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

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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]

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

- 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 -

\[ D_\mu = \partial_\mu - ig_s T^a G^a_\mu - ig_2 T^a W^a_\mu - i Q^T_\phi G A \]

**Gauge Coupling Matrix:**

\[ Q^T_\phi G A = ( Y_i \quad Y_j ) \left( \begin{array}{cc} g_{XX} & g_{XY} \\ g_{YX} & g_{YY} \end{array} \right) \left( \begin{array}{c} A^i_\mu \\ A^j_\mu \end{array} \right) \rightarrow ( Y_i \quad Y_j ) \left( \begin{array}{cc} g_X & \tilde{g} \\ 0 & g_Y \end{array} \right) \left( \begin{array}{c} A^i_\mu \\ A^j_\mu \end{array} \right) \]

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 -

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

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

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

\[ g'_{YX} = 0 \]

[Porod et. al. : 1112.4600]
U(1)$_{B-L}$ extended MSSM (BLSSM)

**Charges of the Superfields**

<table>
<thead>
<tr>
<th>Superfields</th>
<th>$\hat{Q}$</th>
<th>$\hat{U}$</th>
<th>$\hat{D}$</th>
<th>$\hat{L}$</th>
<th>$\hat{E}$</th>
<th>$\hat{\nu}$</th>
<th>$\hat{H}_u$</th>
<th>$\hat{H}_d$</th>
<th>$\hat{\eta}$</th>
<th>$\hat{\bar{\eta}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U(1)_{B-L}$ Charge</td>
<td>$\frac{1}{6}$</td>
<td>$-\frac{1}{6}$</td>
<td>$-\frac{1}{6}$</td>
<td>$-\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>1</td>
</tr>
</tbody>
</table>

- 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 -

$$W = Y_u\hat{U}_i \hat{Q}_j \hat{A}_u - Y_d\hat{D}_i \hat{Q}_j \hat{A}_d - Y_e\hat{E}_i \hat{L}_j \hat{A}_d + \mu \hat{A}_u \hat{A}_d + Y_\nu\hat{L}_i \hat{A}_u \hat{\nu}_j - \mu' \hat{\eta} \hat{\bar{\eta}} + Y_\tilde{\nu}\hat{\tilde{\nu}} \hat{\nu} \hat{\bar{\nu}}$$

we have the additional soft SUSY-breaking terms:

$$\mathcal{L}_{SB} = \mathcal{L}_{MSSM} - \lambda_{\tilde{B}} \lambda_{\tilde{B}'}, M_{BB'} - \frac{1}{2} \lambda_{\tilde{B}} \lambda_{\tilde{B}'}, M_{B'} - m_{\tilde{\eta}}|\tilde{\eta}|^2 - m_{\tilde{\bar{\eta}}}|\tilde{\bar{\eta}}|^2 - m_{\nu,ij}(\tilde{\nu}_i^c)^* \tilde{\nu}_j^c$$

\[ - \tilde{\eta} \tilde{\bar{\eta}} B_{\mu'} + T_{\nu}^{ij} H_u \tilde{\nu}_i^c \tilde{\nu}_j^c + T_{\tilde{\nu}}^{ij} \eta \tilde{\nu}_i^c \tilde{\nu}_j^c \]

In the rotated field basis, the covariant derivative becomes,

$$D_\mu = \partial_\mu - ig_s T^a G^a_\mu - ig_2 T^a W^a_\mu - ig_1 Y B_\mu - i(\tilde{g} Y + g_{BL} Y_{B-L}) B'_\mu$$
Higgs Masses and Mixing:

2 MSSM complex doublets and 2 bilepton complex doublet ⇒ 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 \((\phi_d, \phi_u, \phi_\eta, \phi_\overline{\eta})\):

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

with \(m^2_{hh'} = m^2_{h' h}\); where,

\[
m^2_{hh} = \begin{pmatrix}
m^2_{A_0} s_\beta^2 + \tilde{g}^2 v_u^2 & -m^2_{A_0} c_\beta s_\beta - \tilde{g}^2 v_d v_u \\
-m^2_{A_0} c_\beta s_\beta - \tilde{g}^2 v_d v_u & m^2_{A_0} c_\beta^2 + \tilde{g}^2 v_d^2
\end{pmatrix};
\]

\[
m^2_{hh'} = \begin{pmatrix}
\frac{\bar{g} g_{BL}}{2} v_d v_\eta & -\frac{\bar{g} g_{BL}}{2} v_d v_\overline{\eta} \\
-\frac{\bar{g} g_{BL}}{2} v_u v_\eta & \frac{\bar{g} g_{BL}}{2} v_u v_\overline{\eta}
\end{pmatrix};
\]

\[
m^2_{h' H'} = \begin{pmatrix}
m^2_{A_0} c_\beta' + g_{BL} v_\eta^2 & -m^2_{A_0} c_\beta' s_\beta' - g_{BL}^2 v_\eta v_\overline{\eta} \\
-m^2_{A_0} c_\beta' s_\beta' - g_{BL}^2 v_\eta v_\overline{\eta} & m^2_{A_0} s_\beta'^2 + g_{BL}^2 v_\overline{\eta}^2
\end{pmatrix};
\]

we have defined \(\tilde{g}^2 = \frac{1}{4}(g_1^2 + g_2^2 + \tilde{g}^2)\), \(c_x = \cos(x)\) 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.

\[
m^2_h = m^2_Z \cos^2 2\beta + \delta_t^2 + \delta_\nu^2.
\]

\(\delta_\nu^2\) 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 $U(1)_{B-L}$ ⇒ 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.

