Effect of Gauge Kinectic Mixing on Higgs Sector in B-L Supersymmetric Standard Model

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(Based on 1812.xxxx by U. Chattopadhyay, A. dey, **SM**)

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Outline

1. Generalized Gauge Kinetic Mixing
   - $U(1)_{B-L}$ extension of MSSM
   - Higgs sector
2. Results
   - Impact of g_{YB} & g_{BB}
   - Role of Y_x
3. Summary & Outlook

Between two U(1)s : Gauge kinetic mixing

- ✓ More than one Abelian gauge group is present. [B.Holdom, Phys. Lett. '86, Dines et. al. Nucl Phys. B '97]

$$\mathcal{L}_{gauge} = -\frac{1}{4}F_a^{\mu\nu}F_{a,\mu\nu} - \frac{1}{4}F_b^{\mu\nu}F_{b,\mu\nu} - \frac{\lambda_{ab}}{2}F_a^{\mu\nu}F_{b,\mu\nu}$$

- ✓ For supersymmetric models, this mixing term appears not only in vector bosons related phenomenology, but also for D-terms and gaugino soft-breaking terms.
- ✓ with an extra U(1) symmetry, covariant derivative takes the form -

$$D_\mu = \partial_\mu - ig_s T^a G^a_\mu - ig_2 T^a W^a_\mu - iQ_\phi^T GA$$

Gauge Coupling Matrix:

$$Q_\phi^T.G.A = \begin{pmatrix} Y_i & Y_j \end{pmatrix} \begin{pmatrix} g_{XX} & g_{XY} \\ g_{YX} & g_{YY} \end{pmatrix} \begin{pmatrix} A^i_\mu \\ A^j_\mu \end{pmatrix} \longrightarrow \begin{pmatrix} Y_i & Y_j \end{pmatrix} \begin{pmatrix} g_X & \tilde{g} \\ 0 & g_Y \end{pmatrix} \begin{pmatrix} A'^i_\mu \\ A'^j_\mu \end{pmatrix}$$

The entire impact of gauge kinetic mixing is encoded in one new coupling $\tilde{g}$. In the triangle basis, the relation between g_{ij} and the physical couplings are -

$$g'_{XX} = \frac{g_{XX}g_{YY} - g_{YX}g_{XY}}{\sqrt{g_{YY}^2 + g_{YX}^2}} = g_X$$

$$g'_{YY} = \sqrt{g_{YY}^2 + g_{YX}^2} = g_Y$$

$$g'_{XY} = \frac{g_{XY}g_{YY} + g_{YX}g_{XX}}{\sqrt{g_{YY}^2 + g_{YX}^2}} = \tilde{g}$$

$$g'_{YX} = 0$$

[Porod et. al. : 1112.4600]

$U(1)_{B-L}$ extended MSSM (BLSSM)

Charges of the superfields

Superfields	$\hat{Q}$	$\hat{U}$	$\hat{D}$	$\hat{L}$	$\hat{E}$	$\hat{\nu}$	$\hat{H}_u$	$\hat{H}_d$	$\hat{\eta}$	$\hat{\bar{\eta}}$
$U(1)_{B-L}$ Charge	$\frac{1}{6}$	$-\frac{1}{6}$	$-\frac{1}{6}$	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0	0	-1	1

- ✓ Helps to understand the origin of R-parity and possible spontaneous violation.
- ✓ explains the mechanism of leptogenesis.
- ✓ provides neutrino masses via seesaw mechanism.
- MSSM superfields $+ 3 \times \hat{\nu}_R + \hat{\eta} + \hat{\bar{\eta}}$
- $\hat{\eta}$, $\hat{\bar{\eta}}$: bileptons (SM gauge singlets).

Superpotential is given by -

$$W = Y_u^{ij}\,\hat{U}_i\,\hat{Q}_j\,\hat{H}_u - Y_d^{ij}\,\hat{D}_i\,\hat{Q}_j\,\hat{H}_d - Y_e^{ij}\,\hat{E}_i\,\hat{L}_j\,\hat{H}_d + \mu\,\hat{H}_u\,\hat{H}_d + Y_\nu^{ij}\,\hat{L}_i\,\hat{H}_u\,\hat{\nu}_j - \mu'\,\hat{\eta}\,\hat{\bar{\eta}} + Y_x^{ij}\,\hat{\nu}_i\,\hat{\eta}\,\hat{\nu}_j$$

we have the additional soft SUSY-breaking terms:

