Probing the CP-even Higgs Sector of Natural NMSSM at LHC

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NMSSM scalar potential

Z_3-invariant NMSSM superpotential:

$$W_{Higgs} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$$

The minimum of the scalar potential:

$$V_{Higgs} = (-\lambda v_u v_d + \kappa s^2)^2 + (\lambda s)^2 (v_u^2 + v_d^2) + \frac{g_1^2 + g_2^2}{8} (v_u^2 - v_d^2)^2 + m_S^2 s^2 + m_{H_u}^2 v_u^2 + m_{H_d}^2 v_d^2 - 2\lambda A_\lambda v_u v_d s + \frac{2}{3} \kappa A_\kappa s^3$$

The minimisation equations

$$v_u(m_{H_u}^2 + \mu_{eff}^2 + \lambda^2 v_d^2 + \frac{g_1^2 + g_2^2}{4}(v_u^2 - v_d^2)) - v_d \mu_{eff} B_{eff} = 0$$

$$v_d(m_{H_d}^2 + \mu_{eff}^2 + \lambda^2 v_u^2 + \frac{g_1^2 + g_2^2}{4}(v_d^2 - v_u^2)) - v_u \mu_{eff} B_{eff} = 0$$

$$s(m_S^2 + \kappa A_\kappa s + 2\kappa^2 s^2 + \lambda^2(v_u^2 + v_d^2) - 2\lambda\kappa v_u v_d) - \lambda v_u v_d A_\lambda = 0$$

where $\mu_{eff} = \lambda s$, $B_{eff} = A_\lambda + \kappa s$

Sources of fine-tuning

Solving the first two tadpole equations will gives the Z boson mass(at EW scale):

$$m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2}{cos(2\beta)} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

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- All above parameters are defined at electroweak scale.
- Fine-tunning is the sensitivity of m_Z to variations in the fundamental parameters.

  $F_i = |\frac{\partial ln\ m_Z}{\partial ln\ p_i}|$ [J. R. Eillis, *et. al*.(1986), R. Barbieri, *et. al*.(1988)]
- If we build our models at GUT scale, like mSUGRA, we can get electroweak scale parameters by running RGE.
- Every parameter in the equations can be expressed as a polynomial in initial parameters.

Small μ and Light Stop sector

Considering the gravity mediated NMSSM at GUT scale for example: Without take into account any threshold effects, if we choose $\lambda = 0.62$, $\kappa = 0.30$, $tan\beta = 2.5$ at $Q_{SUSY} = 1$ TeV as a benchmark point, then:

$$m_{H_u}^2 \simeq -.04\bar{A}_t^2 + .19\bar{A}_t M_{1/2} - 2.17 M_{1/2}^2 - .11\bar{m}_{H_d}^2 + .42\bar{m}_{H_u}^2 - .08\bar{m}_S^2 - .33\bar{m}_{\tilde{U}^c}^2 - .43\bar{m}_{\tilde{Q}}^2,$$
$$m_{H_d}^2 \simeq 0.02\bar{A}_t^2 - .02\bar{A}_t M_{1/2} + .50 M_3^2 + .73 m_{H_d}^2 - .14\bar{m}_{H_u}^2 - .13\bar{m}_S^2,$$

So, the Z boson mass can be expressed by fundamental paramerers:

$$\frac{m_Z^2}{2} \simeq 2.68 M_{1/2}^2 - .53\bar{m}_{H_u}^2 + .27\bar{m}_{H_d}^2 + .53\bar{m}_{\tilde{Q}}^2 + .40\bar{m}_{\tilde{U}^c}^2 - .06\bar{A}_t^2 - .22\bar{A}_t M_3 + .07\bar{m}_S^2 - |\mu|^2.$$

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Stop sector at SUSY scale:

$$A_t \simeq 0.19\bar{A}_t - 0.06\bar{A}_\lambda - 1.83M_{1/2},$$
$$m_{\widetilde{U}^c}^2 \simeq 0.61\bar{m}_{\widetilde{U}^c}^2 - 0.26\bar{m}_{\widetilde{Q}}^2 - 0.04\bar{A}_t^2 + 0.14\bar{A}_t M_{1/2} + 3.04M_{1/2}^2 - 0.20\bar{m}_{H_u}^2 + 0.03\bar{m}_S^2,$$
$$m_{\widetilde{Q}}^2 \simeq 0.84\bar{m}_{\widetilde{Q}}^2 - 0.13\bar{m}_{\widetilde{U}^c}^2 - 0.02\bar{A}_t^2 + 0.07\bar{A}_t M_{1/2} + 4.33M_{1/2}^2 - 0.13\bar{m}_{H_u}^2 + 0.02\bar{m}_S^2.$$

