Higgs Sector in B-L Supersymmetric Standard Model

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Introduction

- Despite the absence of direct experimental verification, SUSY is still the most promising candidate for a unified theory beyond the SM.
- SUSY is a generalization of the space-time symmetries of the QFT that relates bosons to fermions .
- SUSY solves the problem of the quadratic divergence in the Higgs sector of the SM in a very elegant natural way.
- The most simple supersymmetric extension of the SM is know as the MSSM.

$$W = h_U Q_L U_L^c H_2 + h_D Q_L D_L^c H_1 + h_L L_L E_L^c H_1 + \mu H_1 H_2 .$$

- Due to R-parity conservation, SUSY particles are produced or destroyed only in pairs.The LSP is absolutely stable, candidate for DM.
- In the MSSM, the mass of the lightest Higgs state can be approximated, at the one-loop level, as

$$m_h^2 \leq M_Z^2 + \frac{3g^2}{16\pi^2 M_W^2} \frac{m_t^4}{\sin^2\beta} \log\left(\frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4}\right) .$$

- MSSM predicts an upper bound for the Higgs mass: $m_h \lesssim 130$ GeV, which was consistent with the measured value of Higgs mass (of order 125 GeV) at the LHC.
- This mass of lightest Higgs boson implies that the SUSY particles are quite heavy. This may justify the negative searches for SUSY at the LHC-run I and II

SUSY $B-L$ Extension of the SM

- The solid experimental evidence for neutrino oscillations, pointing towards non-vanishing neutrino masses, is one of the few firm hints for physics beyond the SM.
- BLSSM is the minimal extension of MSSM, based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$.
- This type of extension implies the existence of extra 3 superfields, one per generation, with $B-L$ charge equal -1, in order to cancel the associate $B-L$ triangle anomaly.
- These superfields are identified with the right-handed neutrinos and will be denoted N_i.
- In addition, in order to break the $B-L$ symmetry at TeV scale, two Higgs superfields $\hat{\chi}_{1,2}$ with ∓ 2 $B-L$ charges are required.

	$\hat{Q}_i$	$\hat{U}_i^c$	$\hat{D}_i^c$	$\hat{\ell}_i$	$\hat{E}_i^c$	$\hat{N}_i^c$	$\hat{H}_1$	$\hat{H}_2$	$\hat{\chi}_1$	$\hat{\chi}_2$
$SU(3)_c$	3	$\bar{3}$	$\bar{3}$	1	1	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	2	2	1	1
$U(1)_Y$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	$-\frac{1}{2}$	$\frac{1}{2}$	0	0
$U(1)_{B-L}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-1	-1	-1	0	0	-2	2

- The superpotential of BLSSM is given by

$$W = Y_U Q H_2 U^c + Y_D Q H_1 D^c + Y_E L H_1 E^c + Y_\nu L H_2 N^c + \frac{1}{2} Y_N N^c N^c \chi_1 + \mu H_1 H_2 + \mu' \chi_1 \chi_2$$

- **The soft breaking terms**

$$V_{\rm soft} = V_{\rm soft}^{\rm MSSM} + m_{\tilde{N}}^2 |\tilde{N}|^2 + m_{\chi_1}^2 |\chi_1|^2 + m_{\chi_2}^2 |\chi_2|^2 + \Big[\Big(\frac{1}{2} M_{1/2} \tilde{Z}' \tilde{Z}' + Y_\nu A_\nu \tilde{L} H_2 \tilde{N}^c + \frac{1}{2} Y_N A_N \tilde{N}^c \chi_1 \tilde{N}^c + B\mu' \chi_1 \chi_2 \Big) + h.c. \Big]$$

- **The Higgs Potential is**

$$V(H_1, H_2, \chi_1, \chi_2) = \frac{g^2 + g'^2}{8} (|H_2|^2 - |H_1|^2)^2 + \frac{1}{2} g''^2 \left(|\chi_2|^2 - |\chi_1|^2 \right)^2 + m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - m_3^2 (H_1 H_2 + h.c.) + \mu_1^2 |\chi_1|^2 + \mu_2^2 |\chi_2|^2 - \mu_3^2 (\chi_1 \chi_2 + h.c.)$$

where

$$m_i^2 = m_0^2 + \mu^2, \quad \mu_i^2 = m_0^2 + \mu'^2, \; i = 1, 2 \qquad m_3^2 = B\mu, \quad \mu_3^2 = B\mu'.$$

