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Possibility of Another Well-mixed Light Higgs

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Next-to-MSSM

Why NMSSM?

Electroweak Symmetry Breaking

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2\tan^2\beta}{\tan^2\beta - 1} - |\mu|^2$$
$$m_{H_u}^2 = m_{H_u}^2|_{tree} - \frac{3}{8\pi^2}\left[|y_t|^2(2m_{\tilde{t}}^2 + |A_t|^2)\ln\frac{M_{mess}}{m_{\tilde{t}}}\right] + \dots$$

- To avoid a fine-tuning, we need
  - Small $m_{\tilde{t}}^2$
  - Small A_t.

$\Leftrightarrow$

Higgs Mass

$$m_h^2 = m_Z^2\cos^2 2\beta + \frac{3y_t^2}{4\pi^2}m_t^2\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2} - \frac{1}{12}\left(\frac{A_t^2}{m_{\tilde{t}}^2}\right)^2\right] + \dots$$

- To get 125 GeV, we need
  - Large $m_{\tilde{t}}^2$
  - Large A_t.

★ In the NMSSM, additional contributions to the Higgs mass can alleviate the tension between them;

- Tree level contribution: $\delta m_h^2 = \frac{2\lambda^2}{g^2+g'^2}m_Z^2\sin^2 2\beta$
- Singlet-doublet mixing w/ keeping the $h \to VV$ signal ratios close to the SM predictions.[1]

⇒ We consider a light singlet-like boson with a sizable fraction of the SM-like Higgs and examine the possibility of detection at collider experiments.

Model Description

A general singlet extension of the MSSM is written with arbitrary functions $f(S)$ and $\tilde{f}(S)$:

$$W = \lambda S H_u H_d + f(S) + (\mathrm{MSSM-Yukawa})$$
$$-\mathcal{L}_{soft} = A_\lambda \lambda S H_u H_d + \tilde{f}(S) + h.c. + (\mathrm{MSSM-soft\ masses,\ A-terms}).$$

Mass Matrix in the CP-even Higgs Sector

The mass matrix is described with 6 independent massive parameters and $\tan\beta = \langle H_u\rangle/\langle H_d\rangle$;

$$M^2 = \begin{pmatrix} m_0^2 - \Lambda_3\sin^2 2\beta & \Lambda_3\sin 2\beta\cos 2\beta & \lambda v[2\mu - \Lambda_1\sin 2\beta] \\ \Lambda_3\sin 2\beta\cos 2\beta & \Lambda_3\sin^2 2\beta + \frac{2\Lambda_2}{\sin 2\beta} & \lambda v\Lambda_1\cos 2\beta \\ \lambda v[2\mu - \Lambda_1\sin 2\beta] & \lambda v\Lambda_1\cos 2\beta & \Lambda_4 \end{pmatrix}$$

with basis (SM-like higgs "$\hat{h}$", another doublet higgs "$\hat{H}$", singlet "$\hat{s}$"), where $\Lambda_3 = M_z^2 - \lambda^2 v^2$ and other Λ's are independent functions dependent on $f^{(n)}(\mu/\lambda)$ and $\tilde{f}^n(\mu/\lambda)$. m_0^2 is defined by M_Z^2 plus quantum corrections to the mass parameter of $\hat{h}$ and $\mu = \lambda\langle s\rangle$.

Mixing Angles and Mass Eigenvalues

Since the mass matrix has enough free parameters, we can reparameterize it with mass eigenvalues ($m_h^2 = 125^2\mathrm{GeV}^2, m_H^2, m_s^2$) and mixing angles ($\theta_1, \theta_2, \theta_3$).

The 125GeV Higgs h becomes a mixture of $\hat{h}$, $\hat{H}$ and $\hat{s}$;

$$h = \cos\theta_1\cos\theta_2\hat{h} - \sin\theta_1\hat{H} - \cos\theta_1\sin\theta_2\hat{s}.$$

Thus its coupling to SM particles are determined by θ_1, θ_2 and $\tan\beta$.

