Long Lived Light Scalars at the LHC

BHUPAL DEV

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BD, R. N. Mohapatra, Y. Zhang, arXiv:1612.09587 [hep-ph] and ongoing.

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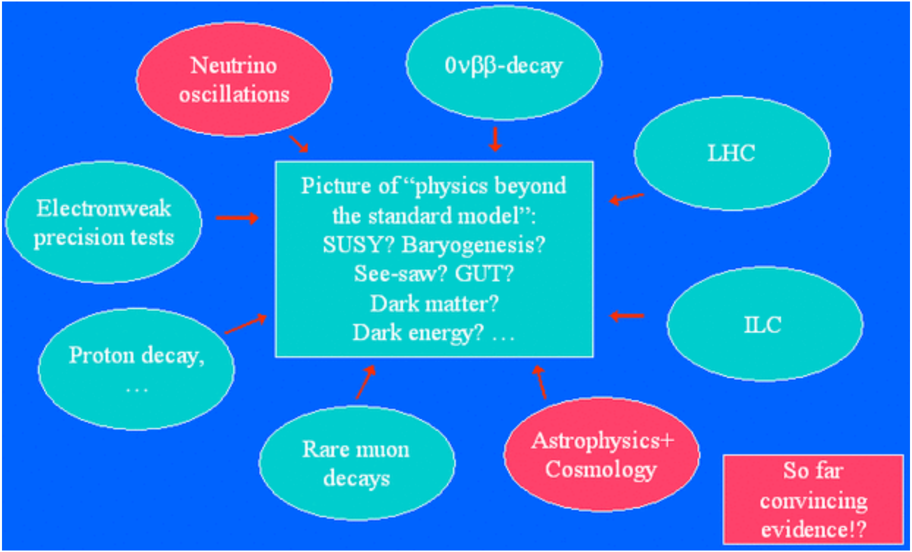
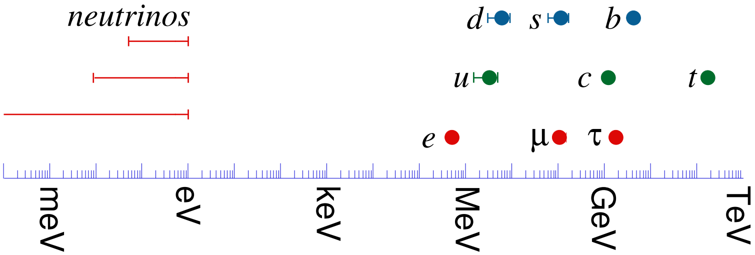
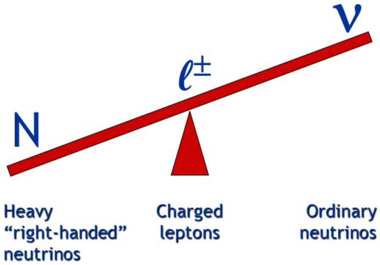


[Figure Courtesy: W. Winter]

Seesaw Mechanism





[Minkowski '77; Mohapatra, Senjanović '79; Yanagida '79; Gell-Mann, Ramond, Slansky '79; Glashow '80]

Origin of $B - L$ Breaking

- Explained in UV-complete seesaw models, e.g. Left-Right, SO(10).
- Spontaneous breaking of $B - L$ involves some BSM Higgs sector.
- Typically predicted to be at $\gtrsim$ multi-TeV scale.
- May/may not have experimentally observable effects.

- A new possibility: the neutral component of the scalar field associated with the $B - L$ breaking can be much lighter.
- Theoretical and experimental constraints force its mixing with other particles to be very small.
- Necessarily long-lived.
- Potentially interesting displaced vertex signatures at the LHC.

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Left-Right Seesaw

[Pati, Salam (PRD '74); Mohapatra, Pati (PRD '75); Mohapatra, Senjanović (PRD '75)]

- Based on the gauge group $\mathcal{G}_{\rm LR} \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.
- Under $\mathcal{G}_{\rm LR}$,

$$Q_{L,i} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i : \left(\mathbf{3}, \mathbf{2}, \mathbf{1}, \frac{1}{3}\right), \qquad Q_{R,i} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i : \left(\mathbf{3}, \mathbf{1}, \mathbf{2}, \frac{1}{3}\right),$$

$$\psi_{L,i} = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_i : (\mathbf{1}, \mathbf{2}, \mathbf{1}, -1), \qquad \psi_{R,i} = \begin{pmatrix} N_R \\ e_R \end{pmatrix}_i : (\mathbf{1}, \mathbf{1}, \mathbf{2}, -1).$$

- RH neutrinos are an essential part of the theory (not put in 'by hand').
- A natural UV-completion of (type-I) seesaw.
- Can be realized at $\gtrsim$ 5 TeV scale, with many observable effects.