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

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

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Fixed Inputs</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$M_1, M_2, M_3$</td>
<td>1700, 2000, 2500 [GeV]</td>
<td>$\mu, \mu'$</td>
<td>500, 4200 [GeV]</td>
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<tr>
<td>$\tan \beta, \tan \beta'$</td>
<td>10, 1.2</td>
<td>$g_{YB}, g_{BB}$</td>
<td>$-0.042, 0.44$</td>
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<td>$m_A, m'_A$</td>
<td>2290, 2000 [GeV]</td>
<td>$M_{Z'}$</td>
<td>4000 [GeV]</td>
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<td>$M_{Q33}, M_{U33}, M_{D33}$</td>
<td>1300 [GeV]</td>
<td>$M_{B'}$</td>
<td>1200 [GeV]</td>
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<td>$M_{L33}, M_{E33}$</td>
<td>1800 [GeV]</td>
<td>$M_{\nu_{11/22/33}}$</td>
<td>220 [GeV]</td>
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<td>$A_t$</td>
<td>$-100$ [GeV]</td>
<td>$Y_{\chi_{11/22/33}}$</td>
<td>$0.40$</td>
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<td>$A_b, A_{\mu}, A_{\tau}$</td>
<td>0 [GeV]</td>
<td>$T_x, T_\nu$</td>
<td>$-200, 0$ [GeV]</td>
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<table>
<thead>
<tr>
<th>Parameters</th>
<th>Outputs</th>
<th>Parameters</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{h1}, m_{h2}$</td>
<td>124.7, 272.3 [GeV]</td>
<td>$m_{\tilde{t}<em>1}, m</em>{\tilde{t}_2}$</td>
<td>1170, 1170 [GeV]</td>
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<tr>
<td>$m_{h3}, m_{h4}$</td>
<td>2301.3, 4476.5 [GeV]</td>
<td>$m_{\chi_0^0}, m_{\chi_1^\pm}$</td>
<td>504, 506 [GeV]</td>
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<tr>
<td>$m_{\tilde{\nu}<em>1^S}, m</em>{\tilde{\nu}_1^P}$</td>
<td>1960, 1960 [GeV]</td>
<td>$m_{\tilde{g}}$</td>
<td>2360 [GeV]</td>
</tr>
<tr>
<td>$\text{Br}(B \to X_s \gamma)$</td>
<td>$3.167 \times 10^{-4}$</td>
<td>$\text{Br}(B_s \to \mu^+ \mu^-)$</td>
<td>$3.263 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

- Throughout the parameter space for this analysis $Z' \to W^+ W^-$ with 99.9 \% branching fraction.
- For a scalar resonance decaying to two vector bosons LHC searches limit $\tan \beta' < 1.5$ and $v_x \geq 7$ 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].
Figure: The effect of $g_{YB}$ on $m_{h_1}$ and $m_{h_2}$ respectively. 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 $m_{h_2}$.
- Variation of Higgs mass with $Y_x$ where $g_{YB}$ is kept constant for each line.
- $\beta_{Y_x}$ 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 $122 < m_h \text{[GeV]} < 128$ 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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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-like Higgs boson can be significantly enhanced by an appropriate choice of $g_{YB}, g_{BB}, Y_x$. 
THANK YOU!
Backup Slides:
Stop masses are significantly modified by the BLSSM specific contribution even at the tree-level.

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

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

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

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 $6 \times 6$ mass matrices for both CP even and CP odd sneutrinos. If the trilinear couplings for this sector or $\mu'$ term become complex then, scalar and pseudoscalar sneutrinos mix yielding $12 \times 12$ mass matrix. Neglecting kinetic mixing and also left-right mixing, the masses of the R-sneutrinos is given by,

$$m_{\tilde{\nu}}^{2} \simeq m_{\tilde{\nu}c}^2 + M_{Z'}^2 \left( \frac{1}{4} \cos(2\beta') + \frac{2Y_x^2}{g_{BL}^2} \sin \beta'^2 \right) + M_{Z'} \frac{\sqrt{2}Y_x}{g_{BL}} (A_x \sin \beta' - \mu' \cos \beta') \; , \; (1)$$

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

The first two terms in 2 always give positive contributions. However depending on the sign of $A_x$ and $\mu'$ 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.
**Figure:** Lightest top squark and sneutrino mass variation with $g_{YB}$.
**Figure:** The left (right) plot shows the variation of $m_{\tilde{t}_1}$ ($m_{\tilde{\nu}_1}$) in $g_{YB} - g_{BL}$ canvas.