Constraints

1. Since the original parameters, especially μ, λ and m_0^2, are not arbitrary, we already have several constraints on mass matrix:
   - perturbative bound
   $$0 < \lambda^2 = \frac{1}{v^2}\left[M_Z^2 - \frac{M_{12}^2}{\sin 2\beta\cos 2\beta}\right] \lesssim 0.7^2$$
   - chargino search
   $$100\mathrm{GeV} \lesssim |\mu| = \left|\frac{M_{13}^2 + M_{23}^2\tan 2\beta}{2\lambda v}\right|$$
   - assuming $A_t = 0$ and the stop mass is above 600GeV and below a few TeV
   $$(105\mathrm{GeV})^2 \lesssim m_0^2 = M_{11}^2 + M_{12}^2\tan 2\beta \lesssim (120\mathrm{GeV})^2$$
2. The Higgs signal ratios $R_h^{ij} \equiv \frac{\sigma_h\mathrm{Br}(h\to ij)}{\sigma_h^{\mathrm{SM}}\mathrm{Br}^{\mathrm{SM}}(h\to ij)}$
   - R_h^{VV} should be close to 1
   $$0.9 \lesssim R_h^{VV} \simeq 1 + (1.7\cot\beta + 1.4\tan\beta)\theta_1 - \theta_2^2 \lesssim 1.1$$
   - Similarly, we have R_h^{ff} and $R_h^{\gamma\gamma}$ but the constraints are not so severe.
   $$R_h^{bb} = R_h^{\tau\tau} \simeq (1 - 2\theta_1\tan\beta)R_h^{VV}$$
   $$R_h^{\gamma\gamma} \simeq (1 - 0.57\theta_1\cot\beta - 2.5\delta C_\gamma)R_h^{VV},$$
   where δC_γ is the radiative correction from the charged higgsino loop[2];
   $$\delta C_\gamma \simeq 0.17\frac{\lambda v}{|\mu|}\theta_2.$$
3. $b \to s\gamma$ constraint on the charged higgs mass
$$m_H \simeq m_{H^\pm} \gtrsim 350\mathrm{GeV}.$$
4. LEP bound on the sVV coupling for $m_s \lesssim 114$GeV, where s will decay dominantly into $b\bar{b}$.

Approximation

In order to keep R_h^{VV} close to 1, we have to cancel the modification from θ_2 with one from θ_1. Since the coefficient of $\sin\theta_1$ is larger than 3 and we are considering $\theta_2 > 0.3$, θ_1 should always be positive and of the order of θ_2^2 or less. Thus we approximate all the relations up to $\theta_1^m\theta_2^n\theta_3^k$ with $2m + n + k = 2$;

