$SO(10)$ INSPIRED GMSB

MEK, W. Porod, F. Staub, **Phys.Rev. D88 (2013) 015014**

– SUSY, TRIESTE 2013 –

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August $27th$, 2013

DFG Deutsche Forschungsgemeinschaft

GRK 1147

How does SUSY breaking work?

- introduce terms in the Lagrangian which explicitly break SUSY
- often considered scenario: CMSSM-like boundaries at M_{GUT}
  easy to handle, based on strong assumptions
- appealing alternative:
  Gauge **M**ediated **S**upersymmetry **B**reaking:
  SUSY masses dynamically generated by gauge interactions

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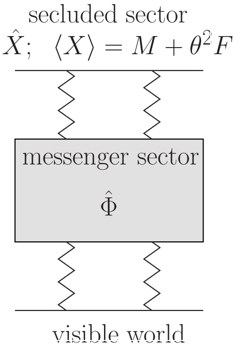

$$\mathcal{W} = \lambda_i \hat{X} \hat{\Phi}_i \hat{\bar{\Phi}}_i$$

- fermion masses: $\lambda_i M$
- boson masses: $\sqrt{|\lambda_i M|^2 \pm |\lambda_i F|}$

$\Rightarrow$ SUSY breaking!

[see, *e.g.*, Giudice, Rattazzi, '99; Martin, '97]

Problem:

Higgs mass in the MSSM:

$$m_{h^0}^2 = \underbrace{M_Z^2 \cos^2 2\beta}_{\text{tree-level mass}} + \frac{3 m_t^2 Y_t^2}{4\pi^2} \left(\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \underbrace{\delta_t}_{\supset A_u} \right) + \ \ldots$$

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⇒ *either:* large stop masses *or:* large trilinear couplings

but: minimal GMSB predicts very small trilinear terms

⇒ Stop mass has to be very large, $m_{\tilde{t}_1} \gtrsim 5$ TeV

[Ajaib, Gogoladze, Nasir, Shafi, '12]

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[Ajaib, Gogoladze, Nasir, Shafi, '12]

ideas:

- enlarge trilinear terms by introducing direct messenger-matter interactions

  [several studies in the literature/see previous plenary and parallel talks]

- enlarge tree-level mass by considering a larger gauge group

The Model

GMSB version of [Hirsch, Porod, Reichert, Staub, '12]

- consider a gauge group inspired by a $SO(10)$ GUT group:

$$SO(10) \xrightarrow{M_{GUT}} SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$
$$\longrightarrow SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$$
$$\xrightarrow{M_R \sim \text{TeV}} SU(3)_c \times SU(2)_L \times U(1)_Y$$

- $U(1)_R \times U(1)_{B-L}$ can be rotated into another basis: $U(1)_Y \times U(1)_\chi$

additional fields:

- two additional Higgs fields $\hat{\chi}_R$, $\hat{\bar{\chi}}_R$ to break $U(1)_Y \times U(1)_\chi \to U(1)_Y$
- singlet fields $\hat{S}$ generate neutrino masses via inverse Seesaw

$$\mathcal{W}_{h,\text{add}} = -\mu_R \hat{\bar{\chi}}_R \hat{\chi}_R$$
$$\mathcal{W}_\nu = Y_\nu \hat{\nu}^c \hat{L} \hat{H}_u + Y_S \hat{\nu}^c \hat{S} \hat{\chi}_R + \mu_S \hat{S} \hat{S}$$

MESSENGER FIELDS

introduce n copies of messenger **10**-plets

	$SU(3)_c \times SU(2)_L$	$U(1)_R \times U(1)_{B-L}$	$U(1)_Y \times U(1)_\chi$
$\hat{\Phi}_1$	$(\mathbf{1}, \mathbf{2})$	$(\frac{1}{2}, 0)$	$(\frac{1}{2}, -\frac{1}{2})$
$\hat{\bar{\Phi}}_1$	$(\mathbf{1}, \mathbf{2})$	$(-\frac{1}{2}, 0)$	$(-\frac{1}{2}, \frac{1}{2})$
$\hat{\Phi}_2$	$(\mathbf{3}, \mathbf{1})$	$(0, -\frac{1}{3})$	$(-\frac{1}{3}, -\frac{1}{2})$
$\hat{\bar{\Phi}}_2$	$(\bar{\mathbf{3}}, \mathbf{1})$	$(0, \frac{1}{3})$	$(\frac{1}{3}, \frac{1}{2})$