Minimal LR Higgs Sector

$$
\begin{aligned}
\Phi &= \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} : (\mathbf{1},\mathbf{2},\mathbf{2},0), \\
\Delta_R &= \begin{pmatrix} \Delta_R^+/\sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+/\sqrt{2} \end{pmatrix} : (\mathbf{1},\mathbf{1},\mathbf{3},2).
\end{aligned}
$$

- $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ by $\langle \Delta_R^0 \rangle \equiv v_R$.
- $SU(2)_L \times U(1)_Y \to U(1)_{\text{em}}$ by $\langle \phi \rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix}$.
- Fermion masses arise from the Lagrangian

$$
\begin{aligned}
\mathcal{L}_Y &= h^a_{q,ij}\bar{Q}_{L,i}\Phi_a Q_{R,j} + \tilde{h}^a_{q,ij}\bar{Q}_{L,i}\tilde{\Phi}_a Q_{R,j} + h^a_{\ell,ij}\bar{\psi}_{L,i}\Phi_a\psi_{R,j} + \tilde{h}^a_{\ell,ij}\bar{\psi}_{L,i}\tilde{\Phi}_a\psi_{R,j} \\
&\quad + f_{ij}\psi^{\mathsf{T}}_{R,i} C i\tau_2 \Delta_R \psi_{R,j} \; + \; \text{H.c.}
\end{aligned}
$$

- The triplet scalar fields are *hadrophobic*.

Physical Higgs Bosons

$$
\begin{aligned}
\phi_1^0 &= \kappa + \frac{1}{\sqrt{2}}\phi_1^{0\,\mathrm{Re}} + \frac{i}{\sqrt{2}}\phi_1^{0\,\mathrm{Im}}, \\
\phi_2^0 &= \kappa' + \frac{1}{\sqrt{2}}\phi_2^{0\,\mathrm{Re}} + \frac{i}{\sqrt{2}}\phi_2^{0\,\mathrm{Im}}, \\
\Delta_R^0 &= v_R + \frac{1}{\sqrt{2}}\Delta_R^{0\,\mathrm{Re}} + \frac{i}{\sqrt{2}}\Delta_R^{0\,\mathrm{Im}}.
\end{aligned}
$$

- 14 scalar fields:
  $\{\phi_1^{0\,\mathrm{Re}},\ \phi_2^{0\,\mathrm{Re}},\ \Delta_R^{0\,\mathrm{Re}},\ \phi_1^{0\,\mathrm{Im}},\ \phi_2^{0\,\mathrm{Im}},\ \Delta_R^{0\,\mathrm{Im}}\},\quad \{\phi_1^\pm,\ \phi_2^\pm,\ \Delta_R^\pm\},\quad \{\Delta_R^{\pm\pm}\}$.
- Two singly-charged pair and neutral states are eaten by $(W^\pm, Z, W_R^\pm, Z_R)$.
- 8 remaining physical fields, denoted by $\{h,\ H_1^0,\ A_1^0,\ H_3^0,\ H_1^\pm,\ H_2^{\pm\pm}\}$.
- Rich phenomenology. [Gunion, Grifols, Mendez, Kayser, Olness (PRD ’89); Polak, Zralek (PLB ’92); Bambhaniya, Chakrabortty, Gluza, Kordiaczyńska, Szafron (JHEP ’14); Dutta, Eusebi, Gao, Ghosh, Kamon (PRD ’14); Bambhaniya, Chakrabortty, Gluza, Jeliński, Kordiaczyńska (PRD ’14, ’15); Maiezza, Nemevsek, Nesti (PRL ’15); BD, Mohapatra, Zhang (JHEP ’16)]