$$\begin{aligned}\mathcal{L}_{SB} =& \mathcal{L}_{MSSM} - \lambda_{\tilde{B}}\lambda_{\tilde{B}'}M_{BB'} - \frac{1}{2}\lambda_{\tilde{B}'}\lambda_{\tilde{B}'}M_{B'} - m_\eta^2|\eta|^2 - m_{\bar{\eta}}^2|\bar{\eta}|^2 - m_{\nu,ij}^2(\tilde{\nu}_i^c)^*\tilde{\nu}_j^c \\ & - \eta\bar{\eta}B_{\mu'} + T_\nu^{ij}H_u\tilde{\nu}_i^c\tilde{L}_j + T_x^{ij}\eta\tilde{\nu}_i^c\tilde{\nu}_j^c\end{aligned}$$

In the rotated field basis, the covariant derivative becomes,

$$D_\mu = \partial_\mu - ig_s T^a G_\mu^a - ig_2 T^a W_\mu^a - ig_1 Y B_\mu - i(\tilde{g}Y + g_{BL}Y_{B-L})B'_\mu$$

Higgs Masses and Mixing:

2 MSSM complex doublets and 2 bilepton complex doublet $\Rightarrow$ 4 CP-even, 2 CP-odd and 2 charged physical scalars. The squared-mass matrix for CP-even neutral Higgs fields at tree level in the basis $(\phi_d, \phi_u, \phi_\eta, \phi_{\bar{\eta}})$:

$$m^2 = \begin{pmatrix} m^2_{hH} & m^2_{hh'} \\ m^2_{h'h} & m^2_{h'H'} \end{pmatrix}$$

with $m^2_{hh'} = m^2_{h'h}$; where,

$$m^2_{hH} = \begin{pmatrix} m^2_{A^0} s^2_\beta + \bar{g}^2 v_u^2 & -m^2_{A^0} c_\beta s_\beta - \bar{g}^2 v_d v_u \\ -m^2_{A^0} c_\beta s_\beta - \bar{g}^2 v_d v_u & m^2_{A^0} c^2_\beta + \bar{g}^2 v_d^2 \end{pmatrix}; \; m^2_{hh'} = \begin{pmatrix} \frac{\tilde{g} g_{BL}}{2} v_d v_\eta & -\frac{\tilde{g} g_{BL}}{2} v_d v_{\bar{\eta}} \\ -\frac{\tilde{g} g_{BL}}{2} v_u v_\eta & \frac{\tilde{g} g_{BL}}{2} v_u v_{\bar{\eta}} \end{pmatrix}$$

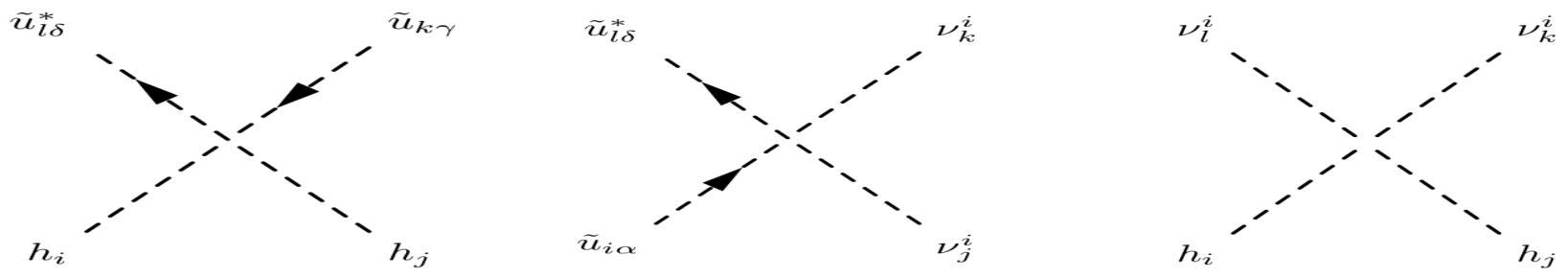
$$m^2_{h'H'} = \begin{pmatrix} m^2_{A^0_\eta} c^2_{\beta'} + g^2_{BL} v^2_\eta & -m^2_{A^0_\eta} c_{\beta'} s_{\beta'} - g^2_{BL} v_\eta v_{\bar{\eta}} \\ -m^2_{A^0_\eta} c_{\beta'} s_{\beta'} - g^2_{BL} v_\eta v_{\bar{\eta}} & m^2_{A^0_\eta} s^2_{\beta'} + g^2_{BL} v^2_{\bar{\eta}} \end{pmatrix}$$

we have defined $\bar{g}^2 = \frac{1}{4}(g_1^2 + g_2^2 + \tilde{g}^2)$, $c_x = \cos(x)$ and $s_x = \sin(x)$ $(x = \beta, \beta')$.
Gauge kinetic terms induce a small mixing between the SU(2) doublet Higgs fields and the bileptons at tree level. For BLSSM, (s)neutrino loop significantly contributes in Higgs mass at the same footing of (s)top loop.