- soft masses calculated at M including gauge kinetic mixing
- numerical implementation in `SARAH`, `SPheno` (code publicly available)
- require gauge coupling unification
- free model parameters: n, F, M, $\tan\beta_{(R)}$, v_R, sign $\mu_{(R)}$, Y_S, Y_i, μ_S

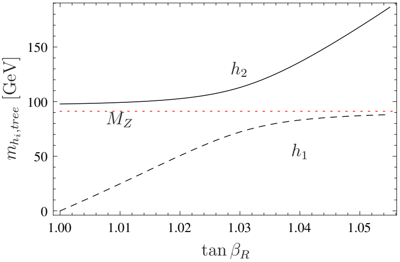
recall: tree level mass in the MSSM:

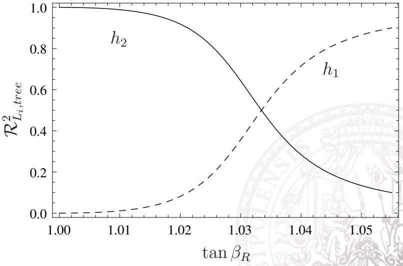
$$m^2_{h,\text{tree}}\Big|_{\text{MSSM}} \leq M_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2$$

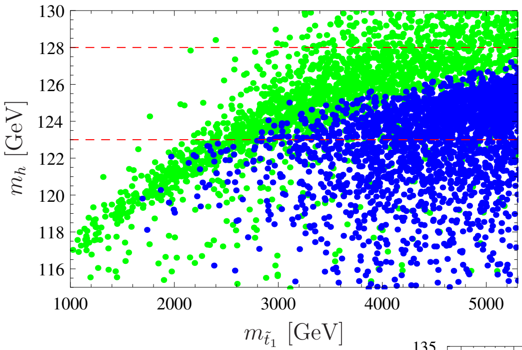
now, with additional $U(1)_\chi$ sector:

$$m^2_{h,\text{tree}} \leq M_Z^2 + \frac{1}{4} g_\chi^2 v^2$$

but: dependent on ratio of the two new *vevs*, $\tan\beta_R = v_{\chi_R}/v_{\bar{\chi}_R}$

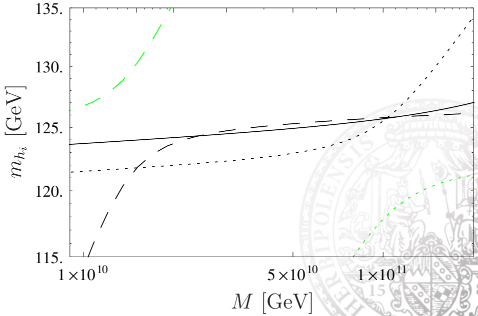






⇒ Stop masses of 2–3 TeV are able to generate large enough Higgs masses (MSSM: $m_{\tilde{t}_1} \gtrsim 5$ TeV)

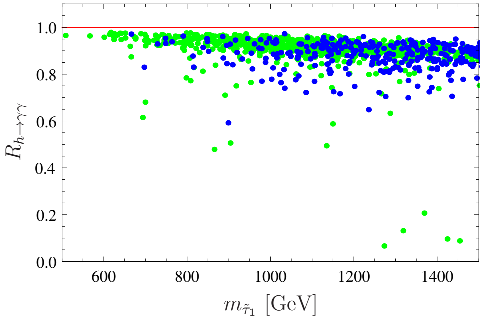
dependent on messenger scale M (with constant F/M):



$h \to \gamma\gamma$

$\exists$ hints to enhanced $BR(h \to \gamma\gamma)$ at the LHC [ATLAS, '12; CMS, '12]

What does this model predict?



$$R_{h\to\gamma\gamma} = \frac{\sigma(pp \to h) \times BR(h \to \gamma\gamma)}{\sigma(pp \to h) \times BR(h \to \gamma\gamma)|_{SM}}$$

