Higgs Sector in Non-Minimal Supersymmetric Standard Model

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Introduction

- **The SM, based on the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$, is in excellent agreement with experimental results.**

- **Three firm observational evidences of new physics beyond the Standard Model :**
  1. **Neutrino Masses**
  2. **Dark Matter**
  3. **Baryon Asymmetry**

- **These three problems may be solved by introducing right-handed neutrinos..**

- **The tremendous success of gauge symmetry in describing the SM indicates that any extension of the SM should be through an extension of its gauge symmetry.**

- **On the other hand, 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.**

Current Status of the MSSM

- **The most simple supersymmetric extension of the SM is know as the MSSM.**

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

- **Universal of soft SUSY breaking terms at GUT scale:** m_0, $m_{1/2}$, A_0.

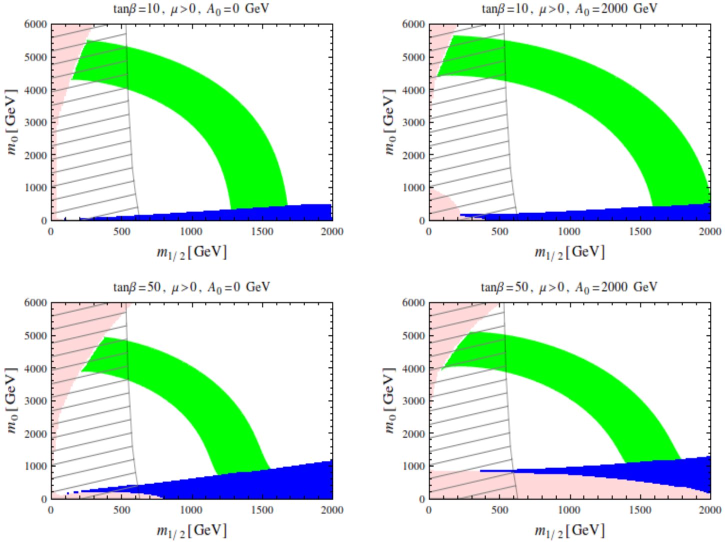
- **Due to** R**-parity conservation, SUSY particles are produced or destroyed only in pairs.The LSP is absolutely stable, candidate for DM.**

- **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 is consistent with the measured value of Higgs mass (**$\sim m125$ **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**

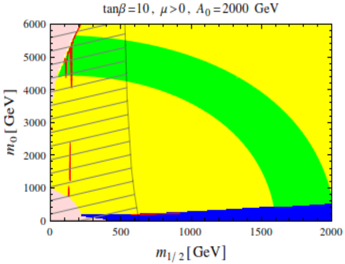


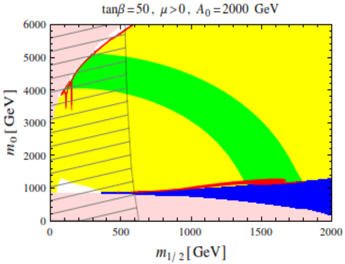
Green region indicates for $124 \lesssim m_h \lesssim 126$ **GeV. Blue region is excluded because the lightest neutralino is not the LSP. Pink region is excluded due to absence of radiative electroweak symmetry breaking. Gray shadow lines denote the excluded area because of** $m_{\tilde{g}} < 1.4$ **TeV.**

Dark Matter Constraints on MSSM parameter space

- **Relic density and DM scattering cross sections on nuclei impose stringent constraints on the parameter space of the MSSM.**
- **With low** $\tan\beta$ (~ 10)**, the region of co-annihilation between LSP and lightest stau corresponds to light** $m_{1/2}$ $(< 500$ **GeV). It is now excluded by the Higgs and gluino mass constraints .**
- **At large** $\tan\beta$**, another region is allowed due to a possible resonance due to s-channel annihilation of the DM pair into fermion-antifermion via the pseudoscalar Higgs boson** A **at** $M_A \simeq 2m_\chi$**.**
- **For** $A_0 = 0$**, a very small part of this region is allowed by the Higgs mass constraint, while for large** A_0 $(\sim 2$ **TeV) a slight enhancement of this part can be achieved.**
- **Combining the collider and astrophysics constraints almost rule out the MSSM.**

