Hefty MSSM-like light Higgs in extended gauge models

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in collaboration with

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  - Tree-level mass lighter than M_Z
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  - D-term mixing: models with extended gauge sector

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motivated by

$$SO(10) \to SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Particles and Superpotential

	Superfield	$SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$	Generations
Matter	$\hat{Q}$	$(\mathbf{3}, \mathbf{2}, 0, +\frac{1}{6})$	3
	$\hat{d^c}$	$(\overline{\mathbf{3}}, \mathbf{1}, +\frac{1}{2}, -\frac{1}{6})$	3
	$\hat{u^c}$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{1}{2}, -\frac{1}{6})$	3
	$\hat{L}$	$(\mathbf{1}, \mathbf{2}, 0, -\frac{1}{2})$	3
	$\hat{e^c}$	$(\mathbf{1}, \mathbf{1}, +\frac{1}{2}, +\frac{1}{2})$	3
	$\hat{\nu^c}$	$(\mathbf{1}, \mathbf{1}, -\frac{1}{2}, +\frac{1}{2})$	3
	$\hat{S}$	$(\mathbf{1}, \mathbf{1}, 0, 0)$	3
Higgs	$\hat{H}_u$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2}, 0)$	1
	$\hat{H}_d$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 0)$	1
	$\hat{\chi}_R$	$(\mathbf{1}, \mathbf{1}, +\frac{1}{2}, -\frac{1}{2})$	1
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Superpotential

$$W = Y_u \hat{u^c} \hat{Q} \hat{H}_u - Y_d \hat{d^c} \hat{Q} \hat{H}_d + Y_\nu \hat{\nu^c} \hat{L} \hat{H}_u - Y_e \hat{e^c} \hat{L} \hat{H}_d + \mu \hat{H}_u \hat{H}_d$$
$$- \mu_R \hat{\bar{\chi}}_R \hat{\chi}_R + Y_s \hat{\nu^c} \hat{\chi}_R \hat{S}$$

Features of the model

- Inverse seesaw can be included to explain neutrino data
- The $U(1)_{B-L} \times U(1)_R$ breaking can be at the TeV scale without spoiling gauge unification

  $\rightarrow$ One-step breaking $SU(2)_L \times U(1)_{B-L} \times U(1)_R \rightarrow U(1)_{em}$

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Parametrization of the Higgs sector

$$\chi_R = \frac{1}{\sqrt{2}}\left(\sigma_R + i\varphi_R + v_{\chi_R}\right) \;,\; \bar{\chi}_R = \frac{1}{\sqrt{2}}\left(\bar{\sigma}_R + i\bar{\varphi}_R + v_{\bar{\chi}_R}\right) \;,$$

$$H_d^0 = \frac{1}{\sqrt{2}}\left(\sigma_d + i\varphi_d + v_d\right) \;, \quad H_u^0 = \frac{1}{\sqrt{2}}\left(\sigma_u + i\varphi_u + v_u\right) \;.$$

with $\tan\beta = v_u/v_d$ and $\tan\beta_R = v_{\chi_R}/v_{\bar{\chi}_R}$.

Pseudo scalar Higgs masses

The left and right pseudo scalars decouple at tree-level:

Basis : $(\varphi_d, \varphi_u, \varphi_R, \bar{\varphi}_R)^T \rightarrow \qquad M^2_{AA} = \begin{pmatrix} M^2_{AA,L} & 0 \\ 0 & M^2_{AA,R} \end{pmatrix}$

with

$$M^2_{AA,L} = B_\mu \begin{pmatrix} \tan\beta & 1 \\ 1 & \cot\beta \end{pmatrix} \;,\; M^2_{AA,R} = B_{\mu_R} \begin{pmatrix} \tan\beta_R & 1 \\ 1 & \cot\beta_R \end{pmatrix}$$

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Masses of CP odd Higgs similar to the MSSM

$$m^2_A = B_\mu(\tan\beta + 1/\tan\beta), \qquad m^2_{A_R} = B_{\mu_R}(\tan\beta_R + 1/\tan\beta_R)$$