125 GeV SM-like Higgs

A 125 GeV Higgs boson is a little heavy for SUSY. There are three ways in NMSSM that can lift the SM-like Higgs boson mass:

- A small tanβ and large λ are needed to maximise the tree level Higgs mass. But $\lambda \lesssim 0.7$ to avoid Landau pole at GUT scale.
- The SM-like Higgs gets radiative correction from $\tilde{t}$:

$$\frac{3m_t^4(Q)}{4\pi^2 v^2}[log\frac{m_{\tilde{t}}^2}{m_t^2(Q)} + \frac{X_t^2}{m_{\tilde{t}}^2}(1 - \frac{X_t^2}{12m_{\tilde{t}}^2})]$$

  So heavy $\tilde{t}$ is needed. Conflict with naturalness!
- If the singlet is the lightest scalar, its mixing with doublet Higgs will lift the SM-like Higgs mass.

The Higgs basis(Goldstone basis) [D.J. Miller *et. al.*.(2003)]

It is convenient to work in (S_1, S_2, S_3) basis:

$$
\begin{aligned}
H_u^0 =& v_u + \frac{1}{\sqrt{2}}(S_1 \cos\beta + S_2 \sin\beta) + \frac{i}{\sqrt{2}}(P_1 \cos\beta + G^0 \sin\beta), \\
H_d^0 =& v_d + \frac{1}{\sqrt{2}}(-S_1 \sin\beta + S_2 \cos\beta) + \frac{i}{\sqrt{2}}(P_1 \sin\beta - G^0 \cos\beta), \\
S =& v_s + \frac{S_3 + iP_2}{\sqrt{2}},
\end{aligned}
$$

Higgs mass matrix

$$(M_S^2)_{11} = M_A^2 + (m_Z^2 - \lambda^2 v^2)\sin^2 2\beta,$$

$$(M_S^2)_{12} = -\frac{1}{2}(m_Z^2 - \lambda^2 v^2)\sin 4\beta,$$

$$(M_S^2)_{13} = -(M_A^2 \sin 2\beta + 2\lambda\kappa v_s^2)\cos 2\beta \frac{v}{v_s},$$

$$(M_S^2)_{22} = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta, \rightarrow \textit{SM like Higgs}$$

$$(M_S^2)_{23} = \frac{1}{2}(4\lambda^2 v_s^2 - M_A^2 \sin^2 2\beta - 2\lambda\kappa v_s^2 \sin 2\beta)\frac{v}{v_s},$$

$$(M_S^2)_{33} = \frac{1}{4} M_A^2 \sin^2 2\beta \left(\frac{v}{v_s}\right)^2 + 4\kappa^2 v_s^2 + \kappa A_\kappa v_s - \frac{1}{2}\lambda\kappa v^2 \sin 2\beta.$$

$\rightarrow$ *singlet component*

where $M_A^2 = \frac{\lambda v_s}{sin2\beta}(\sqrt{2}A_\lambda + \kappa v_s)$

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So, M^2_A is the largest scale in Higgs mass matrix. And mass of H_3 is approximated by:

$$m^2_{H_3} \simeq M^2_{11} + (M^2_{13})^2/M^2_{11} \simeq M^2_A \simeq (\frac{2\mu}{sin2\beta})^2 \sim (\mathcal{O}(400)\ \text{GeV})^2$$

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So, M_A^2 is the largest scale in Higgs mass matrix. And mass of H_3 is approximated by:

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- $C_{H_1H_2H_3} \sim -\frac{\lambda A_\lambda}{\sqrt{2}}$
- $C_{H_3gg} \propto$ cot$\beta \times S_1$ component of H_3

Scanning in NMSSM

We scan the parameters in the natural NMSSM framework:

- μ : $[100, 200]$ GeV, λ : $[0.6, 0.7]$, $\tan\beta$: $[1.3, 3.0]$
- Fix $m_{\tilde{Q}_3} = m_{\tilde{U}_3} = 500$ GeV and $A_t = -1000$ GeV
- H_2 is the SM-like Higgs in $[125, 127]$ GeV
- H_1 is safe under the LEP searches.

