Hint of High Scale Supersymmetry from Low Scale 2HDM

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1. Introduction

- LHC Higgs data are tantalizingly close to Standard Model predictions.
- Maybe we have to live with the hierarchy problem, lack of gauge unification, etc.
- BSM models mostly predict what to look for, leaving no clue on where — i.e. on the mass scales.

⇒ Any principle that gives ideas of probable mass scales deserves special attention.

2. A Specific Example

- The 2HDM is a simple extension of the SM scalar structure; it provides an additional source of CP violation; MSSM is also structured around a 2HDM.
- It may be viewed as an effective low-energy model arising from a more fundamental, UV-complete scenario with massive states at an inaccessibly high scale.
- In the 2HDM, h (125 GeV), H, A and $\mathrm{H}^{\pm}$ might be below a TeV — still possible! — and suppose all parameters of $\mathrm{V}_{\mathrm{eff}}$ are measured.
- By studying their RG evolution we can test whether the 2HDM has descended from a more fundamental theory, e.g. supersymmetry.

3. 2HDM Parameters

$$V_{eff} = m^2_{11}\, \Phi_1^\dagger\Phi_1 + m^2_{22}\, \Phi_2^\dagger\Phi_2 - (m^2_{12}\, \Phi_1^\dagger\Phi_2 + h.c.) + (\lambda_1/2) (\Phi_1^\dagger\Phi_1)^2 + (\lambda_2/2) (\Phi_2^\dagger\Phi_2)^2 + \lambda_3 (\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+ \lambda_4 (\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [(\lambda_5/2) (\Phi_1^\dagger\Phi_2)^2 + \{ \lambda_6 (\Phi_1^\dagger\Phi_1) + \lambda_7 (\Phi_2^\dagger\Phi_2) \} (\Phi_1^\dagger\Phi_2) + h.c.]$$

- Three mass parameters; seven quartic couplings.
- Symmetry limits of the potential:

  m_{12} , λ_5 , λ_6 , $\lambda_7 = 0$ $\Rightarrow$ U(1) global symmetry
  m_{12} , λ_6 , $\lambda_7 = 0$ $\Rightarrow$ U(1) broken, but Z_2 intact
  $\lambda_6 = \lambda_7 = 0$ $\Rightarrow$ Z_2 softly broken by m_{12}
- When Z_2 is preserved by the Yukawa couplings $\Rightarrow$ type II 2HDM.
- After EWSB, the parameters are:

  m_h (125 GeV), m_H, m_A, m_+, v (246 GeV), $\tan\beta = v_2/v_1$, and the alignment angle $\cos(\beta-\alpha)$.

4. Masses and Couplings

After SSB, λ_1, λ_2, λ_3 and λ_4 are determined in terms of the masses ($\lambda_{5,6,7} = 0$):

$$\lambda_1 = g_{11} + g_{22} \tan^2\beta - 2\, g_{12} \tan\beta$$
$$\lambda_2 = g_{11} + g_{22} \cot^2\beta + 2\, g_{12} \cot\beta$$
$$\lambda_3 = g_{11} - g_{22} + 2\, g_{12} \cot(2\beta) + 2\, g_+$$
$$\lambda_4 = -\, 2\, g_+$$

where

$$g_{11}\, v^2 = m_H^{\ 2} \cos^2(\beta-\alpha) + m_h^{\ 2} \sin^2(\beta-\alpha)$$
$$g_{12}\, v^2 = (\, m_h^{\ 2} - m_H^{\ 2}\,) \cos(\beta-\alpha) \sin(\beta-\alpha)$$
$$g_{22}\, v^2 = m_H^{\ 2} \sin^2(\beta-\alpha) + m_h^{\ 2} \cos^2(\beta-\alpha) - m^2_{\ A}$$
$$g_+\, v^2 = m^2_{\ +} - m^2_{\ A}$$

5. RG Analysis

Define $D \equiv \dfrac{d}{d\,(lnM)}$.

- $D\left(g^2+g_Y^2\right) = \dfrac{-3\,g^4+7\,g_Y^4}{8\,\pi^2} = 0.003 \quad \text{at } M_Z$

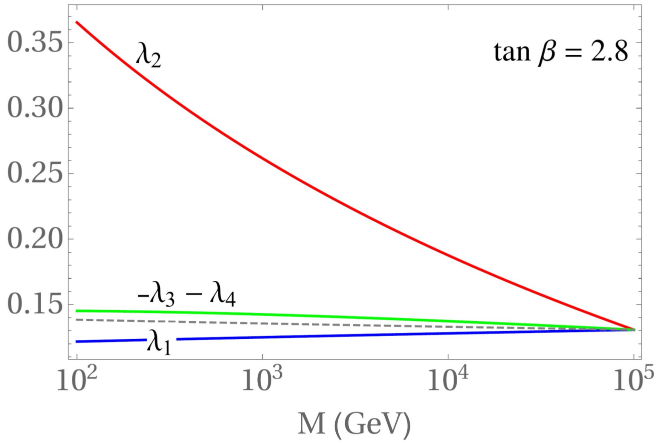
Thus ($g^2 + g_Y^{\,2}$) does not run much — it is essentially constant.