Scalar Higgs masses

D-Term mixing between left and right CP even Higgs

$$\text{Basis}: (\sigma_d, \sigma_u, \sigma_R, \bar{\sigma}_R)^T \rightarrow \qquad M_{hh}^2 = \begin{pmatrix} m_{LL}^2 & m_{LR}^2 \\ m_{LR}^{2,T} & m_{RR}^2 \end{pmatrix}$$

with

$$m_{LR}^2 = \begin{pmatrix} g_R^2 v v_R c_\beta c_{\beta_R} & -g_R^2 v v_R c_\beta s_{\beta_R} \\ -g_R^2 v v_R s_\beta c_{\beta_R} & g_R^2 v v_R s_\beta s_{\beta_R} \end{pmatrix}$$

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D-Term mixing

To obtain the mass of the light Higgs fields, the entire 4×4 matrix has to be diagonalized

$\rightarrow$ Tree-level mass of MSSM-like Higgs depends on new parameters like v_R and β_R

Gauge couplings and neutral gauge bosons

Gauge couplings

Assuming a GUT unification, the gauge couplings at the SUSY scale are given by

$$g_{BL} = 0.46 \text{ and } g_R = 0.48$$

We define in addition $g_Z^2 = (g_L^2 + g_R^2)/4$ and $g_{Z_R}^2 = (g_{BL}^2 + g_R^2)/4$

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Z' searches

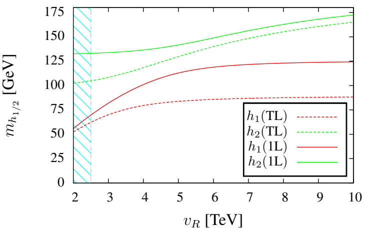
Stringent bounds on $g_{Z_R}^2 v_R^2\,[= m_{Z'}^2 + O(v^2/v_R^2)]$

$\rightarrow v_R > 2.5$ TeV necessary

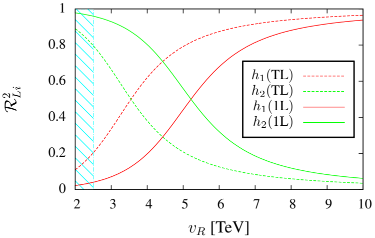
Numerical setup: used computer codes

- Model has been implemented in SARAH [FS,0806.0538,0909.2863,1002.0840]
  - Calculation of all mass matrices and vertices
  - Derivation of all formulas for a complete one-loop calculation
- SARAH creates Fortran code for SPheno to calculate the entire mass spectrum [Porod,hep-ph/0301101],[Porod,FS,1104.1573]
- HiggsBounds has been used to check existing bounds coming from Higgs searches [Bechtle et al.,1102.1898]
- SPheno checks also leptonic constraints like $\mu \to e\gamma$

Dependence on v_R



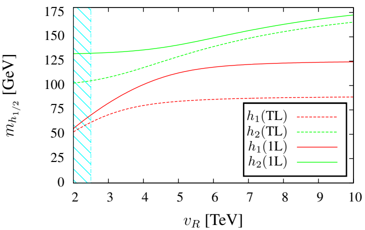
tree level and 1-loop masses of the two lightest scalars



$SU(2)_L$ doublet fraction
$R^2_{i1} + R^2_{i2}$

Shaded blue area excluded by Z' searches
Mass spectrum based on parameters: $M_{1/2} = 600$ GeV, $m_0 = 120$ GeV, $A_0 = 0$, $\tan\beta = 10$.
Top/Stop sector: $m_{\tilde{Q}_3} = m_{\tilde{U}_3} = 2$ TeV, $T_{u33} = 3$ TeV, $m_t = 172.9$ GeV.
Higgs Sector: $v_R = 5$ TeV, $\mu = 800$ GeV,$m_A = 800$ GeV, $\mu_\chi = -500$ GeV, $m_{A_R} = 2$ TeV,$\tan\beta_R = 1.1$