$$m_h^2 = m_Z^2 \cos^2 2\beta + \delta_t^2 + \delta_\nu^2.$$

δ_ν^2 can enhance SM-like Higgs mass as large as $\mathcal{O}(100)^2$ GeV^2 depending on parameter choices.

Vertices in the radiative corrections of Higgs mass via gauge-kinetic mixing



Relevant four point scalar interactions contributing to the Higgs mass via stop & sneutrino loops. [Ref : SARAH-SPheno]

- The non-vanishing gauge kinetic mixing of $U(1)_Y$ and $U(1)_{B-L}$ $\Rightarrow$ many additional radiative contributions to the Higgs mass arise already at one loop through $\tilde{g}, g_{BL}$ & Y_X.
- The neutrino Yukawa couplings($Y_{\nu_{ij}}$) don't play any role in this context because the correct explanation of neutrino data requires them to be very small.
- Sizeable loop corrections due to Y_x couplings from neutrino-sneutrino loop.
- Two loop contributions involve sneutrino correction in stop mass.
- ✓ The observed Higgs mass can be manifested by varying $\tilde{g}$ without the need of large trilinear A parameters.

$$\text{Vertices} \sim a_1 g_1^2 + a_2 g_2^2 + a_3 g_{YB}^2 + a_4 g_{BY}^2 + a_5 g_1 g_{YB} + a_6 g_1 g_{BY} + a_7 g_{YB} g_{BB} + a_8 g_{BB}^2 + a_9 Y_x^2$$

$a_9 \neq 0$ only for higgs-sneutrino vertex. The a_i's are functions of mixing matrices connecting the flavor and mass basis for corresponding particles.

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Focus is to investigate the BLSSM specific contributions to the scalar sector.

Parameters	Fixed Inputs	Parameters	Fixed Inputs
M_1, M_2, M_3	1700, 2000, 2500 [GeV]	μ, μ'	500, 4200 [GeV]
$\tan\beta$, $\tan\beta'$	10, 1.2	g_{YB}, g_{BB}	$-0.042, 0.44$
m_A, m'_A	2290, 2000 [GeV]	$m_{Z'}$	4000 [GeV]
$M_{Q_{33}}$, $M_{U_{33}}$, $M_{D_{33}}$	1300 [GeV]	$M_{B'}$	1200 [GeV]
$M_{L_{33}}$, $M_{E_{33}}$	1800 [GeV]	$M_{\nu_{11/22/33}}$	220 [GeV]
A_t	-100 [GeV]	$Y_{x_{11/22/33}}$	0.40
A_b, A_μ, A_τ	0 [GeV]	T_x, T_ν	-200, 0 [GeV]
Parameters	**Outputs**	**Parameters**	**Outputs**
m_{h_1}, m_{h_2}	124.7, 272.3 [GeV]	$m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$	1170, 1170 [GeV]
m_{h_3}, m_{h_4}	2301.3, 4476.5 [GeV]	$m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}$	504, 506 [GeV]
$m_{\tilde{\nu}_1^S}, m_{\tilde{\nu}_1^P}$	1960, 1960 [GeV]	$m_{\tilde{g}}$	2360 [GeV]
$\mathrm{Br}(B \to X_s\gamma)$	3.167×10^{-4}	$\mathrm{Br}(B_s \to \mu^+\mu^-)$	3.263×10^{-9}

- Throughout the parameter space for this analysis $Z' \longrightarrow W^+W^-$ with 99.9 % branching fraction.
- For a scalar resonance decaying to two vector bosons LHC searches limit $\tan\beta' < 1.5$ and $v_x \geqslant 7$ TeV at 95% C.L. [arXiv : 1405.4123, 1412.6302].
- A heavy vector boson decaying to WW with mass upto 3500 GeV is excluded from ATLAS [arXiv : 1808.02380.]

