Higgs Sector in B-L Supersymmetric Standard Model

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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.**

Superfield	Spin-0	Spin-$\frac{1}{2}$	Generations	$\mathbb{G}_{SM} \otimes U(1)_{B-L}$
$\hat{Q}$	$\tilde{Q}$	Q	3	$(\mathbf{3}, \mathbf{2}, \frac{1}{6}, \frac{1}{3})$
$\hat{d}^c$	$\tilde{d}^c$	d^c	3	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3}, -\frac{1}{3})$
$\hat{u}^c$	$\tilde{u}^c$	u^c	3	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}, -\frac{1}{3})$
$\hat{L}$	$\tilde{L}$	L	3	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, -1)$
$\hat{E}^c$	$\tilde{e}^c$	e^c	3	$(\mathbf{1}, \mathbf{1}, 1, 1)$
$\hat{N}^c$	$\tilde{N}^c$	N^c	3	$(\mathbf{1}, \mathbf{1}, 0, 1)$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 0)$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\mathbf{1}, \mathbf{2}, \frac{1}{2}, 0)$
$\hat{\chi}_1$	χ_1	$\tilde{\chi}_1$	1	$(\mathbf{1}, \mathbf{1}, 0, -2)$
$\hat{\chi}_2$	χ_2	$\tilde{\chi}_2$	1	$(\mathbf{1}, \mathbf{1}, 0, 2)$

- **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 supersymmetry-breaking terms relevant to the BLSSM, under the usual universality assumptions at the GUT scale, are :**

$$\begin{aligned} -\mathcal{L}_{\rm soft} &= m_0^2 \sum_\phi |\phi|^2 + Y_u^A \tilde{Q} H_2 \tilde{U}^c + Y_d^A \tilde{Q} H_1 \tilde{D}^c + Y_e^A \tilde{L} H_1 \tilde{E}^c + Y_\nu^A \tilde{L} H_2 \tilde{\nu}^c + Y_S^A \tilde{\nu}^c \eta_1 \tilde{S}_2 \\ &+ \left[B \left(\mu H_1 H_2 + \mu' \eta_1 \eta_2 \right) + \frac{1}{2} m_{1/2} \left(\tilde{g}^a \tilde{g}^a + \tilde{W}^a \tilde{W}^a + \tilde{B} \tilde{B} + \tilde{B}' \tilde{B}' \right) + h.c. \right], \end{aligned}$$

- **The $B - L$ symmetry can be radiatively broken by the following non-vanishing Vacuum Expectation Values (VEVs):**

$$\langle \chi_1 \rangle = v_1', \ \text{and}| \ \langle \chi_2 \rangle = v_2'.$$

- **We define $\tan\beta'$ as the ratio of these VEVs ($\tan\beta' = v_1'/v_2'$) in analogy to the MSSM case ($\tan\beta = v_2/v_1$).**

- **After $B-L$ symmetry breaking, the new gauge boson, Z', acquires its mass from the kinetic term of the $B-L$ Higgs fields, $\chi_{1,2}$.**

$$M_{Z'}^2 = g_{BL}^2 v'^2 + \frac{1}{4}\tilde{g}^2 v^2.$$

- **$\tilde{g}$ is the gauge kinetic mixing between $U(1)_Y$ and $U(1)_{B-L}$, The mixing angle between the (SM) Z and (BLSSM) Z' states is given by**

$$\tan 2\theta' = \frac{2\tilde{g}\sqrt{g_1^2+g_2^2}}{\tilde{g}^2 + 16(\frac{v'}{v})^2 g_{BL}^2 - g_2^2 - g_1^2} \lesssim 10^{-3}$$

- **The BLSSM framework allows for the implementation of a type I seesaw mechanism, through**

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

- **Upon the breaking of the $B-L$ symmetry and electroweak symmetry breaking, the neutrino mass matrix M_ν is formed as**

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}, \quad \Longrightarrow \quad m_\nu = -m_D M_R^{-1} m_D^T.$$