- **It is clear that the full scalar potential can be, trivially, splited into two separated terms:**

$$V(H_1, H_2, \chi_1, \chi_2) = V_1(H_1, H_2) + V_2(\chi_1, \chi_2)$$

- **The condition of stability of $V_2(\chi_1, \chi_2)$:** $2\mu_3^2 < \mu_1^2 + \mu_2^2$

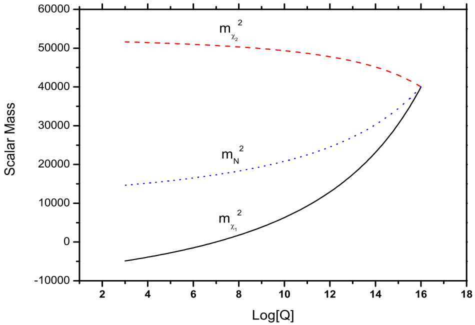
- **Also, to get a non-zero vev, we must impose the condition:** $\mu_1^2 \mu_2^2 < \mu_3^4$

- **And, as before, these two conditions can not be satisfied simultaneously for positive values of μ_1^2, μ_2^2.**

And the solution is in the RGE's.

Radiative $B-L$ symmetry breaking in the BLSSM

- **The breaking of $B-L$ can spontaneously occur through the VEV of $\chi_{1,2}$ or $\tilde{N}_3^c$.**
- **The running from the GUT down to the $B-L$ breaking scale shows that masses of the of Higgs singlets χ_1 and χ_2 run differently in such a way that $m^2_{\chi_1}$ can became negative whereas $m^2_{\chi_2}$ remains positive.**



The evolution of the $B-L$ scalar masses from the GUT to the TeV scale for $Y_{N_3} \sim \mathcal{O}(0.1)$.

S.K., A. Masiero (2008)

$$\frac{dm^2_{\chi_1}}{dt} = 9\tilde{\alpha}_{B-L}\, M^2_{B-L} - 2\tilde{Y}_N\, (m^2_{\chi_1} + 2m^2_{\tilde{N}} + A^2_N)$$

Neutrino Masses in BLSSM

- **A type I seesaw can be obtained from the BLSSM super potential:**

$$\mathcal{L}_{B-L} \in Y_\nu \bar{l} H_2 \nu_R + \frac{1}{2} Y_N \bar{\nu_R^c} \chi_1 \nu_R^c + h.c.$$

- **Majorana mass , after B-L symmetry breaking is generated:**

$$M_R = Y_N \langle \chi_1 \rangle = Y_N v'$$

Thus $v' \sim \mathcal{O}(1)\mathrm{TeV}, \;\; Y_N \sim \mathcal{O}(1) \Rightarrow M_R \sim \mathcal{O}(1)\mathrm{TeV}$

- **Dirac mass (after Electroweak symmetry breaking):**

$$m_D = Y_\nu \langle H_2 \rangle = Y_\nu v$$

- **Thus, the follow neutrino mass matrix is obtained:**

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

- **The light neutrino mass is** $m_\nu = -m_D M_R^{-1} m_D^T$.
- **Thus** $m_\nu \sim \mathcal{O}(1)$ **eV if** $m_D \sim 10^{-4}$ GeV $\Rightarrow Y_\nu \sim 10^{-6} \sim Y_E$

Higgs Bosons in BLSSM

- **In BLSSM, we have 2 Higgs doublet and 2 Higgs singlet superfields, i.e. 12 degrees of freedom:**
  - ⋆ **4 have been eaten by $W^\pm$, Z, and Z'.**
  - ⋆ **2 neutral pseudoscalar Higgs bosons A.**
  - ⋆ **2 charged Higgs bosons $H^\pm$.**
  - ⋆ **4 neutral scalar Higgs bosons h, H.**
- **The squared-mass matrix of the BLSSM CP-odd neutral Higgs fields at tree level is given by**

$$m^2_{A,A'} = \begin{pmatrix} B_\mu \tan\beta & B_\mu & 0 & 0 \\ B_\mu & B_\mu \cot\beta & 0 & 0 \\ 0 & 0 & B_{\mu'} \tan\beta' & B_{\mu'} \\ 0 & 0 & B_{\mu'} & B_{\mu'} \cot\beta' \end{pmatrix}.$$

- **It is clear that the MSSM-like CP-odd Higgs A is decoupled from the BLSSM-like one A' (at tree level).**
- **Due to the dependence of B_μ on v', $m_A^2 = \frac{2B_\mu}{\sin 2\beta} \sim m_{A'}^2 = \frac{2B_{\mu'}}{\sin 2\beta'} \sim \mathcal{O}(1\ \text{TeV})$.**