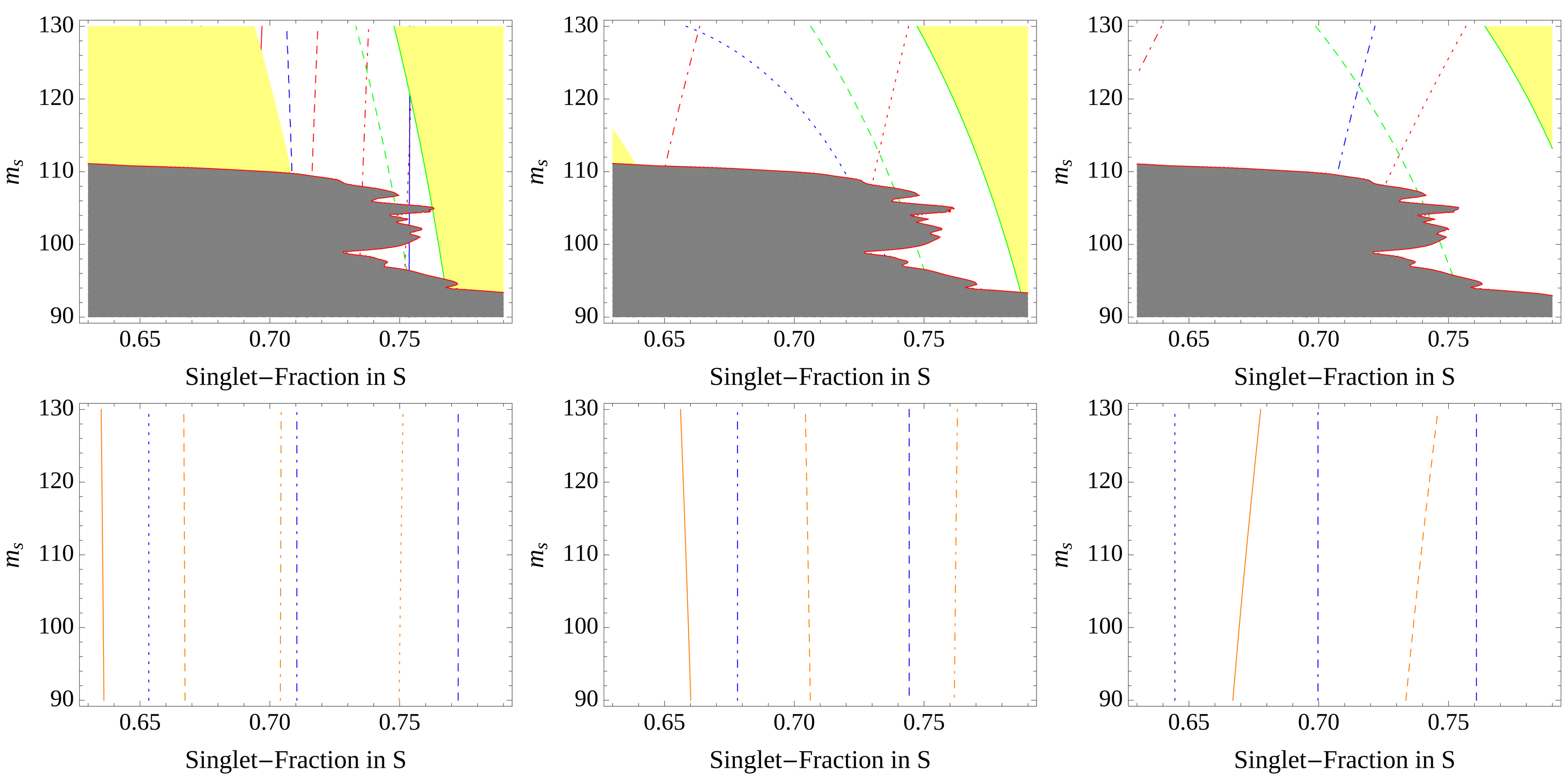
$$\lambda^2 \simeq \frac{1}{v^2}\left\{M_Z^2 - \frac{1}{2}(\tan\beta - \cot\beta)\left[(m_h^2 - m_0^2) - (m_h^2 - m_s^2)\theta_2^2\right]\right\}$$
$$\mu \simeq -\frac{m_H^2 - m_s^2\theta_3}{2v\cos^2 2\beta\,\lambda}\left(1 - \frac{1}{2}(\tan\beta - \cot\beta)\frac{m_h^2 - m_s^2\theta_2}{m_H^2 - m_s^2\theta_3}\right)$$
$$\theta_1 \simeq \frac{(R_h^{VV} - 1) + \theta_2^2}{1.67\cot\beta + 1.39\tan\beta}$$
$$\theta_3 \simeq \frac{\theta_1}{\theta_2}\frac{m_H^2 - m_h^2}{m_H^2 - m_s^2}\left(1 - \frac{1}{\theta_1}\frac{M_Z^2 - \lambda^2 v^2}{m_H^2 - m_h^2}\right).$$

We have several implications from the above relations.

- λ^2 is roughly determined by m_0 and $\tan\beta$.
- The larger m_H becomes, the more constrained is θ_3.
- If m_H is small, also μ becomes small.
- When m_H is small, we need a small $\tan\beta$ and a small λ.
- If R_h^{VV} is enhanced, μ gets slightly large.

Examples

Fixing $(m_H, \theta_3, \tan\beta, R_h^{VV})$, we can draw these constraints and signal ratios on singlet-fraction vs. m_s planes. The upper figures show values of μ, λ, and m_0 and the constraints. Meanwhile the bottom ones show corresponding R_h^{bb} and $R_h^{\gamma\gamma}$. The yellow regions are excluded by the constraint on m_0^2. The gray regions are excluded by the LEP search. In all figures, θ_2 is negative.



(1TeV, -0.1, 3, 1) (400GeV, -0.12, 2, 1) (400GeV, -0.17, 2, 1.1)

Summary

- A sizable singlet component in 125GeV higgs can be compatible with the current data within low energy SUSY.
- When the singlet-doublet mixing is sizable and R_h^{VV} is close to 1, R_h^{ff} is suppressed. Meanwhile if higgsinos are light, $R_h^{\gamma\gamma}$ is suppressed or enhanced depending on the sign of θ_2.
- Less fine-tuned mixing angles require small m_H and then μ is constrained to be small. Thus the LSP will have a sizable higgsino component.
- If one allows fine-tuned mixing angles, μ can be large.
- It is still possible to observe another Higgs boson at future collider experiments and if it is observed, the higgsinos and the other higgs bosons will be naturally light.

References

[1]K. Choi, S. H. Im, K. S. Jeong, M. Yamaguchi, 1211.0875/hep-ph.
[2]D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, 1207.1718/hep-ph.