- **If $m_D \simeq 10^{-4}$ GeV, *i.e.*, $Y_\nu \simeq 10^{-6}$, which is comparable to the Yukawa coupling Y_E associated with charged leptons.**

- **Consequently, m_ν is estimated to be around 1 eV.**

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.**

- **One obtains the masses of the physical neutral BLSSM Higgs states in terms of the Higgs fields:**

$$H^0_{1,2} = \frac{1}{\sqrt{2}}(v_{1,2} + \sigma_{1,2} + i\phi_{1,2}) \,, \qquad \chi^0_{1,2} = \frac{1}{\sqrt{2}}(v'_{1,2} + \sigma'_{1,2} + i\phi'_{1,2}).$$

- **The CP-odd neutral Higgs mass-squared matrix at the tree-level in the basis $(\phi_1, \phi_2, \phi'_1, \phi'_2)$ is given by**

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

- **The MSSM-like CP-odd Higgs boson, A, is decoupled from the BLSSM-like CP-odd Higgs boson, denoted as A', at the tree level.**

- **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', $m^2_A = \frac{2B_\mu}{\sin 2\beta} \sim m^2_{A'} = \frac{2B_{\mu'}}{\sin 2\beta'} \sim \mathcal{O}(1$ TeV).**

- **The CP-even neutral Higgs mass-squared matrix at the tree-level in the basis $(\sigma_1, \sigma_2, \sigma_1', \sigma_2')$ is given by**

$$\mathcal{M}^2 = \left(\begin{array}{cc} \mathcal{M}^2_{hH} & \mathcal{M}^2_{hh'} \\ (\mathcal{M}^2_{hh'})^T & \mathcal{M}^2_{h'H'} \end{array} \right),$$

- 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).**

- **The BLSSM mass matrix** $\mathcal{M}_{h'H'}$ **reads**

$$\mathcal{M}^2_{h'H'} = \left(\begin{array}{cc} m^2_{A'} c^2_{\beta'} + g^2_{BL} v'^2_1 & -\frac{1}{2} m^2_{A'} s_{2\beta'} - g^2_{BL} v'_1 v'_2 \\ -\frac{1}{2} m^2_{A'} s_{2\beta'} - g^2_{BL} v'_1 v'_2 & m^2_{A'} s^2_{\beta'} + g^2_{BL} v'^2_2 \end{array} \right)$$

with $c_x = \cos x$ **and** $s_x = \sin x$. **Thus, the eigenvalues of this matrix can be given as**

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

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

- **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.**
- **The CP-even physical Higgs mass states can be obtained by diagonalising the Higgs mass-squared matrix given by with a unitary matrix $\mathcal{R}$ as**

$$\mathcal{R}\mathcal{M}^2\mathcal{R}^\dagger = \mathrm{diag}\{m_h^2, m_{h'}^2, m_H^2, m_{H'}^2\}\,.$$

- **A numerical scan confirms that the mass of the h' state can either be lighter or heavier than the mass of the SM-like Higgs boson. However, the other two CP-even states, H and H', are generally found to be quite heavy.**

  As an example of BP that leads to the SM Higgs mass of 125 GeV and second CP even neutral Higgs, h', with a mass of approximately 400 GeV:

  $g_{BL} = 0.67$, $\tilde{g} = -0.64$, $\tan\beta = 11$, $\tan\beta' = 1.3$, **and** $v' = 4.8$ **TeV.** $M_1 = 7.7\times 10^2$ **GeV,** $M_2 = 8.5\times 10^2$ **GeV,** $M_3 = 6.8\times 10^2$ **GeV,** $M_{\tilde{B}'} = 1.5\times 10^3$ **GeV, and soft scalar masses of order** 10^3 **GeV.**

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**

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

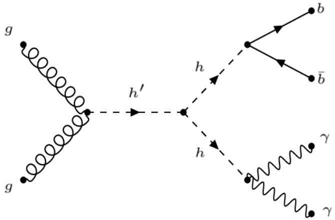
- **The signal of this process is well below the background.**