Dependence on v_R



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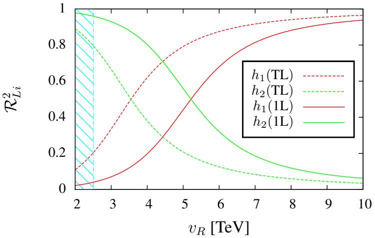

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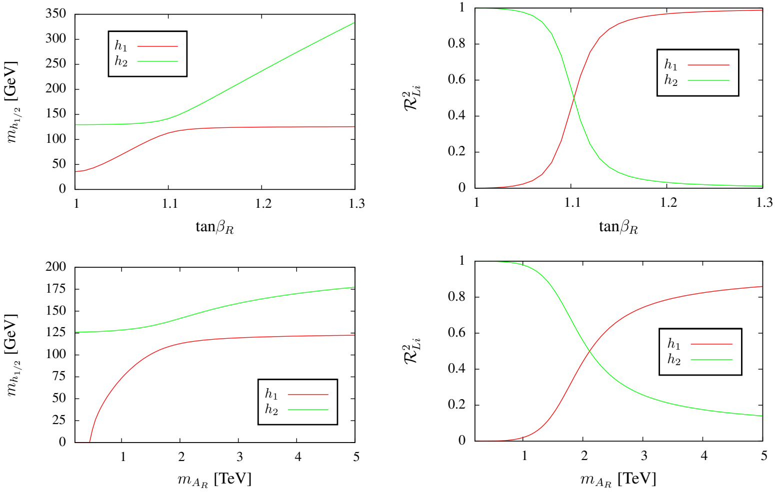
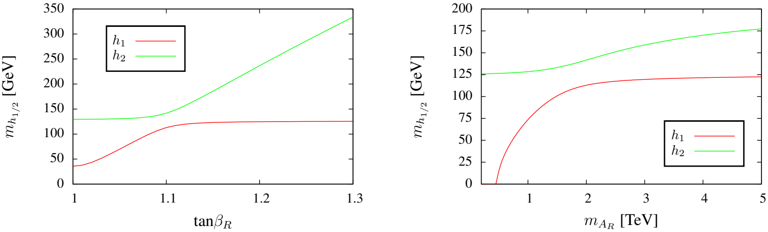
Increased MSSM Higgs mass

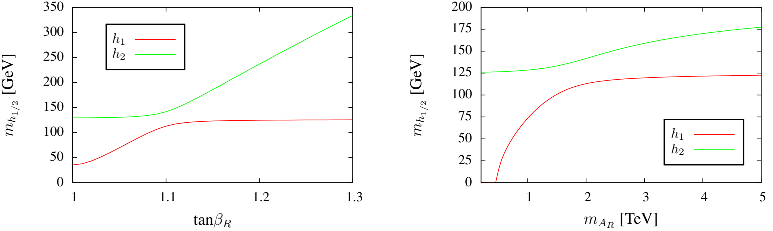
Near and below the level crossing the mass of the MSSM-like Higgs is significantly increased


350
300
250
200
150
100
50
0
1
1.1
1.2
1.3
$\tan\beta_R$
$m_{h_{1/2}}$ [GeV]
h_1
h_2
1
0.8
0.6
0.4
0.2
0
$\mathcal{R}^2_{Li}$
200
175
150
125
100
75
50
25
0
1
2
3
4
5
m_{A_R} [TeV]



- Only small ranges for $\tan\beta_R$ possible (D-flatness) because of contributions to sfermion masses due to D-terms:

$$D \simeq \pm g_{BL}^2(v_{\chi_R}^2 - v_{\bar{\chi}_R}^2) + g_R^2(v_u^2 - v_d^2)$$



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- Higgs masses of 140 GeV possible for MSSM-like states
- Very light, right-handed Higgs pass all constraints
  $\rightarrow$ Decay of MSSM-like Higgs into two light scalars possible

Large loop corrections

In inverse seesaw large loop-corrections to Higgs masses are possible due to large neutrino Yukawa couplings Y_ν [Elsayed,1106.2130]