Dependence of SM-like and bilepton like Higgs mass on g_{YB}.

$$-0.2 \leq g_{YB} \leq 0.2.$$

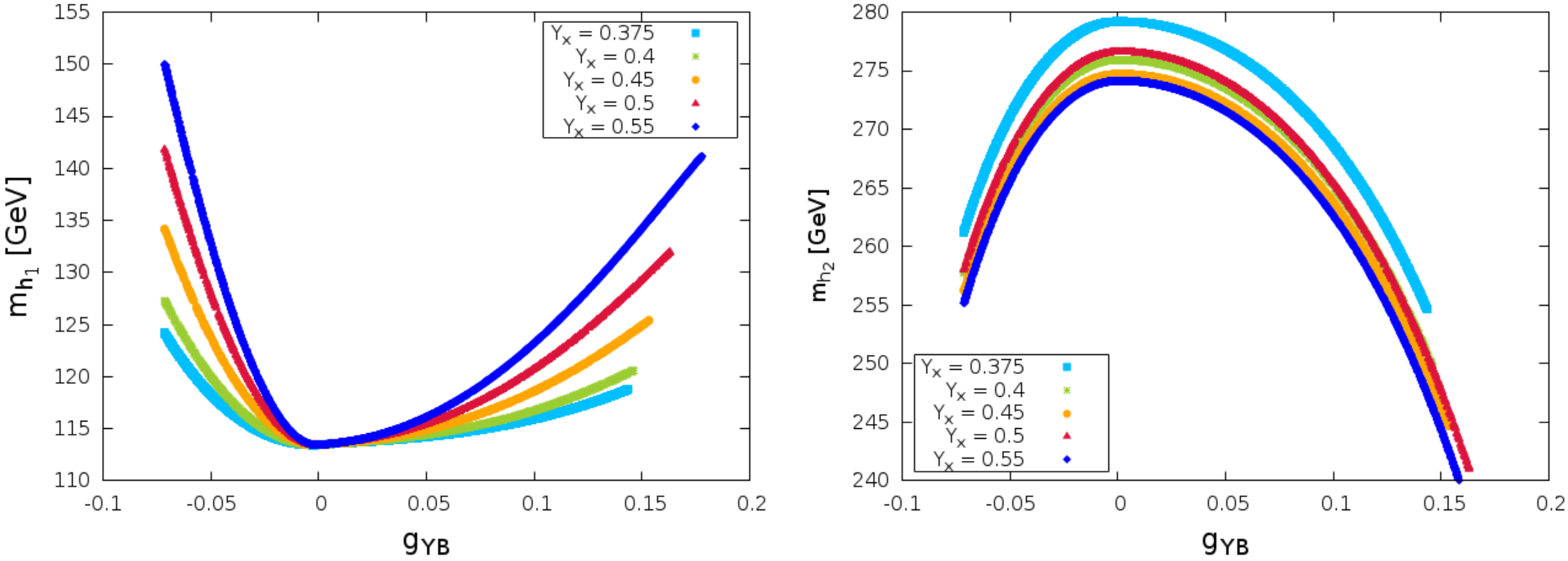


FIGURE: The effect of g_{YB} on m_{h_1} and m_{h_2} respectivly. This result corresponds to exclusive scan over g_{YB}. The lightest Higgs Boson is found to be purely MSSM like. While the second lightest Higgs Boson is purely B-L like. Both the plots are shown for several values of Y_x.

The asymmetry about g_{YB} $\Leftrightarrow$ presence of linear term in the vertex factors. Unlike g_{YB} large values of Y_X in general enhance both m_{h_1} and m_{h_2}.

Impact of g_{BB} & g_{YB} | $-0.44 \leq g_{BB} \leq 0.44.$ | $-0.15 \leq g_{YB} \leq 0.15$