- **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.**



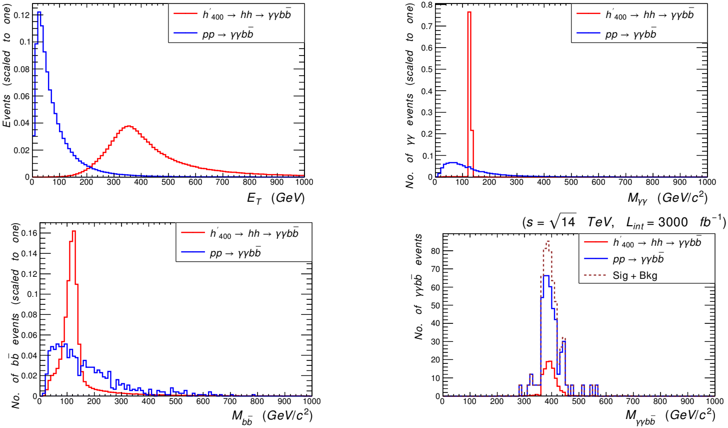
- **This process has smaller cross section than $\sigma(pp \to h' \to hh \to 4b)$ but is more promising due to the clean di-photons trigger with excellent mass resolution and low background contamination.**

- **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.**



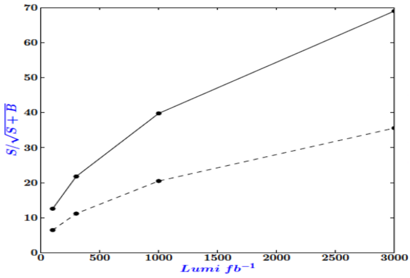
- **We present the distributions of the signal and background with respect to various variables: E_T (transverse energy), $M_{\gamma\gamma}$ (diphoton invariant mass), $M_{b\bar{b}}$ (b-jet invariant mass), and $M_{\gamma\gamma b\bar{b}}$ (diphoton and b-jet invariant mass combination).**

- **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.

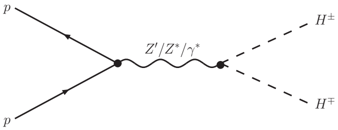


- Data are produced at $\sqrt{s} = 13$ TeV and the points correspond to an integrated luminosity of 100, 300, 1000 and 3000 fb^{-1}. Notice that event rates are computed after implementing the acceptance cuts.

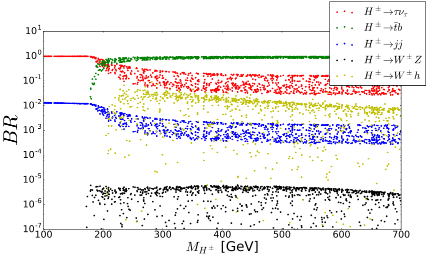
Searching for Charged Higgs Bosons in the BLSSM

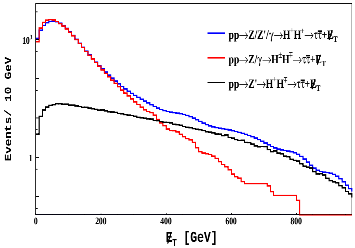
- While single $H^{\pm}$ production here is not dissimilar from the MSSM case, a notable difference emerges in the case of double $H^{\pm}$ production.

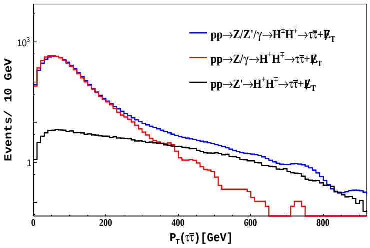
- In the MSSM cross sections of $pp \to H^{+}H^{-}X$ processes are small, hence charged Higgs boson pairs are never produced resonantly. In the BLSSM, with $M_{Z'} > 2M_{H^{\pm}}$ is naturally realized.



- 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