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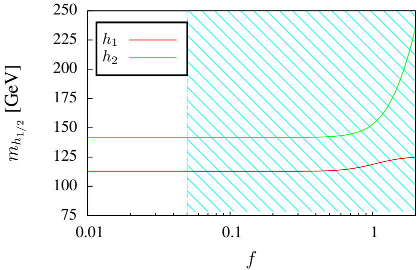

$$Y_\nu = f \begin{pmatrix} 0 & 0 & 0 \\ a & a & -a \\ 0 & 1 & 1 \end{pmatrix}$$

Shaded area: BR$(\mu \to e\gamma) > 2.4 \cdot 10^{-12}$

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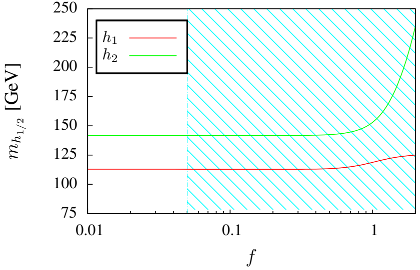

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Shaded area: BR$(\mu \to e\gamma) > 2.4 \cdot 10^{-12}$

$\rightarrow$ In general excluded because of large contributions to $\mu \to e\gamma$

Might be possible to circumvent with some fine-tuning of the parameters.

Summary

- We have discussed a SUSY model based on a $U(1)_R \times U(1)_{B-L}$ gauge sector
- Additional Higgs fields are needed to break this gauge sector
- D-Term mixing between the MSSM-like Higgs fields and the new states
- The mass of the lightest MSSM-like Higgs can be significantly larger than in the pure MSSM (up to 140 GeV)
- Decays into two light scalars possible

$$m^2_{LL} = \begin{pmatrix} g_Z^2 v^2 c_\beta^2 + m_A^2 s_\beta^2 & -\frac{1}{2}\left(m_A^2 + g_Z^2 v^2\right) s_{2\beta} \\ -\frac{1}{2}\left(m_A^2 + g_Z^2 v^2\right) s_{2\beta} & g_Z^2 v^2 s_\beta^2 + m_A^2 c_\beta^2 \end{pmatrix},$$

$$m^2_{LR} = \begin{pmatrix} g_R^2 v v_R c_\beta c_{\beta_R} & -g_R^2 v v_R c_\beta s_{\beta_R} \\ -g_R^2 v v_R s_\beta c_{\beta_R} & g_R^2 v v_R s_\beta s_{\beta_R} \end{pmatrix},$$

$$m^2_{RR} = \begin{pmatrix} g_{Z_R}^2 v_R^2 c_{\beta_R}^2 + m_{A_R}^2 s_{\beta_R}^2 & -\frac{1}{2}\left(m_{A_R}^2 + g_{Z_R}^2 v_R^2\right) s_{2\beta_R} \\ -\frac{1}{2}\left(m_{A_R}^2 + g_{Z_R}^2 v_R^2\right) s_{2\beta_R} & g_{Z_R}^2 v_R^2 s_{\beta_R}^2 + m_{A_R}^2 c_{\beta_R}^2 \end{pmatrix},$$

$$M^2_{VV} = \frac{1}{4}\begin{pmatrix} g_L^2 v^2 & 0 & -g_L g_R v^2 \\ 0 & g_{BL}^2 v_R^2 & -g_{BL} g_R v_R^2 \\ -g_L g_R v^2 & -g_{BL} g_R v_R^2 & g_R^2\left(v^2 + v_R^2\right) \end{pmatrix},$$

$$\begin{aligned} m_\gamma &= 0 \\ m_Z^2 &= \tfrac{1}{8}\left(A - \sqrt{A^2 - 4B}\right) \\ m_{Z'}^2 &= \tfrac{1}{8}\left(A + \sqrt{A^2 - 4B}\right) \end{aligned}$$

$$A = \left(g_L^2 + g_R^2\right) v^2 + \left(g_{BL}^2 + g_R^2\right) v_R^2, B = \left[g_L^2\left(g_R^2 + g_{BL}^2\right) + g_{BL}^2 g_R^2\right] v^2 v_R^2$$