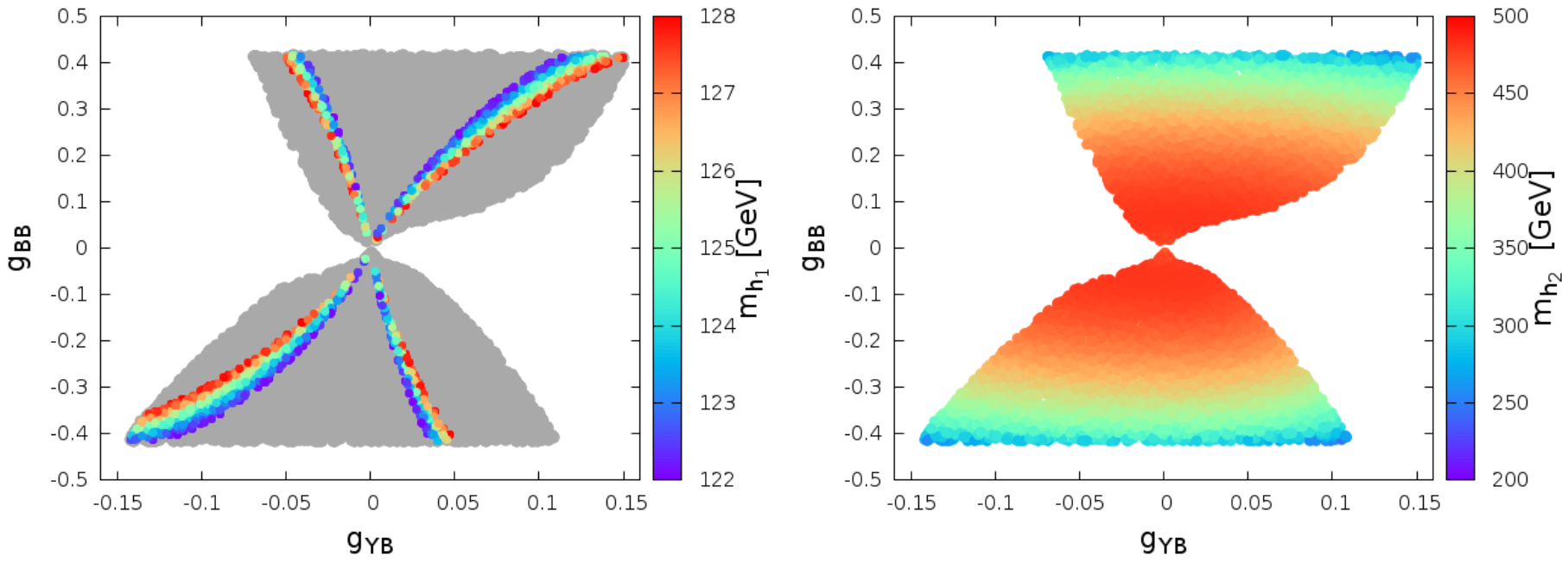
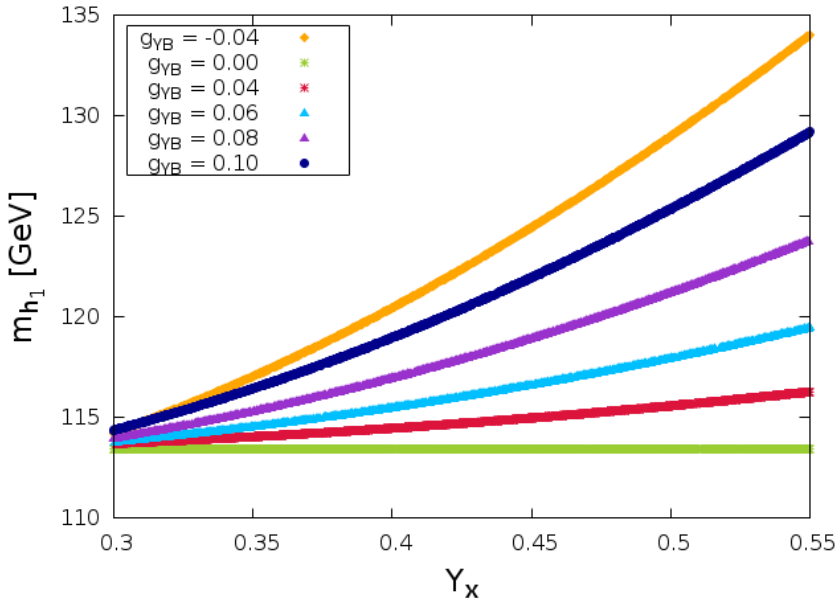
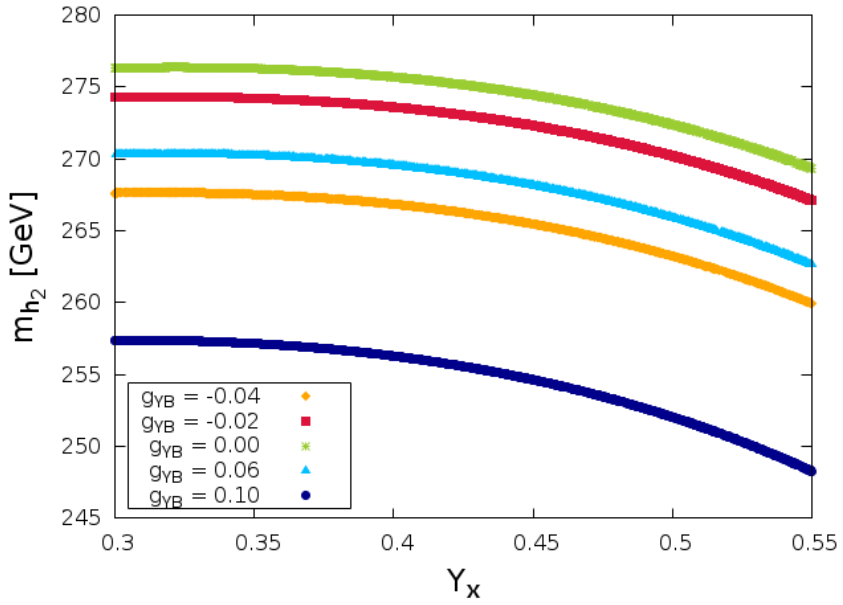