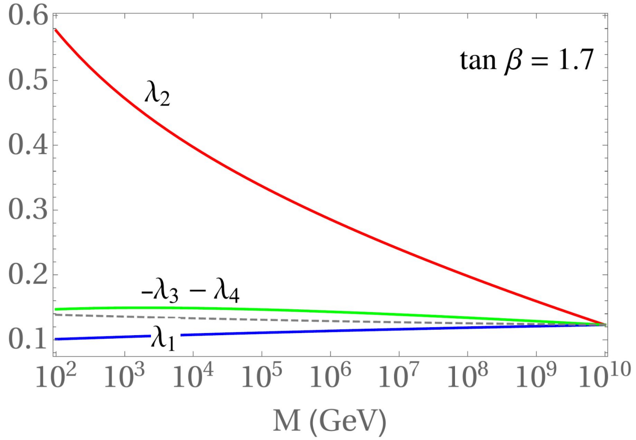
- The RGEs for the λ_i depend on the gauge and Yukawa couplings. (*One-loop formulae are shown below, but two-loop expressions are used in the analysis*)

$$\begin{aligned}
\mathcal{D}\,\lambda_1 &= f_1\,(\,g, g_Y, \lambda_1, \lambda_3, \lambda_4\,;\; y_b, y_\tau\,) \\
\mathcal{D}\,\lambda_2 &= 12\,\lambda_2\, y_t^{\,2} - \mathbf{12\, y_t^{\,4}} + f_2\,(\,g, g_Y, \lambda_2, \lambda_3, \lambda_4\,) \\
\mathcal{D}\,\lambda_3 &= 6\,\lambda_3\, y_t^{\,2} - 12\, y_t^{\,2}\, y_b^{\,2} + f_3\,(\,g, g_Y, \lambda_1, \lambda_2, \lambda_3, \lambda_4\,;\; y_b, y_\tau\,) \\
\mathcal{D}\,\lambda_4 &= 6\,\lambda_4\, y_t^{\,2} + 12\, y_t^{\,2}\, y_b^{\,2} + f_4\,(\,g, g_Y, \lambda_1, \lambda_2, \lambda_3, \lambda_4\,;\; y_b, y_\tau\,)
\end{aligned}$$

- λ_1 and $-(\lambda_3 + \lambda_4)$ do not run much, but λ_2 does.
- The evolution of λ_2 does not affect λ_1.

6. High Scale SUSY Indication

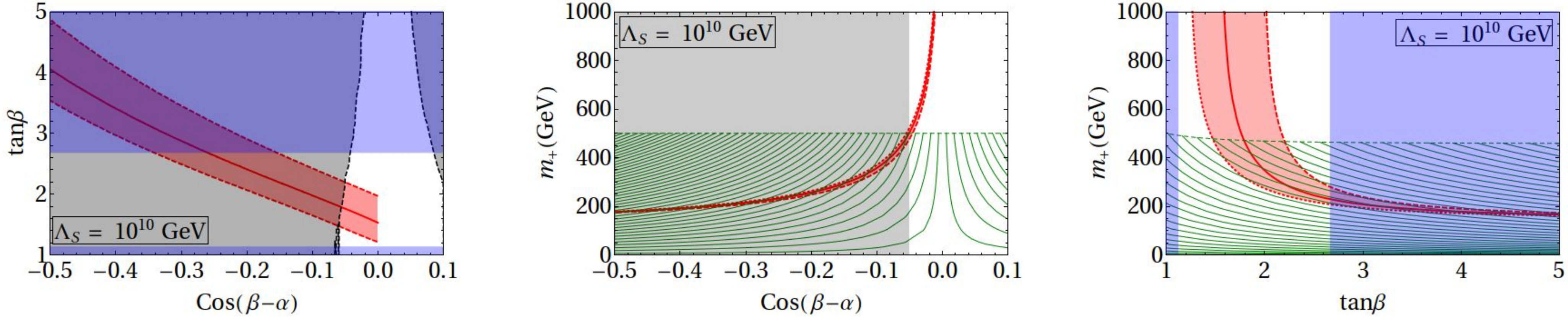




A measurement of the quartic couplings will favour high scale SUSY if:

- $\lambda_1 \sim -(\lambda_3 + \lambda_4)$ at the electroweak scale, close to ¼ ($g^2 + g_Y{}^2$) $\simeq$ 0.14.
- λ_2 should be much larger than 0.14 at the electroweak scale, due to the large negative y_t-induced correction.
- We then get a quantitative estimate of the SUSY scale Λ_S, the scale where λ_2 reaches its high scale boundary value ¼ ($g^2 + g_Y{}^2$).
- If λ_1 or $-(\lambda_3 + \lambda_4)$ is found to be very different from 0.14 or so, it will be impossible to satisfy the SUSY boundary conditions at the high scale.