W. Abdallah, S.K. (2015)





Non-minimal Supersymmetric Extension of the SM

- **Non-minimal supersymmetric extensions of the SM with a larger particle content or a higher symmetry can evade the problems of the MSSM.**

- **Such models may be well-motivated by Grand Unified Theories (GUTs) and can provide a rich new phenomenology.**

- **Potential examples of non-minimal SUSY models can be classified in two categories:**

  (i) **Extended Higgs sector,** *eg.* **NMSSM**

  (ii) **Extended Gauge sector,** *eg.* $U(1)$**-MSSM**

$B - L$ Supersymmetric Standard Model with Inverse Sessaw

- **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 $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$. The particle content of this model is given as follows:**

Superfield	Spin 0	Spin $\frac{1}{2}$	Generations	$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
$\hat{Q}$	$\tilde{Q}$	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	$(\mathbf{1}, \overline{\mathbf{3}}, -\frac{2}{3}, -\frac{1}{3})$
$\hat{L}$	$\tilde{L}$	L	3	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, -1)$
$\hat{e}^c$	$\tilde{e}^c$	e^c	3	$(\mathbf{1}, \mathbf{1}, 1, 1)$
$\hat{\nu}^c$	$\tilde{\nu}^c$	ν^c	3	$(\mathbf{1}, \mathbf{1}, 0, 1)$
$\hat{s}_1$	$\tilde{S}_1$	S_1	3	$(\mathbf{1}, \mathbf{1}, 0, 2)$
$\hat{s}_2$	$\tilde{S}_2$	S_2	3	$(\mathbf{1}, \mathbf{1}, 0, -2)$
$\hat{H}_d$	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	$(\mathbf{1}, \mathbf{1}, 0, 1)$
$\hat{\chi}_2$	χ_2	$\tilde{\chi}_2$	1	$(\mathbf{1}, \mathbf{1}, 0, -1)$

S.K. (2010)

- **The Superpotential of the leptonic sector in this model is given by**

$$W = -\mu_\eta\, \hat{\chi}_1\, \hat{\chi}_2 + \mu\, \hat{H}_u\, \hat{H}_d + \mu_S\, \hat{s}_2\, \hat{s}_2 - Y_d\, \hat{d}\, \hat{q}\, \hat{H}_d - Y_e\, \hat{e}\, \hat{l}\, \hat{H}_d + Y_u\, \hat{u}\, \hat{q}\, \hat{H}_u + Y_s\, \hat{\nu}\, \hat{\chi}_1\, \hat{s}_2 + Y_\nu\, \hat{\nu}\, \hat{l}\, \hat{H}_u.$$

- **The SUSY soft breaking Lagrangian is given by**

$$-\mathcal{L}_{\rm soft} = m_0^2\Big[|\tilde{q}|^2 + |\tilde{u}|^2 + |\tilde{d}|^2 + |\tilde{l}|^2 + |\tilde{e}_R^*|^2 + |\tilde{\nu}_R^*|^2 + |\tilde{S}_1|^2 + |\tilde{S}_2|^2 + |H_d|^2 + |H_u|^2 + |\chi_1|^2 + |\chi_2|^2\Big] + \Big[Y_u^A \tilde{q} H_u \tilde{u}_R^* + Y_d^A \tilde{q} H_d \tilde{d}_R^* + Y_e^A \tilde{l} H_d \tilde{e}_R^* + Y_\nu^A \tilde{l} H_u \tilde{\nu}_R^* + Y_s^A \tilde{\nu}_R^* \chi_1 \tilde{S}_2\Big] + \left[B(\mu H_1 H_2 + \mu' \chi_1 \chi_2) + h.c.\right] + \frac{1}{2} M_{1/2}\Big[\tilde{g}^a \tilde{g}^a + \tilde{W}^a \tilde{W}^a + \tilde{B}\tilde{B} + \tilde{B}'\tilde{B}' + h.c.\Big],$$

where the trilinear terms are defined as $(Y_f^A)_{ij} = (Y_f A)_{ij}$.