FIGURE: These two display the result in $g_{BL} - g_{YB}$ plane where we study the dependence of m_{h_1} and the mass of the second lightest higgs m_{h_2} on the former BLSSM specific parameters. Lack of data points in the second quadrant is due to inconsistency of the tadpole equations.

It is evident from the plot, that g_{YB} has minimal effect on m_{h_2}. However, g_{BL} significantly modifies m_{h_2}.

Role of Y_x | $0.3 < Y_x < 0.55$





- Variation of Higgs mass with Y_x where g_{YB} is kept constant for each line.
- β_{Y_x} shows that, $Y_x \geq 0.55$ spoils the perturbativity of the model at the GUT scale or below. [Khalil, Moretti et. al. **PHYS. REV. D 96, 055004 (2017)**]
- This mass variation is also $M_{Z'}$ dependent through sneutrino masses and tadpole solutions.
- All points within $122 < m_h$ [GeV] < 128 are ofcourse allowed by HiggsBounds and HiggsSignals.
- Variation of 2nd lightest Higgs mass with Y_x is also shown for fixed g_{YB}.

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Wrap-up

✓ **Gauge kinetic mixing in the framework of U(1)$_{B-L}$ extended MSSM.**

FEATURES:

- Allowed in models with multiple Abelian gauge groups.
- The effects rely on the primary and secondary interaction vertices of the sparticles and SUSY D-term interaction term.
- Enlarges the viable parameter space.
- Softens the need for large radiative corrections only from $\tilde{t}$ loop.
- Especially, the mass of SM-lke Higgs boson can be significantly enhanced by an appropriate choice of g_{YB}, g_{BB}, Y_x.

THANK YOU!

Backup Slides :

Stops in BLSSM

Stop masses are significantly modified by the BLSSM specific contribution even at the tree-level.

$$m_{\tilde{u}}^2 = \begin{pmatrix} m_{LL} & \frac{1}{\sqrt{2}}\left(v_u T_u - v_d \mu^* Y_u\right) \\ \frac{1}{\sqrt{2}}\left(v_u T_u^\dagger - v_d \mu Y_u^\dagger\right) & m_{RR} \end{pmatrix}$$

$$m_{LL} = m_Q^2 + \frac{v_u^2}{2} Y_u^\dagger Y_u + \frac{1}{24}\Big((g_1^2 - 3g_2^2 + \tilde{g}^2 + \tilde{g} g_{BL})(v_u^2 - v_d^2) + 2(\tilde{g} g_{BL} + g_{BL}^2)(v_{\bar{\eta}}^2 - v_\eta^2)\Big)\mathbf{1}$$

$$m_{RR} = m_U^2 + \frac{v_u^2}{2} Y_u Y_u^\dagger + \frac{1}{24}\Big(2(g_{BL}^2 + 4\tilde{g} g_{BL})(v_\eta^2 - v_{\bar{\eta}}^2) + (4g_1^2 + 4\tilde{g}^2 + \tilde{g} g_{BL})(v_d^2 - v_u^2)\Big)\mathbf{1}$$

Inclusion of radiative corrections arising out of sneutrino loops lead to further modification stop mass in light of g_{YB}, g_{BL}, Y_X. This effectively modifies m_{h_1}, at two loop level.

