Beyond the MSSM (BMSSM)

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Based on

M. Dine, N.S., and S. Thomas, to appear

Assume

- The LHC (or the Tevatron) will discover some of the particles in the MSSM.
- These include some or all of the 5 massive Higgs particles of the MSSM.
- No particle outside the MSSM will be discovered.

The Higgs potential

The generic two Higgs doublet potential depends on 13 real parameters:

- The coefficients of the three quadratic terms can be taken to be real

$$m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_{ud}^2(H_u H_d + c.c.).$$

- The 10 quartic terms may lead to CP violation.
- The minimum of the potential is parameterized as

$$|\langle H_u \rangle| = v \sin\beta$$

$$|\langle H_d \rangle| = v \cos\beta.$$

The MSSM Higgs potential

- The tree level MSSM potential depends only on the 3 coefficients of the quadratic terms. All the quartic terms are determined by the gauge couplings.

- The potential is CP invariant, and the spectrum is
  - a light Higgs h
  - a CP even Higgs and a CP odd Higgs $H,\ A$
  - a charged Higgs $H^{\pm}$
- It is convenient to express the 3 independent parameters in terms of $v,\ m_A,\ \tan\beta.$
- For simplicity we take $\tan\beta \gg 1$ with fixed $m_A.$ Soon we will physically motivate this choice.

The tree level Higgs spectrum

$$m_h^2 = M_Z^2 - \mathcal{O}(\cot^2\beta)$$

$$m_H^2 = M_A^2 + \mathcal{O}(\cot^2\beta)$$

$$m_{H^\pm}^2 = M_A^2 + M_W^2$$

- The corrections to the first relation are negative, and therefore $m_h \leq M_Z$.
- Since the quartic couplings are small, $m_h^2 \approx M_Z^2 \ll v^2$.
- The second relation reflects a *U(1)* symmetry of the potential for large $\tan\beta$.
- The last relation is independent of $\tan\beta$. It reflects an *SU(2)* custodial symmetry of the scalar potential for $g = 0$.

The lightest Higgs mass

- The LEPII bound
$$m_h \gtrsim 114 GeV$$
already violates the first mass relation $m_h \leq M_Z$.

- To avoid a contradiction we need both large $\tan\beta$ and large radiative corrections.

- Intuitively, large $\tan\beta$ means:
  - The electroweak breaking is mostly due to $\langle H_u \rangle \approx v$.
  - The light Higgs h is predominantly from H_u.
  - The four massive Higgses $H^{\pm}, H, A$ are predominantly from H_d.

Role of radiative corrections

- The radiative corrections depend on the two stop masses $m_{\tilde{t}_L}, m_{\tilde{t}_R}$ and on the trilinear coupling (A-term)

$$A_t \lambda_t \tilde{t}_L H_u \tilde{t}^c_R,$$

  where λ_t is the top Yukawa coupling. (There is also some dependence on the bottom sector.)
- Consistency with the LEP bound is achieved either with heavy sto $m_{\tilde{t}_L}, m_{\tilde{t}_R} \sim 600 - 1000\ GeV$

  or with large A-terms $A_t \sim 2 m_{\tilde{t}}$.

- Large A-terms are hard to achieve in specific models of supersymmetry breaking, and are fine tuned in the UV.

The problem with large stop mass

- With large stop mass the radiative corrections to the quadratic terms in the potential need to be fine tuned.
  - Intuitively, the superpartners make the theory natural and they should not be too heavy.
  - More quantitatively,

$$m^2 = m_0^2 - \frac{6\lambda_t^2}{16\pi^2}(2m_{\tilde{t}}^2 + |A_t|^2)\ln(\Lambda/m_{\tilde{t}}).$$

For small A-terms and high cutoff Λ, this amounts to roughly 1% fine tuning in the UV theory.

- This problem is known as the SUSY little hierarchy problem.

Corrections to the MSSM

- Assume that there is new physics beyond the MSSM at a scale M , much above the electroweak scale μ and the scale of the SUSY breaking terms m_{SUSY}

$$\epsilon \sim \frac{m_{SUSY}}{M} \sim \frac{\mu}{M} \ll 1$$

- The corrections to the MSSM can be parameterized by operators suppressed by inverse powers of M; i.e. by powers of ϵ .
- The suppression of an operator is not merely by its dimension. It is by its "effective dimension" (examples below).