$\Rightarrow \quad R_{h\to\gamma\gamma} \leq 1$

complies with recent data from CMS [CMS, '13]

LSP AND NLSP

Gravitino $\tilde{G}$ is the LSP:

$$m_{3/2} = \frac{F}{\sqrt{3} m_{Pl}} \sim \mathcal{O}(\text{MeV})$$

$\exists$ three possibilities for NLSP:

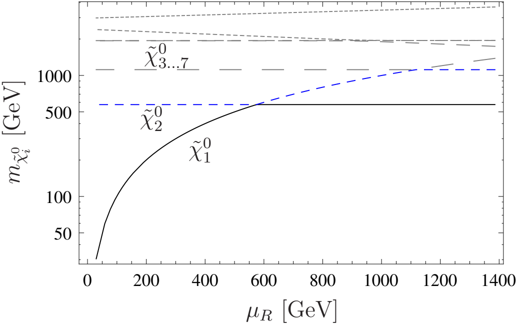
- lightest neutralino $\tilde{\chi}_1^0$ ($\tilde{B}$ or $\tilde{\chi}_R$):
  ($n \leq 2$ and Y_S nonhierarchical, or small μ_R)
- lightest slepton $\tilde{\tau}$:
  ($n > 2$, Y_S nonhierarchical and large $\tan\beta$)
- lightest sneutrino $\tilde{\nu}$ ($\tilde{S}$):
  (Y_S hierarchical)

$\Rightarrow$ new with respect to usual GMSB considerations:
$\tilde{S}$- and $\tilde{\chi}_R$-like NLSP

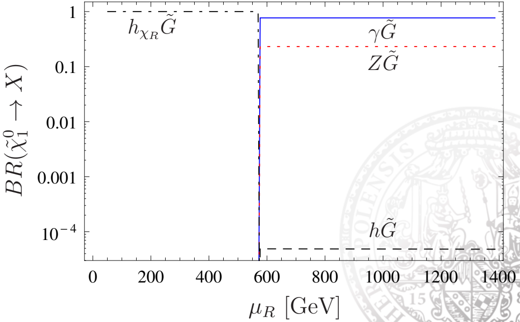
PHENOMENOLOGY OF THE NLSP AND THE Z'

$\tilde{\chi}_1^0$ NLSP:

- $\mu_R > M_1$: bino NLSP
- $\mu_R < M_1$: new higgsino NLSP

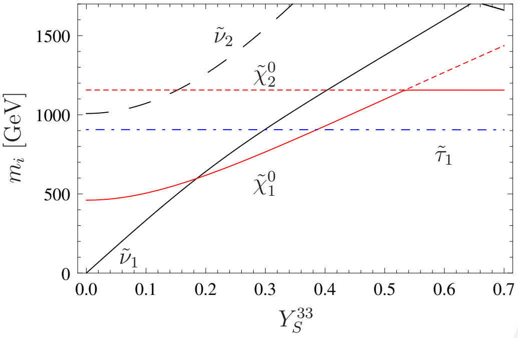


possibly interesting: new Higgs h_{χ_R} in SUSY cascade decays



$\tilde{\nu}$ ($\tilde{S}$) NLSP

- fermionic (bosonic) singlet fields S ($\tilde{S}$) mix with (s)neutrinos
- $m^2_{\tilde{S}\tilde{S}} \approx v_R^2 \sin^2 \beta_R Y_S^\dagger Y_S/2$
- hierarchical diagonal Y_S entries can give a light $\tilde{S}$-like NLSP:



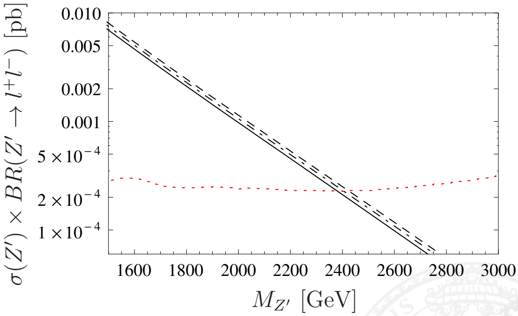
possibly interesting:
heavy neutrino ν_h in SUSY cascade decays: $\tilde{\chi}_1^0 \to \tilde{\nu}_1 \nu_h \to \nu \tilde{G} W^{(*)} l$