- **After the** $B-L$ **and EW symmetry breaking, the neutrinos mix with the fermionic singlet fields to build up the following** 9×9 **mass matrix:**

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_s \end{pmatrix},$$

where $m_D = \frac{1}{\sqrt{2}} Y_\nu v$ **and** $M_R = \frac{1}{\sqrt{2}} Y_s v'$

$$m_{\nu_l} = m_D M_R^{-1} \mu_s (M_R^T)^{-1} m_D^T,$$

$$m_{\nu_H} = m_{\nu_{H'}} = \sqrt{M_R^2 + m_D^2}.$$

- **One finds that the light neutrino masses can be of order eV, with a TeV scale M_R, if $\mu_s \ll M_R$, and a order one Yukawa coupling Y_ν.**

- **Such large coupling is crucial for testing the BLSSM with IS and probing the heavy neutrinos at the LHC.**

- **The mixings between light and heavy neutrinos are of order $\mathcal{O}(0.01)$. Therefore, the decay widths of these heavy neutrinos into SM fermions are sufficiently large.**

- **In addition, the second SM singlet fermion, S_1, remains light with mass given by**

$$m_{S_1} = \mu_s \simeq \mathcal{O}(1)\ \mathrm{keV},$$

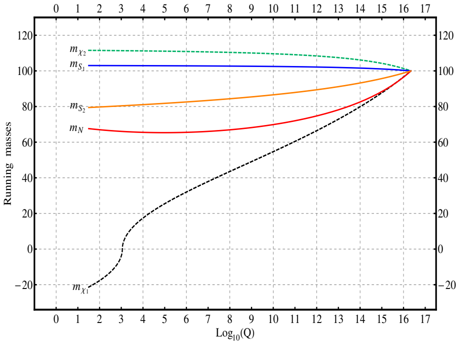
  where S_1 is a sort of inert neutrino that has no mixing with the active neutrinos.

- **The sterile neutrino S_1 can therefore be a good candidate for warm DM.**

E.El-Zant, A. Sil, S.K. (2014)

Radiative $B-L$ symmetry breaking in the BLSSM-IS

- **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 the 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 $m_0 = M_{1/2} = A_0 = 100$ GeV and $Y_{N_3} \sim \mathcal{O}(0.1)$.

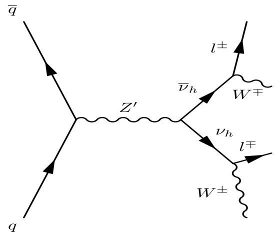
S.K., A. Masiero (2008)

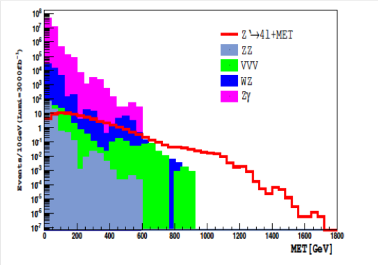
- **The $U(1)_Y$ and $U(1)_{B-L}$ gauge kinetic mixing can be absorbed in the covariant derivative redefinition. In this basis, one finds**

$$M_Z^2 = \frac{1}{4}(g_1^2 + g_2^2)v^2, \qquad M_{Z'}^2 = g_{BL}^2 v'^2 + \frac{1}{4}\tilde{g}^2 v^2.$$

- **A truly smoking-gun signature of the BLSSMIS would be to produce a Z' and heavy neutrinos simultaneously.**

- **Once such a Z' state is produced and decays into $\nu_h \bar{\nu}_h \to WW\ell\ell \to 4\ell + 2\nu_\ell$.**