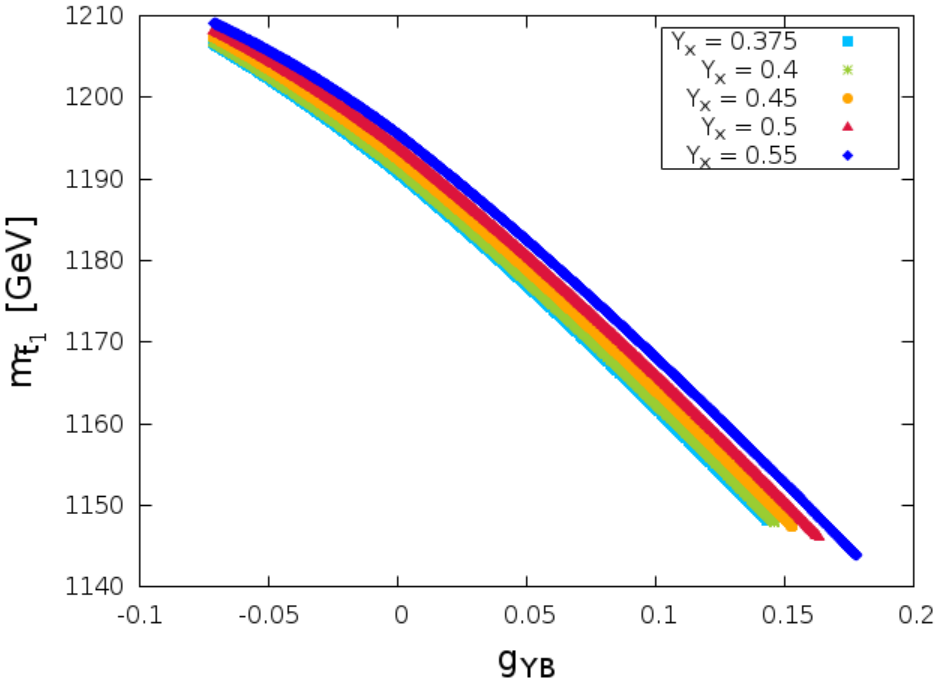
Sneutrinos in BLSSM

Sneutrino sector for this model gets augmented by the additional superpartners of the right handed neutrinos. There is 6×6 mass matrices for both CP even and CP odd sneutrinos. If the trilinear couplings for this sector or μ' term become complex then, scalar and pseudoscalar sneutrinos mix yielding 12×12 mass matrix.
Neglecting kinetic mixing and also left-right mixing, the masses of the R-sneutrinos is given by,

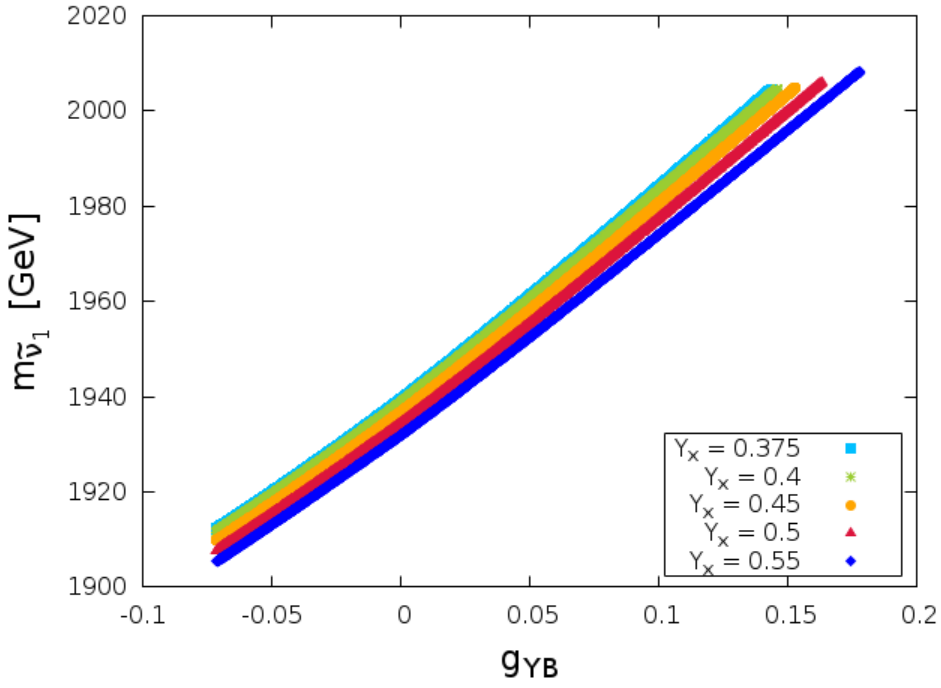
$$m^2_{\nu^S} \simeq m^2_{\nu^c} + M^2_{Z'} \left(\frac{1}{4} \cos(2\beta') + \frac{2Y_x^2}{g_{BL}^2} \sin \beta'^2 \right) + M_{Z'} \frac{\sqrt{2} Y_x}{g_{BL}} \left(A_x \sin \beta' - \mu' \cos \beta' \right) , \quad (1)$$