Z' PHENOMENOLOGY

bounds on Z' mass
using ATLAS '13 data:

$M_{Z'} \gtrsim 2.4$ TeV

$v_R \gtrsim 6.6$ TeV



possibly interesting Z' decays: $Z' \to \nu_h \nu_h, \ Z' \to \tilde{\nu}\tilde{\nu}$

Conclusions

- Higgs mass is a major problem for minimal GMSB models
- extended gauge structure allows for enhanced tree-level Higgs mass
- in a $SO(10)$-inspired model: minimal GMSB is not dead yet!

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Thank you for your attention!

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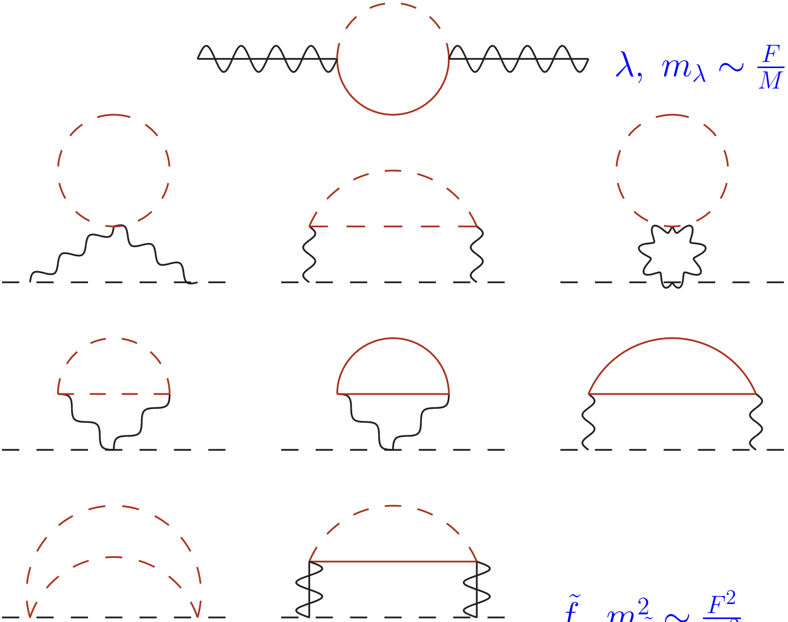
interested?

MEK, Porod, Staub, Phys.Rev. **D88**, 015014, arXiv:1304.0769

BACKUP



$\lambda, \; m_\lambda \sim \frac{F}{M}$

$\tilde{f}, \; m^2_{\tilde{f}} \sim \frac{F^2}{M^2}$

The superpotential reads

$$\mathcal{W} = Y_u^{ij}\,\hat{u}_i^c\,\hat{Q}_j\,\hat{H}_u - Y_d^{ij}\,\hat{d}_i^c\,\hat{Q}_j\,\hat{H}_d - Y_e^{ij}\,\hat{e}_i^c\,\hat{L}_j\,\hat{H}_d + \mu\,\hat{H}_u\hat{H}_d$$
$$+ Y_\nu^{ij}\,\hat{\nu}_i^c\,\hat{L}_j\,\hat{H}_u + Y_S^{ij}\,\hat{\nu}_i^c\,\hat{S}_j\,\hat{\chi}_R - \mu_R\hat{\bar{\chi}}_R\hat{\chi}_R + \mu_S^{ij}\,\hat{S}_i\,\hat{S}_j$$

The soft SUSY breaking terms are

$$\mathcal{V}_{soft} = m_{ij}^2\phi_i^*\phi_j + \Big(\frac{1}{2}M_{ab}\lambda_a\lambda_b + B_\mu H_u H_d + B_{\mu_R}\bar{\chi}_R\chi_R$$
$$+ B_{\mu_S}\tilde{S}\tilde{S} + T_d^{ij}\,H_d\,\tilde{d}_i^c\,\tilde{Q}_j + T_u^{ij}\,H_u\,\tilde{u}_i^c\,\tilde{Q}_j$$
$$+ T_e^{ij}\,H_d\,\tilde{e}_i^c\,\tilde{L}_j + T_\nu^{ij}\,H_u\tilde{\nu}_i^c\,\tilde{L}_j + T_S^{ij}\,\chi_R\tilde{\nu}_i^c\,\tilde{S}_j + \text{ h.c.}\Big)$$