Scanning result:

At 14 TeV LHC $gg \to H_3 \to H_2 H_1 \to W(\to l\nu)W(\to jj)b\bar{b}$:

$$\sigma_{H_3} = 0.025 \frac{\sigma_{\rm GF}(h_{\rm SM})}{10\,{\rm pb}} \left(\frac{C_{3,g}}{0.4}\right)^2 \frac{{\rm Br}(H_3 \to H_1 H_2)}{20\%} \frac{{\rm Br}(H_1 \to b\bar{b})}{90\%} \frac{{\rm Br}(H_2 \to W_\ell W_h)}{28\% \times 30\%} {\rm pb}$$

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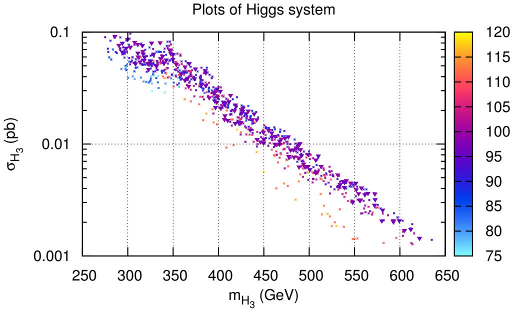

The large triangle points satisfy the LEP hint: $C^2_{1,V} \frac{Br(H_1 \to b\bar{b})}{Br_{SM}(H_1 \to b\bar{b})} \sim 0.1 - 0.25$, $m_{H_1} \sim 95 - 100$ GeV

The benchmark scenario

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- Typical cross section ~ 25 fb
- The $p_T(H_1) \sim \mathcal{O}(100\ \text{GeV})$, which is moderately boosted. The Higgs jet substructure can be a good probe.
- Two main backgrounds:
  1. $t\bar{t}$ pair production with semi-leptonic decay($\sigma \sim \mathcal{O}(240)$ pb)
  2. $W(\rightarrow l\nu)b\bar{b}$+*jets* ($\sigma \sim \mathcal{O}(40)$ pb)

The event trigger

We will follow the BDRS procedure J. M. Butterworth *et. al.*(2008) of Higgs jet tagging with the basic cuts chosen as the following:

- At least two $R = 1.4$ C/A jets with $p_T > 40$ GeV in each event, which satisfy two conditions: a significant mass drop $m_{j_1} < 2/3 m_j$ and not too asymmetric splitting of the two subjets $y = \frac{min(p_{tj1}^2, p_{tj2}^2)}{m_j^2} \Delta R_{j1,j2}^2 > 0.09$
- Exactly one isolated lepton with $p_T > 10$ GeV is required.

The Cuts:

- Cut1: $p_{T,b\bar{b}} > 150\,\mathrm{GeV}, \quad p_{T,jj\ell\,\nu} > 120\,\mathrm{GeV}, \quad |p_{T,b\bar{b}} - p_{T,jj\ell\,\nu}| < 20\,\mathrm{GeV}$
- Cut2: $95\,\mathrm{GeV} < m_{b\bar{b}} < 100\,\mathrm{GeV}, \quad m_{jj,\ell\,\nu} < 150\,\mathrm{GeV}, \quad m_{b\bar{b},jj,\ell\,\nu} < 440\,\mathrm{GeV}$
- Cut3: $|\Delta\phi_{\ell j}| < 1.5$
- Cut4: $\Delta R_{H_1,b\bar{b}} < 0.01$
- Cut5: $M_C = \sqrt{p^2_{T,jj\ell} + m^2_{jj\ell}} + E_T^{miss} < 220\,\mathrm{GeV}$

The Cuts flow:

	$t\bar{t}+jets$	$W(\to l\nu jj)b\bar{b}+jets$	Signal
Events	1.2×10^8	1.91×10^7	1.25×10^4
Trigged	4.95×10^6	1.45×10^6	1456.75
Cut1	3.77×10^5	1.61×10^5	639.5
Cut2	1932	203	119.75
Cut3	1512	155.2	105.5
Cut4	108	47.75	56.25
Cut5	84	47.75	55

Table : Number of events after each cut for background and signal, which have been normalised to 500 fb^{-1}. The signal significance reaches 4.02.

Different masses:

	m_{H_1}(GeV)	m_{H_3}(GeV)	σ (fb)	$\frac{S}{\sqrt{S+B}}$
B1	98	400	25	4.73
B2	65	400	20	7.68
B3	100	300	70	0.81
B4	65	300	50	3.84
B5	100	600	2	2.79
B6	65	600	2	4.99

Table : Number of events after each cut for different benchmark points, which have been normalized to 500 fb^{-1}

- For a given m_{H_3}, a lighter H_1 shows a better discovery potential
- A relatively heavy H_3 is required to boost the H_1. However, heavy H_3 suffers from small cross section.
- Most of the parameter space are discoverable except for simultaneously light H_3 and heavy H_1.

Conclusion

- Naturalness of NMSSM predict a light CP-even Higgs sector.
- The light CP-even Higgs sector is discoverable at 14TeV LHC.