$$m^2_{\nu^P} \simeq m^2_{\nu^c} + M^2_{Z'} \left(\frac{1}{4} \cos(2\beta') + \frac{2Y_x^2}{g_{BL}^2} \sin \beta'^2 \right) - M_{Z'} \frac{\sqrt{2} Y_x}{g_{BL}} \left(A_x \sin \beta' - \mu' \cos \beta' \right) . \quad (2)$$

The first two terms in 2 always give positive contributions. However depending on the sign of A_x and μ' third term can act in both ways. Here the chosen value of $M_{Z'}$ plays an important role. We note that in 2 the second term goes quadratically with $M_{Z'}$ whereas the third term is linear in it. So, for very large $M_{Z'}$ practically the first two terms dominates the eigenvalue. Changing Y_x or A_x one can get no drastic change in the sneutrino sector.

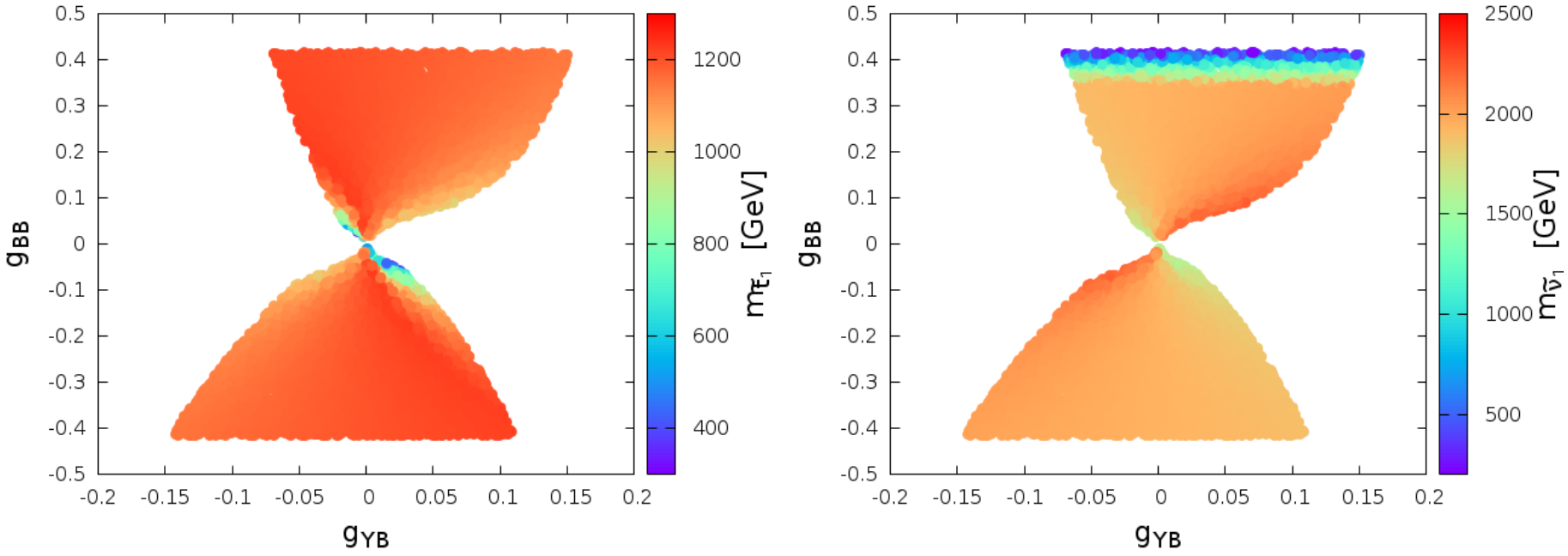


(c)



(d)

FIGURE: Lightest top squark and sneutrino mass variation with g_{YB}.



(a) (b)

FIGURE: The left (right) plot shows the variation of $m_{\tilde{t}_1}$ ($m_{\tilde{\nu}_1}$) in $g_{YB} - g_{BL}$ canvas.