- **The mass matrix of BLSSM CP-even neutral Higgs at tree level is given by**

$$M^2 = \begin{pmatrix} M^2_{hH} & M^2_{hh'} \\ {M^2_{hh'}}^T & M^2_{h'H'} \end{pmatrix}$$

- M^2_{hH} **is MSSM neutral CP-even Higgs mass matrix** $\Rightarrow m_h \sim 125$ **GeV** $\& m_H \sim m_A \sim \mathcal{O}(1$ **TeV).**

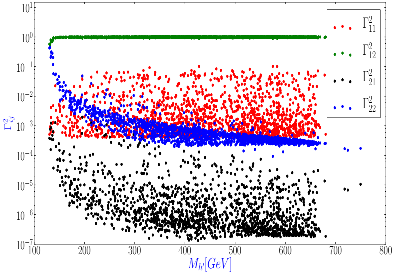
- $M^2_{h'H'} = \begin{pmatrix} m^2_{A'} c^2_{\beta'} + g^2_{BL} v'^2_1 & -\frac{1}{2} m^2_{A'} s_{2\beta'} - g^2_{BL} v'_1 v'_2 \\ -\frac{1}{2} m^2_{A'} s_{2\beta'} - g^2_{BL} v'_1 v'_2 & m^2_{A'} s^2_{\beta'} + g^2_{BL} v'^2_2 \end{pmatrix}$

$$\Rightarrow m^2_{h',H'} = \frac{1}{2}\left[(m^2_{A'} + M^2_{Z'}) \mp \sqrt{(m^2_{A'} + M^2_{Z'})^2 - 4 m^2_{A'} M^2_{Z'} \cos^2 2\beta'}\right]$$

$$\Rightarrow m_{h'} \simeq \left(\frac{m^2_{A'} M^2_{Z'} \cos^2 2\beta'}{m^2_{A'} + M^2_{Z'}}\right)^{\frac{1}{2}} \simeq \mathcal{O}(100 \text{ GeV})$$

- **Finally,** $$M^2_{hh'} = \frac{1}{2}\tilde{g}g_{BL}\begin{pmatrix} v_1 v_1' & -v_1 v_2' \\ -v_2 v_1' & v_2 v_2' \end{pmatrix}$$
- **This mixing is crucial for generating mixing between BLSSM Higgs bosons and MSSM-like Higgs states.**
- **A numerical scan confirms that, while $\tan'\beta \leq 1.2$, the h' state can be the second Higgs boson mass whereas the other two CP-even states H, H' are heavy, i.e.,**

$$h' = \Gamma_{21}\ \sigma_1 + \Gamma_{22}\ \sigma_2 + \Gamma_{23}\ \sigma_1' + \Gamma_{24}\ \sigma_2'.$$



Decomposition of the BLSSM Higgs boson, h', and the SM-like Higgs, h, versus $M_{h'}$.

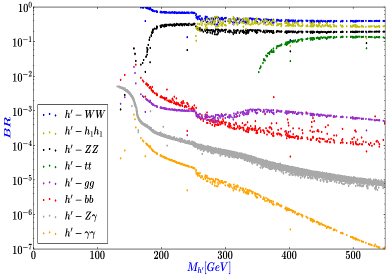
- Thus, the couplings of the h' with up- and down-quarks are given by:

$$g_{h' u\bar{u}} = -i\frac{m_u \times \Gamma_{22}}{\upsilon \sin\beta}, \qquad g_{h' d\bar{d}} = -i\frac{m_d \times \Gamma_{21}}{\upsilon \cos\beta}.$$

- The h' couplings with the W^+W^- and ZZ gauge boson are given by:

$$g_{h' WW} = i\; g_2 M_W \left(\Gamma_{22}\sin\beta + \Gamma_{21}\cos\beta\right), \quad g_{h' ZZ} = i\; g_z\, M_Z \left(\Gamma_{22}\sin\beta + \Gamma_{21}\cos\beta\right).$$

- Finally, the scalar trilinear coupling between h' and hh is given by: $\lambda_{h' hh} = \frac{-i\tilde{g}g_{BL}}{4}\Gamma_{12}^2\left(2v_2'\Gamma_{24} - v_1'\Gamma_{23}\right)$.