- **The transverse mass of the '4 lepton+ $E_T^{\rm miss}$' system. The expected SM backgrounds are included . The luminosity assumed here is** $3000\ fb^{(-1)}$**.**
  Huitu, SK, Okada, Rai (2008)

Higgs Bosons in BLSSM

- **In BLSSM, we have 2 Higgs doublet and 2 Higgs singlet superfields: 12 degrees of freedom**
  - **4 have been eaten by $W^{\pm}$, Z and Z'**
  - **2 neutral pseudoscalar Higgs bosons A**
  - **2 charged Higgs bosons $H^{\mp}$**
  - **4 neutral scalar Higgs bosons h, H**

- **The gauge kinetic term induces mixing at tree level between the $H^0_{1,2}$ and $\chi^0_{1,2}$ in the scalar potential. We write**

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

- **The BLSSM CP-odd neutral Higgs mass matrix, 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 A is decoupled from the BLSSM-like one A'.**

- **Due to the dependence of B_μ on v', one finds**

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

BLSSM CP-even Higgs Bosons

- The BLSSM CP-even neutral Higgs mass matrix, in the basis $(\sigma_1, \sigma_2, \sigma'_1, \sigma'_2)$, is given by

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

  where M^2_{hH} is the usual MSSM neutral CP-even Higgs mass matrix, which leads to the SM-like Higgs boson with mass, at one loop level, of order 125 GeV and a heavy Higgs boson with mass $m_H \sim m_A \sim \mathcal{O}(1 \text{ TeV})$.

- The BLSSM matrix $M^2_{h'H'}$ is given by

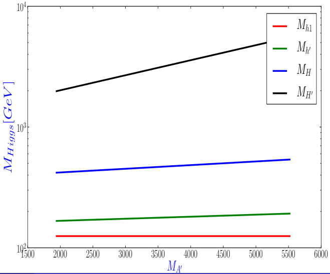
$$M^2_{h'H'} = \begin{pmatrix} m^2_{A'} c^2_{\beta'} + g^2_{BL} v'^2_1 & -\frac{1}{2} m^2_{A'} s_{2\beta'} - g^2_{BL} v'_1 v'_2 \\ -\frac{1}{2} m^2_{A'} s_{2\beta'} - g^2_{BL} v'_1 v'_2 & m^2_{A'} s^2_{\beta'} + g^2_{BL} v'^2_2 \end{pmatrix}.$$

- The eigenvalues of this mass matrix are given by

$$m^2_{h',H'} = \frac{1}{2}\Big[(m^2_{A'} + M^2_{Z'}) \mp \sqrt{(m^2_{A'} + M^2_{Z'})^2 - 4m^2_{A'} M^2_{Z'}}$$

If $\cos^2 2\beta' \ll 1$, one finds

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

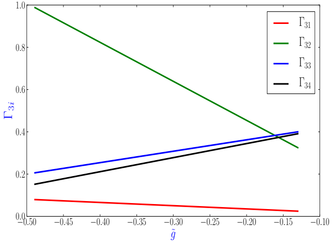


- The mixing matrix $M^2_{hh'}$ is proportional to $\tilde{g}$ and can be written as

$$M^2_{hh'} = \frac{1}{2}\tilde{g} g_{BL} \begin{pmatrix} v_1 v_1' & -v_1 v_2' \\ -v_2 v_1' & v_2 v_2' \end{pmatrix}.$$

- These off-diagonal terms are about one order of magnitude smaller than the diagonal ones.
- They are still crucial for generating interaction vertices between the genuine BLSSM Higgs bosons and the MSSM-like Higgs states.
- The CP-even neutral Higgs mass matrix can be diagonalized by a unitary transformation:

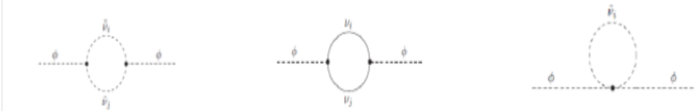
$$\Gamma M^2 \Gamma^\dagger = \mathrm{diag}\{m_h^2, m_{h'}^2, m_H^2, m_{H'}^2\} \quad \& \quad h' = \Gamma_{21}\sigma_1 + \Gamma_{22}\sigma_2 + \Gamma_{23}\sigma_1' + \Gamma_{24}\sigma_2'$$



The mixing of h', Γ_{3i}, versus the gauge kinetic mixing, $\tilde{g}$.

