundancy

  - additional couplings can be important

    e.g. enhanced squark production and Higgs decays into b-quarks

  - Higgs mass: can increase but not too much

- Stability + higgs mass at large $\tan\beta$: dim-6 operators relevant

  - corrections can lift m_H above LEPII bound (just from dim-6)

- light stop or 'heavier' higgs at LHC $\Rightarrow$ new physics beyond MSSM