Leading corrections to the MSSM

- There are only two operators at order ϵ

$$\mathcal{O}_1 = \frac{1}{M}\int d^2\theta (H_u H_d)^2$$

$$\mathcal{O}_2 = \frac{m_{SUSY}}{M}(H_u H_d)^2 = \frac{m_{SUSY}}{M}\int d^2\theta\theta^2 (H_u H_d)^2$$

- The operator $\mathcal{O}_1$ is a higher dimension supersymmetric operator.
- The operator $\mathcal{O}_2$ represents (hard) supersymmetry breaking.
- Both operators can lead to CP violation.

The first operator

$$\mathcal{O}_1 = \frac{1}{M} \int d^2\theta (H_u H_d)^2$$

- Using the MSSM term $\mu H_u H_d,$ it corrects the scalar potential by

$$2\epsilon_1 (H_u^2 H_u^* H_d + H_d^2 H_d^* H_u) + c.c.$$

$$\epsilon_1 \equiv \frac{\mu}{M}$$

- It contributes also to the charginos and neutralinos masses and to their couplings.
- Note, this operator is of dimension four but its effective dimension is five – it is suppressed by one power of M .

The second operator

$$\mathcal{O}_2 = \frac{m_{SUSY}}{M}(H_u H_d)^2 = \frac{m_{SUSY}}{M}\int d^2\theta\theta^2(H_u H_d)^2$$

- It corrects only the quartic terms of the potential by

$$\epsilon_2(H_u H_d)^2 + c.c.$$

$$\epsilon_2 \equiv \frac{m_{SUSY}}{M}$$

- Note, this operator is also of dimension four but effective dimension five.

Leading corrections to Higgs masses

$$\delta m_h^2 \approx 16 v^2 \cot\beta \ \mathrm{Re}\,\epsilon_1 + \mathcal{O}(\epsilon_{1,2} \cot^2\beta)$$

$$\delta m_H^2 = 4 v^2 \mathrm{Re}\,\epsilon_2 + \mathcal{O}(\epsilon_{1,2} \cot\beta)$$

$$\delta m_{H^\pm}^2 = 2 v^2 \mathrm{Re}\,\epsilon_2$$

$$\delta m_A^2 = 0$$

Recall, we express the masses in terms of m_A.

- For large $\tan\beta$
  - The leading order corrections are independent of ϵ_1, $\mathrm{Im}\epsilon_2$.
  - They over-determine one real number, $\mathrm{Re}\,\epsilon_2$.
  - The light Higgs mass is not corrected at leading order.
- The corrections to $m_{H^\pm}$ are independent of $\tan\beta$.

Corrections to the light Higgs mass

The order ϵ correction to m_h is suppressed for $\cot\beta \ll 1.$

Yet, we can have light stops $(\sim 300\ GeV)$ and small A-terms (hence no little hierarchy problem), and be consistent with the LEPII bound $m_h \gtrsim 114 GeV.$

This can be achieved in various ways, e.g.

- Use the order ϵ correction with $\tan\beta \sim 10,\ \epsilon_1 \gtrsim .06.$
- Continue to order $\epsilon^2,$ where there are several operators leading to $\delta m_h^2 = v^2\epsilon_3^2$ and use $\epsilon_3 \gtrsim .3.$

We conclude that the SUSY little hierarchy problem can be avoided with $M \sim 1 - 5\ TeV.$

What is the new physics?

It is easy to find microscopic models which lead to such new terms:

- Add an *SU(2)* singlet (or an *SU(2)* triplet) S with couplings

$$\int d^2\theta (MS^2 + SH_uH_d)$$

- Add *SU(2)* triplets $T^\pm$ with couplings

$$\int d^2\theta (MT^+T^- + T^+H_u^2 + T^-H_d^2)$$

- Add *U(1)'* gauge fields
- Have a strongly coupled Higgs sector

Consequences

- The SUSY little hierarchy problem can be avoided by allowing corrections to the MSSM. Equivalently, the little hierarchy problem should be interpreted as a pointer to new physics.
  - Various existing solutions to the little hierarchy problem fit an effective action framework.

- There could be measurable deviations from MSSM relations at the LHC. These could point to new higher energy physics.
  - A systematic organization of the corrections in terms of operators will over-determine their coefficients (or alternatively will bound them).

An optimistic scenario

- The LHC discovers SUSY.
- A light stop (~300 GeV) is discovered, and hence there is no little hierarchy problem.
- With such a light stop the radiative corrections cannot lift the light Higgs mass to the desired value (assuming no large A-terms).
- Similarly, the (radiatively corrected) mass relations of the heavy Higgses are not satisfied.

- Hence, there must be new physics in the TeV range. It can be parameterized by our operators.
- There is a rationale for building the next machine to explore this new physics.