The BRs of h' versus $M_{h'}$ for $0.1 \leq \tilde{g} \leq 0.25$ and $g_{BL} = 0.5$

- For $m_{h'} \geq 200$ GeV, h' decays are dominated by the W^+W^- and hh channels.
- In the BLSSM the $\mathrm{BR}(h' \to Z\gamma)$ is typically larger than the $\mathrm{BR}(h' \to \gamma\gamma)$, unlike the MSSM and SM where it is the other way around.

Search for a heavy BLSSM Higgs boson at the LHC

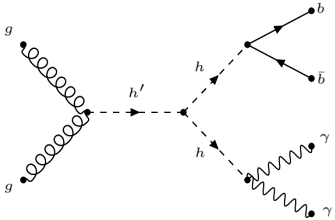
- **The heavy BLSSM Higgs boson, h', is mainly produced at the LHC from gluon-gluon fusion process, which induces about 90% of its total production cross section.**
- **The total cross section of h' decay to $4b$ final state is given by**

$$\sigma(pp \to h' \to hh \to 4b) = \sigma(pp \to h') \times \mathrm{BR}(h' \to hh) \times \mathrm{BR}(h \to b\bar{b})^2$$

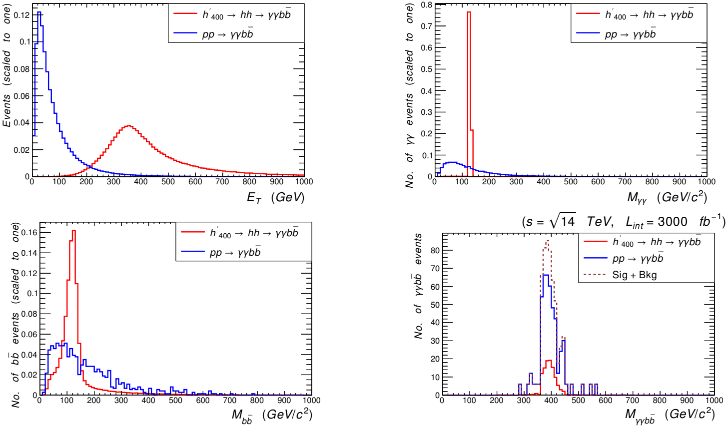
- **The signal of this process is well below the background.**
- **Different $m_{h'}$ values, from 300 GeV to 1 TeV, are considered at $\sqrt{s} = 13$ TeV and 100 fb^{-1} of luminosity.**
- **The signal would never be accessible, neither with standard nor with upgraded luminosities (due to the huge $t\bar{t}$ background)..**

Search for h' Higgs boson in $h' \to hh \to bb\gamma\gamma$

- The on-shell SM Higgs pair production from h', followed by their decays $h' \to hh \to bb\gamma\gamma$, is shown in this Feynman diagram.



- This process has smaller cross section than $\sigma(pp \to h' \to hh \to 4b)$ but is more promising due to the clean di-photons trigger with excellent mass resolution and low background contamination.
- Utilizing the above mentioned BP, one finds $BR(h' \to hh) = 0.26$, and the production cross section for the process $pp \to h'$ at a center-of-mass energy of $\sqrt{s} = 14$ TeV is $\sigma(pp \to h') = 163.4$ fb.
- Total cross section for the process $pp \to h' \to hh \to \bar{b}b\gamma\gamma$ is estimated to be of the order of 0.12 fb.
- Although $\sigma(pp \to h' \to hh \to b\bar{b}\gamma\gamma)$, is smaller compared to $\sigma(pp \to h' \to hh \to 4b)$, we find it more promising due to several factors.
- The clean di-photons trigger offers excellent mass resolution and minimal background contamination, which enhances the signal sensitivity.



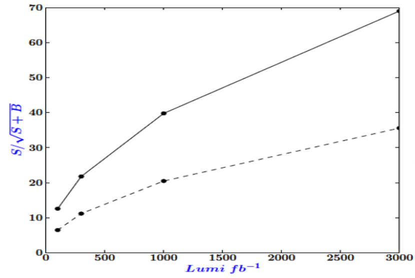
- **We present the distributions of the signal and background with respect to various variables: E_T (transverse energy), $M_{\gamma\gamma}$ (diphoton invariant mass), $M_{b\bar{b}}$ (b-jet invariant mass), and $M_{\gamma\gamma b\bar{b}}$ (diphoton and b-jet invariant mass combination).**

- **The event rates presented after applying acceptance cuts. These cuts help select events that meet specific criteria, ensuring that only relevant events are considered in the analysis.**