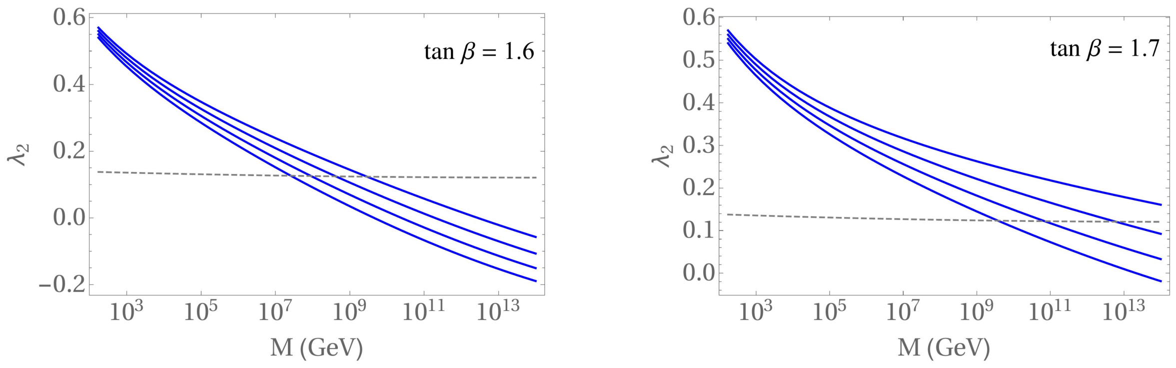
7. Constraints and Uncertainties



- Allowed space (red) consistent with $m_h = 125 \pm 0.6$ GeV and $m_t = 173 \pm 1$ GeV.
- Region where tanβ values are disfavoured from stability (blue).
- Hatched region disfavoured by $b \rightarrow s\gamma$.
- Grey region disfavoured by alignment constraints, $\cos(\beta-\alpha) \sim 0$.

  $\Rightarrow$ **ONLY low values of tanβ can reproduce m_h .**

8. Evolution of λ_2



For $\cos(\beta-\alpha) \sim 0$, i.e. in the alignment limit:

$$m_h^{\,2} = M_Z^{\,2} \left[(\tan^2\beta - 1) / (\tan^2\beta + 1) \right]^2 + \Delta\lambda_2 v^2 \left[\tan^2\beta/(1 + \tan^2\beta) \right]^2$$

$$\text{where} \quad \Delta\lambda_2 = \lambda_2(M_Z) - \lambda_2(\Lambda_S)$$

- For a fixed $\tan\beta$, the low energy value of λ_2 is uniquely determined by m_h.
- The larger the gap between Λ_S and M_Z, the more room λ_2 gets to grow under RG, and a smaller $\tan\beta$ is required to reproduce m_h.
- Λ_S is extremely sensitive to $\tan\beta$ — e.g. if $\tan\beta \simeq 2.2$, then $\Lambda_S \leq 10^{10}$ GeV. A precise determination of $\tan\beta$ may happen at a future linear collider.

9. Conclusions and Outlook

- The 2HDM is a specific example, but our methodology is quite general and can be applied to a wide variety of UV scenarios in which all quartic couplings are fixed at a high scale Λ_S.

- If, for example, all $\lambda_i = 0$ at Λ_S, then $m_h = 125$ GeV, $v = 246$ GeV, $\cos(\beta-\alpha) \sim 0$ and absolute stability up to Λ_S require $\tan\beta \sim 50$. This makes $m_+ \approx 180$ GeV, which is ruled out by $b \to s\gamma$.

- In the context of supersymmetry, λ_1 and $-(\lambda_3 + \lambda_4)$ should stay close to their boundary value ¼ ($g^2 + g_Y^{\ 2}$), while λ_2 can move significantly from Λ_S to M_Z.

- Λ_S can be estimated as the scale where λ_2 matches the boundary value ¼ ($g^2 + g_Y^{\ 2}$). This requires $\tan\beta$ to be determined with percent-level precision $\Rightarrow$ **a linear collider**!

Thank You