Rotations

The gauge couplings and charges of $U(1)_R \times U(1)_{B-L}$ and $U(1)_Y \times U(1)_\chi$ are (without GUT normalization) related via

$$A^\mu \to A'^\mu = \begin{pmatrix} A^\mu_Y \\ A^\mu_\chi \end{pmatrix}, \quad Q \to Q' = \begin{pmatrix} q_{B-L} + q_R \\ \frac{3}{2} q_{B-L} - q_R \end{pmatrix},$$

$$G \to G' = \begin{pmatrix} g_Y & g_{Y\chi} \\ 0 & g_\chi \end{pmatrix},$$

with

$$g_Y = \frac{g_{BL} g_R - g_{BLR} g_{RBL}}{\sqrt{(g_{BLR} - g_R)^2 + (g_{BL} - g_{RBL})^2}},$$

$$g_\chi = \frac{2}{5} \sqrt{(g_{BLR} - g_R)^2 + (g_{BL} - g_{RBL})^2},$$

$$g_{Y\chi} = \frac{2(g_{BL}^2 + g_{BLR}^2) + g_{BLR} g_R + g_{BL} g_{RBL} - 3(g_R^2 + g_{RBL}^2)}{5\sqrt{(g_{BLR} - g_R)^2 + (g_{BL} - g_{RBL})^2}}$$

boundary conditions from GMSB

- masses of SUSY particles [*e.g.* Giudice, Rattazzi, '99; Martin, '97]:

$$M_a = \frac{g_a^2}{16\pi^2}\Lambda \sum_i n_a(i) g(x_i)$$

$$m_k^2 = 2\Lambda^2 \sum_a C_a(k) \frac{g_a^4}{(16\pi^2)^2} \sum_i n_a(i) f(x_i)$$

- including gauge kinetic mixing effects
  using [Fonseca, Malinskyi, Porod, Staub, '11]

$$M_{A\neq Abelian} = \frac{g_A^2}{16\pi^2}\Lambda \sum_i n_A(i) g(x_i)$$

$$M_{kl=Abelian} = \frac{1}{16\pi^2}\Lambda \Big(\sum_i g(x_i) G^T N Q_i Q_i^T N G \Big)_{kl}$$

$$m_k^2 = \frac{2}{(16\pi^2)^2}\Lambda^2 \Big(\sum_{A\neq Abelian} C_A(k) g_A^4 \sum_i f(x_i) n_A(i) + \sum_i f(x_i) (Q_k^T N G G^T N Q_i)^2 \Big)$$