- **Signal (for two h' mass values) and continuum background events in the $\gamma\gamma b\bar{b}$ channel as a function of several mass selection cuts. The energy is $\sqrt{s} = 13$ TeV whereas the luminosity is 100 fb^{-1}.**

Applied cut	Signal, $m_{h'} = 300$	Signal, $m_{h'} = 480$	Continuum background
After acceptance cuts	626	237	4758
$M_{\gamma\gamma} \leq 135$ GeV	625	234	4375
$M_{\gamma\gamma} \geq 115$ GeV	616	223	182
$M_{b\bar{b}} \leq 145$ GeV	536	210	98
$M_{b\bar{b}} \geq 105$ GeV	351	86	30

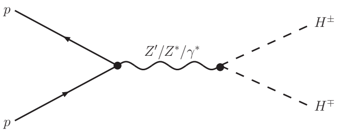
- **Significance of the $h' \to \gamma\gamma b\bar{b}$ signal (for $m_{h'} = 300$ and 480 GeV) versus the luminosity**
- **Number of events for signal and background for variable luminosity.**



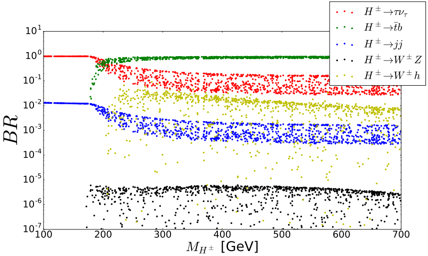
- **Data are produced at $\sqrt{s} = 13$ TeV and the points correspond to an integrated luminosity of 100, 300, 1000 and 3000 fb^{-1}. Notice that event rates are computed after implementing the acceptance cuts.**

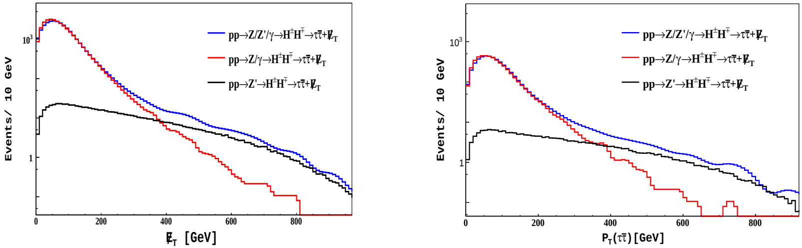
Searching for Charged Higgs Bosons in the BLSSM

- While single $H^{\pm}$ production here is not dissimilar from the MSSM case, a notable difference emerges in the case of double $H^{\pm}$ production.
- In the MSSM cross sections of $pp \to H^+H^-X$ processes are small, hence charged Higgs boson pairs are never produced resonantly. In the BLSSM, with $M_{Z'} > 2M_{H^{\pm}}$ is naturally realized.



- Such a signal is best searched for via the $\tau\nu_\tau$ and jj channels.





- **The total cross section for $pp \to Z' \to H^+H^- \to \tau\bar{\tau} + \not{E}_T$ at 14 TeV, which is already a significant 2.5×10^{-3} pb, through the effect of the interference is enhanced by more than one order of magnitude.**

- **Heavy Z' pushes the final state particles to the high end of these distributions, which is not the case for the MSSM wherein the final state particles cannot be extracted from the huge irreducible background existing at low values of these kinematic observables.**

- **Imposing a minimum requirement on $\not{E}_T$ and/or $p_T(\tau\bar{\tau})$ of several hundreds of GeV, one should be able to extract a BLSSM signal.**

- **The drawback of this approach is that event rates for the signal might turn out be rather small in the end, so that event samples generated by the HL-LHC may indeed be needed to pursue this analysis.**

Conclusions

- **BLSSM nicely combines the theoretically appealing features of SUSY with key experimental evidence of Beyond the SM physics in the form of neutrino masses.**
- **We highlighted the striking feature of the BLSSM in the Higgs sector, in the form of a peculiar decay in the BLSSM is $h' \to hh$.**
- **We have shown that the associate $\gamma\gamma bb$ signature can be spectacularly visible over a wide mass interval, from, say, 300 to 480 GeV.**
- **We also assessed the scope of the High Luminosity Large Hadron Collider (HL-LHC) in accessing charged Higgs bosons ($H^{\pm}$) produced in pairs from Z' decays. We show that, by pursuing both di-jet and tau-neutrino decays, several signals can be established for $H^{\pm}$.**
- **In short, the BLSSM represents a viable realization of SUSY, compliant with all current data and giving distinctive signatures at the LHC which will enable one to disentangle it from alternative BSM scenarios.**

Thank you