(S)Neutrino Corrections to the Lightest Higgs Boson Mass

- **In BLSSM-IS, the one-loop radiative correction of Higgs mass received significant contribution from right-handed (s)neutrinos (similar to (s)top effect in MSSM).**



- **Such effects can be as large as** $\mathcal{O}(100)$ **GeV.**

- **This enhancement greatly reconciles theory and experiment, by alleviating the so-called 'little hierarchy problem' of the minimal SUSY realization.**

- **All three generations of the (s)neutrino sector may lead to important effects since the neutrino Yukawa couplings are generally not hierarchical.**

- **For** $M_A \gg M_Z$ **and** $\cos 2\beta \simeq 1$**, one finds that**

$$m_h^2 \simeq M_Z^2 + \delta_t^2 + \delta_\nu^2 .$$

- **If** $\tilde{m} \simeq \mathcal{O}(1)$ **TeV,** $Y_\nu \simeq \mathcal{O}(1)$ **and** $M_N \simeq \mathcal{O}(500)$ **GeV, one finds that** $\delta_\nu^2 \simeq \mathcal{O}(100\ \mathrm{GeV})^2$**, thus the Higgs mass is of order** $\sqrt{(90)^2 + \mathcal{O}(100)^2 + \mathcal{O}(100)^2}$ **GeV** $\simeq 170$ **GeV.**

A. Elsayed, S.K., S. Moretti (2012)

BLSSM Higgs (h') Phenomenology

- **The couplings of the h' with up- and down-quarks:**

$$g_{h'uu} = -i\frac{m_u \times \Gamma_{32}}{v \sin\beta}, \qquad g_{h'dd} = -i\frac{m_d \times \Gamma_{31}}{v \cos\beta}.$$

- **The h' couplings with W^+W^- and ZZ gauge boson pairs:**

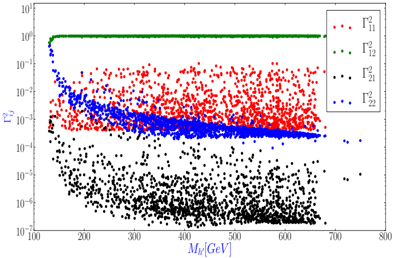
$$g_{h'WW} = ig_2 M_W(\Gamma_{32}\sin\beta + \Gamma_{31}\cos\beta), \qquad g_{h'ZZ} \simeq ig_z M_Z(\Gamma_{32}\sin\beta + \Gamma_{31}\cos\beta)$$

- **The scalar trilinear coupling between h' and hh:**

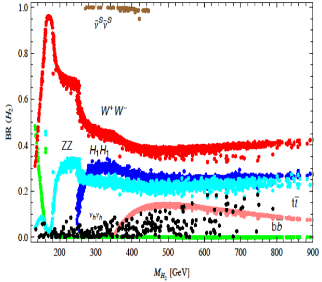
$$\lambda_{h'hh} = -i\frac{\tilde{g}g_{B-L}}{4}\Gamma_{i2}^2(2v_2'\Gamma_{24} - v_1'\Gamma_{23})$$