Particle Content

	s=0	s=$\frac{1}{2}$	Gen.	$SU(3)_c \times SU(2)_L$	$U(1)_R \times U(1)_{B-L}$	$U(1)_Y \times U(1)_\chi$
$\hat{Q}$	$\tilde{Q}$	Q	3	$(\mathbf{3}, \mathbf{2})$	$(0, \frac{1}{6})$	$(\frac{1}{6}, \frac{1}{4})$
$\hat{d}^c$	$\tilde{d}^c$	d^c	3	$(\overline{\mathbf{3}}, \mathbf{1})$	$(\frac{1}{2}, -\frac{1}{6})$	$(\frac{1}{3}, -\frac{3}{4})$
$\hat{u}^c$	$\tilde{u}^c$	u^c	3	$(\overline{\mathbf{3}}, \mathbf{1})$	$(-\frac{1}{2}, -\frac{1}{6})$	$(-\frac{2}{3}, \frac{1}{4})$
$\hat{L}$	$\tilde{L}$	L	3	$(\mathbf{1}, \mathbf{2})$	$(0, -\frac{1}{2})$	$(-\frac{1}{2}, -\frac{3}{4})$
$\hat{e}^c$	$\tilde{e}^c$	e^c	3	$(\mathbf{1}, \mathbf{1})$	$(\frac{1}{2}, \frac{1}{2})$	$(1, \frac{1}{4})$
$\hat{\nu}^c$	$\tilde{\nu}^c$	ν^c	3	$(\mathbf{1}, \mathbf{1})$	$(-\frac{1}{2}, \frac{1}{2})$	$(0, \frac{5}{4})$
$\hat{S}$	$\tilde{S}$	S	3	$(\mathbf{1}, \mathbf{1})$	$(0, 0)$	$(0, 0)$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(\mathbf{1}, \mathbf{2})$	$(-\frac{1}{2}, 0)$	$(-\frac{1}{2}, \frac{1}{2})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\mathbf{1}, \mathbf{2})$	$(\frac{1}{2}, 0)$	$(\frac{1}{2}, -\frac{1}{2})$
$\hat{\chi}_R$	χ_R	$\tilde{\chi}_R$	1	$(\mathbf{1}, \mathbf{1})$	$(\frac{1}{2}, -\frac{1}{2})$	$(0, -\frac{5}{4})$
$\hat{\bar{\chi}}_R$	$\bar{\chi}_R$	$\tilde{\bar{\chi}}_R$	1	$(\mathbf{1}, \mathbf{1})$	$(-\frac{1}{2}, \frac{1}{2})$	$(0, \frac{5}{4})$

Tadpole equations

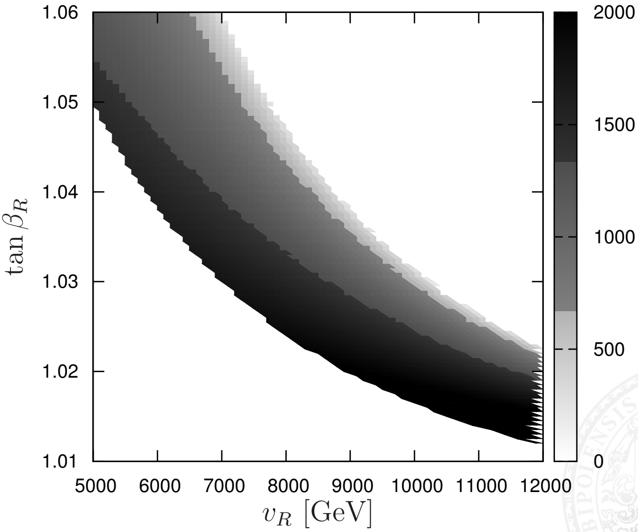
$$B_\mu = \frac{t_\beta}{t_\beta^2 - 1}\Big(m_{H_d}^2 - m_{H_u}^2 + \frac{v^2}{4} c_{2\beta}\big(g_L^2 + g_Y^2 + (g_\chi - g_{Y\chi})^2\big) + \frac{5 v_R^2}{8} c_{2\beta_R} g_\chi (g_\chi - g_{Y\chi})\Big)\,,$$

$$B_{\mu_R} = \frac{t_{\beta_R}}{t_{\beta_R}^2 - 1}\Big(m_{\bar\chi_R}^2 - m_{\chi_R}^2 - \frac{5 v^2}{8} c_{2\beta} g_\chi (g_\chi - g_{Y\chi}) + \frac{25 v_R^2}{16} c_{2\beta_R} g_\chi^2\Big)\,,$$

$$|\mu|^2 = \frac{1}{t_\beta^2 - 1}\Big(m_{H_d}^2 - m_{H_u}^2 t_\beta^2 - \frac{v^2}{8}\big(g_L^2 + g_Y^2 + (g_\chi - g_{Y\chi})^2\big)(t_\beta^2 - 1)$$

$$+ \frac{5 v_R^2}{16} c_{2\beta_R} (1 + t_\beta^2) g_\chi (g_\chi - g_{Y\chi})\Big)\,,$$

$$|\mu_R|^2 = \frac{1}{t_{\beta_R}^2 - 1}\Big(m_{\bar\chi_R}^2 - m_{\chi_R}^2 t_{\beta_R}^2 + \frac{5 v^2}{16} c_{2\beta} (t_{\beta_R}^2 + 1) g_\chi (g_\chi - g_{Y\chi}) - \frac{25 v_R^2}{32} (t_{\beta_R}^2 - 1) g_\chi^2\Big)$$