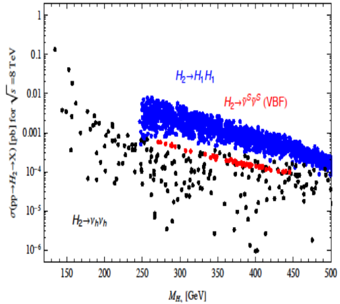
- **This should be compared with the MSSM trilinear scalar coupling**

$$\lambda_{Hhh}^{\rm MSSM} = -i\frac{g_1^2 + g_2^2}{4}v\,[2\sin 2\alpha \sin(\beta+\alpha) - \cos 2\alpha \cos(\beta+\alpha)]$$



- **BRs for h' with $M_{h'} > M_h = 125$ GeV:**
  - $h' \to hh$: $BR\ 30 - 40\%$
  - $h' \to \nu_h \nu_h$: $BR\ 10 - 20\%$.
- $h' \to \tilde{\nu}\tilde{\nu}$, **providing fully invisible decays of the heavy Higgs.**
- **The cross section of** $h' \to hh$ **is** $1 - 10\ fb$ **for** $250 < M_{H_2} < 400$ **GeV.**
- **The most constraining channels,** $H \to WW \to \ell \nu jj$ **and** $H \to WW \to 2\ell 2\nu$ **are also compared to the exclusions at the LHC for** $\sqrt{s} = 8$ **TeV.**
- **The displayed configurations are allowed by the current searches. This is because of the suppression of the heavy Higgs boson cross sections due to the small scalar mixing.**





Basso (2015)

Search for BLSSM h' at the LHC

- **We analyze possible signatures of the lightest genuine BLSSM scalar boson h' when it is rather heavy, with mass between 300 GeV and 1 TeV, at Run 2 of the LHC.**

- **We start the process $pp \to h' \to hh \to 4b$.**

- **The total cross section for the $4b$ final state is given by**

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

and is dominated by ggF which is in turn obtained as (for a CM energy of 13 TeV)

$$\sigma(pp \to h) \times \Gamma_{22}^2 \simeq \mathcal{O}(1)\ \mathrm{pb}$$

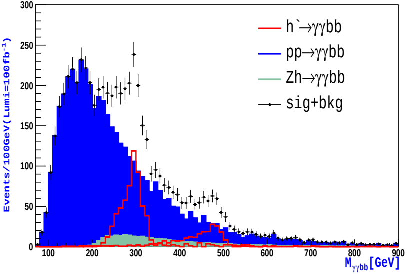
- **For $m_{h'} \simeq 350$ GeV, the $\mathrm{BR}(h' \to hh) \sim 0.5$ and the $\mathrm{BR}(h \to b\bar{b}) \sim 0.6$.**

- **Thus, one finds that $\sigma(pp \to h' \to hh \to 4b)$ in the BLSSM $\sim 10^{-1}$ pb.**

- **Altough the high total cross section, the huge contribution from background b-jet radiation exceed the signal, so that the associated events would not appear as significant over the SM background.**

$hh \to b\bar{b}\gamma\gamma$ decay of a heavy BLSSM Higgs boson

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



- **Number of signal events of $h' \to hh \to bb\gamma\gamma$ for $m_{h'} = 300$ and 400 GeV versus $bb\gamma\gamma$ invariant mass at $\sqrt{s} = 13$ TeV and 100 fb^{-1} of luminosity.**

- **After our preselection is enforced ($|\eta| \leq 2.4$, $p_T \geq 35$ GeV), already at standard luminosity of Run 2, the signal is clearly visible above all backgrounds, both at 300 and 480 GeV.**

Conclusions

- **BLSSM-IS nicely combines the theoretically appealing features of SUSY with key experimental evidence of Beyond the SM physics in the form of neutrino masses.**
- **We have described the emerging particle spectrum, by singling out the dynamics in the three specifically BLSSM-IS sectors: i.e., the Z', Higgs and (s)neutrino parts.**
- **we described Z' production and decay into a variety of leptonic signatures producing via heavy neutrinos.**
- **We highlighted the striking feature of the BLSSM-IS 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, 250 to 500 GeV.**
- **In short, the BLSSM-IS 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.**