1.06
1.05
1.04
1.03
1.02
1.01
$\tan\beta_R$
5000
6000
7000
8000
9000
10000
11000
12000
v_R [GeV]
2000
1500
1000
500
0

Messenger Fields

	$SU(3)_c \times SU(2)_L$	$U(1)_R \times U(1)_{B-L}$	$U(1)_Y \times U(1)_\chi$
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$$M_{kl = Abelian} = \frac{1}{16\pi^2} \Lambda \left(\sum_i g(x_i) G^T N Q_i Q_i^T N G \right)_{kl} \,,$$

$$m_k^2 = \frac{2}{(16\pi^2)^2} \Lambda^2 \left(\sum_{A \neq Abelian} C_A(k) g_A^4 \sum_i f(x_i) n_A(i) \right.$$

$$\left. + \sum_i f(x_i) (Q_k^T N G G^T N Q_i)^2 \right)$$

inverse Seesaw mechanism

singlet fields $\hat{S}$ generate neutrino masses via inverse Seesaw

$$\mathcal{W}_\nu = Y_\nu \hat{\nu}^c \hat{L} \hat{H}_u + Y_S \hat{\nu}^c \hat{S} \hat{\chi}_R + \mu_S \hat{S} \hat{S}$$

$$m_\nu = \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} v_u Y_\nu^T & 0 \\ \frac{1}{\sqrt{2}} v_u Y_\nu & 0 & \frac{1}{\sqrt{2}} v_{\chi_R} Y_S \\ 0 & \frac{1}{\sqrt{2}} v_{\chi_R} Y_S^T & \mu_S \end{pmatrix}$$

$$m_\nu^{\mathrm{IS}} \simeq -\frac{v_u^2}{v_{\chi_R}^2} Y_\nu^T Y_S^{-1} \mu_S (Y_S^T)^{-1} Y_\nu$$

i.e.

- smallness of ν masses: μ_S small and/or $\frac{v_u}{v_{\chi_R}}$ small
- ν mixing: structure of μ_S and/or Y_ν and/or Y_S

Higgs mass matrix

On tree level, the scalar Higgs mass matrix in the basis $(\sigma_d, \sigma_u, \bar{\sigma}_R, \sigma_R)$ is given by

$$m^2_{h^0} =$$

$$\begin{pmatrix} \frac{1}{4}\tilde{g}^2_\Sigma v^2 c^2_\beta + m^2_A s^2_\beta & -\frac{s_{2\beta}}{8}(\tilde{g}^2_\Sigma v^2 + 4m^2_A) & \frac{5}{8}\tilde{g}^2_\chi v v_R c_\beta c_{\beta_R} & -\frac{5}{8}\tilde{g}^2_\chi v v_R c_\beta s_{\beta_R} \\ -\frac{s_{2\beta}}{8}(\tilde{g}^2_\Sigma v^2 + 4m^2_A) & \frac{1}{4}\tilde{g}^2_\Sigma v^2 s^2_\beta + m^2_A c^2_\beta & -\frac{5}{8}\tilde{g}^2_\chi v v_R s_\beta c_{\beta_R} & \frac{5}{8}\tilde{g}^2_\chi v v_R s_\beta s_{\beta_R} \\ \frac{5}{8}\tilde{g}^2_\chi v v_R c_\beta c_{\beta_R} & -\frac{5}{8}\tilde{g}^2_\chi v v_R s_\beta c_{\beta_R} & \frac{25}{16} g^2_\chi v^2_R c^2_{\beta_R} + m^2_{A_R} s^2_{\beta_R} & -\frac{s_{2\beta_R}}{32}(25 g^2_\chi v^2_R + 16 m^2_{A_R}) \\ -\frac{5}{8}\tilde{g}^2_\chi v v_R c_\beta s_{\beta_R} & \frac{5}{8}\tilde{g}^2_\chi v v_R s_\beta s_{\beta_R} & -\frac{s_{2\beta_R}}{32}(25 g^2_\chi v^2_R + 16 m^2_{A_R}) & \frac{25}{16} g^2_\chi v^2_R s^2_{\beta_R} + m^2_{A_R} c^2_{\beta_R} \end{pmatrix}$$

where $\tilde{g}^2_\Sigma = g^2_L + g^2_Y + (g_\chi - g_{Y\chi})^2$, $\tilde{g}^2_\chi = g_\chi(g_\chi - g_{Y\chi})$, and $s_x,\ c_x = \sin x,\ \cos x$.
The parameters m_A and m_{A_R} are the tree-level masses of the pseudoscalar Higgs bosons, which are given by
$m^2_A = B_\mu/(s_\beta c_\beta)$ and $m^2_{A_R} = B_{\mu_R}/(s_{\beta_R} c_{\beta_R})$.

Neutralino mass matrix

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{g_Y v_d}{2} & \frac{g_Y v_u}{2} & \frac{M_{Y\chi}}{2} & 0 & 0 \\ 0 & M_2 & \frac{g_L v_d}{2} & -\frac{g_L v_u}{2} & 0 & 0 & 0 \\ -\frac{g_Y v_d}{2} & \frac{g_L v_d}{2} & 0 & -\mu & \frac{(g_\chi - g_{Y\chi}) v_d}{2} & 0 & 0 \\ \frac{g_Y v_u}{2} & -\frac{g_L v_u}{2} & -\mu & 0 & -\frac{(g_\chi - g_{Y\chi}) v_u}{2} & 0 & 0 \\ \frac{M_{Y\chi}}{2} & 0 & \frac{(g_\chi - g_{Y\chi}) v_d}{2} & -\frac{(g_\chi - g_{Y\chi}) v_u}{2} & M_\chi & \frac{5 g_\chi v_{\bar{\chi}_R}}{4} & -\frac{5 g_\chi v_{\chi_R}}{4} \\ 0 & 0 & 0 & 0 & \frac{5 g_\chi v_{\bar{\chi}_R}}{4} & 0 & -\mu_R \\ 0 & 0 & 0 & 0 & -\frac{5 g_\chi v_{\chi_R}}{4} & -\mu_R & 0 \end{pmatrix} .$$

Sneutrino mass matrix

$$M_{\tilde{\nu}}^2 =$$

$$\begin{pmatrix} m_L^2 + \frac{v^2 s_\beta^2}{2} Y_\nu^\dagger Y_\nu + D_L' \mathbf{1} & \frac{v}{\sqrt{2}} (T_\nu^\dagger s_\beta - \mu Y_\nu^\dagger c_\beta) & \frac{1}{2} v v_R Y_\nu^\dagger Y_S s_\beta s_{\beta_R} \\ \frac{v}{\sqrt{2}} (T_\nu s_\beta - \mu^* Y_\nu c_\beta) & m_{\nu^c}^2 + \frac{v_R^2 s_{\beta_R}^2}{2} Y_S Y_S^\dagger + \frac{v^2 s_\beta^2}{2} Y_\nu Y_\nu^\dagger + D_R' \mathbf{1} & \frac{v_R}{\sqrt{2}} (T_S s_{\beta_R} - \mu_R^* Y_S c_{\beta_R}) \\ \frac{1}{2} v v_R Y_S^\dagger Y_\nu s_\beta s_{\beta_R} & \frac{v_R}{\sqrt{2}} (T_S^\dagger s_{\beta_R} - \mu_R Y_S^\dagger c_{\beta_R}) & m_S^2 + \frac{v_R^2 s_{\beta_R}^2}{2} Y_S^\dagger Y_S \end{pmatrix},$$

with

$$D_L' = \frac{1}{32} \Big(2(-3g_\chi^2 + g_\chi g_{Y\chi} + 2(g_L^2 + g_Y^2 + g_{Y\chi}^2)) v^2 c_{2\beta} - 5 g_\chi (3 g_\chi + 2 g_{Y\chi}) v_R^2 c_{2\beta_R} \Big),$$

$$D_R' = \frac{5 g_\chi}{32} \Big(2(g_\chi - g_{Y\chi}) v^2 c_{2\beta} + 5 g_\chi v_R^2 c_{2\beta_R} \Big).$$