Scalar Potential

$$
\begin{aligned}
\mathcal{V} \quad = \quad & -\mu_1^2 \, \mathrm{Tr}(\Phi^\dagger \Phi) - \mu_2^2 \left[\mathrm{Tr}(\tilde{\Phi} \Phi^\dagger) + \mathrm{Tr}(\tilde{\Phi}^\dagger \Phi) \right] - \mu_3^2 \, \mathrm{Tr}(\Delta_R \Delta_R^\dagger) \\
& + \lambda_1 \left[\mathrm{Tr}(\Phi^\dagger \Phi) \right]^2 + \lambda_2 \left\{ \left[\mathrm{Tr}(\tilde{\Phi} \Phi^\dagger) \right]^2 + \left[\mathrm{Tr}(\tilde{\Phi}^\dagger \Phi) \right]^2 \right\} \\
& + \lambda_3 \, \mathrm{Tr}(\tilde{\Phi} \Phi^\dagger) \mathrm{Tr}(\tilde{\Phi}^\dagger \Phi) + \lambda_4 \, \mathrm{Tr}(\Phi^\dagger \Phi) \left[\mathrm{Tr}(\tilde{\Phi} \Phi^\dagger) + \mathrm{Tr}(\tilde{\Phi}^\dagger \Phi) \right] \\
& + \rho_1 \left[\mathrm{Tr}(\Delta_R \Delta_R^\dagger) \right]^2 + \rho_2 \, \mathrm{Tr}(\Delta_R \Delta_R) \mathrm{Tr}(\Delta_R^\dagger \Delta_R^\dagger) \\
& + \alpha_1 \, \mathrm{Tr}(\Phi^\dagger \Phi) \mathrm{Tr}(\Delta_R \Delta_R^\dagger) + \left[\alpha_2 e^{i\delta_2} \mathrm{Tr}(\tilde{\Phi}^\dagger \Phi) \mathrm{Tr}(\Delta_R \Delta_R^\dagger) + \mathrm{H.c.} \right] \\
& + \alpha_3 \, \mathrm{Tr}(\Phi^\dagger \Phi \Delta_R \Delta_R^\dagger) \, .
\end{aligned}
$$

Neutral Sector

$$\begin{pmatrix} h \\ H_1^0 \\ H_3^0 \\ G_Z \\ A_1^0 \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\xi^2-\frac{\alpha_1^2\epsilon^2}{8\rho_1^2} & \xi & -\frac{\alpha_1\epsilon}{2\rho_1} & 0 & \alpha\xi \\ -\xi & 1-\frac{1}{2}\xi^2-\frac{8\alpha_2^2\epsilon^2}{(4\rho_1-\alpha_3)^2} & -\frac{4\alpha_2\epsilon}{4\rho_1-\alpha_3} & -\alpha\xi & 0 \\ \frac{\alpha_1\epsilon}{2\rho_1} & \frac{4\alpha_2\epsilon}{4\rho_1-\alpha_3} & 1-\frac{\alpha_1^2\epsilon^2}{8\rho_1^2}-\frac{8\alpha_2^2\epsilon^2}{(4\rho_1-\alpha_3)^2} & 0 & 0 \\ 0 & \alpha\xi & 0 & 1-\frac{1}{2}\xi^2 & -\xi \\ -\alpha\xi & 0 & 0 & \xi & 1-\frac{1}{2}\xi^2 \end{pmatrix} \begin{pmatrix} \phi_1^{0\,\mathrm{Re}} \\ \phi_2^{0\,\mathrm{Re}} \\ \Delta_R^{0\,\mathrm{Re}} \\ \phi_1^{0\,\mathrm{Im}} \\ \phi_2^{0\,\mathrm{Im}} \end{pmatrix}$$

$$\begin{aligned} M_h^2 &= \left(4\lambda_1-\frac{\alpha_1^2}{\rho_1}\right)\kappa^2\,, \\ M_{H_1^0}^2 &= \alpha_3(1+2\xi^2)v_R^2+4\left(2\lambda_2+\lambda_3+\frac{4\alpha_2^2}{\alpha_3-4\rho_1}\right)\kappa^2\,, \\ M_{H_3^0}^2 &= 4\rho_1 v_R^2+\left(\frac{\alpha_1^2}{\rho_1}-\frac{16\alpha_2^2}{\alpha_3-4\rho_1}\right)\kappa^2\,, \\ M_{A_1^0}^2 &= \alpha_3(1+2\xi^2)v_R^2+4\left(\lambda_3-2\lambda_2\right)\kappa^2\,. \end{aligned}$$

Charged Sector

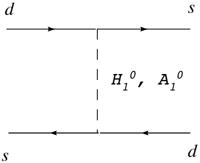
$$\begin{pmatrix} G_L^+ \\ H_1^+ \\ G_R^+ \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\xi^2 & -\xi(1-i\alpha) & 0 \\ \xi(1+i\alpha) & 1-\frac{1}{2}\xi^2-\frac{1}{4}\epsilon^2 & \frac{1}{\sqrt{2}}\epsilon \\ 0 & -\frac{1}{\sqrt{2}}\epsilon & 1-\frac{1}{4}\epsilon^2 \end{pmatrix} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \\ \Delta_R^+ \end{pmatrix},$$

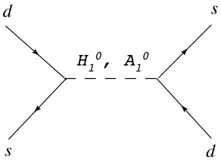
$$M^2_{H_1^\pm} = \alpha_3\left[(1+2\xi^2)v_R^2 + \frac{1}{2}\kappa^2\right].$$

$$M^2_{H_2^{\pm\pm}} = 4\rho_2 v_R^2 + \alpha_3\kappa^2\,.$$

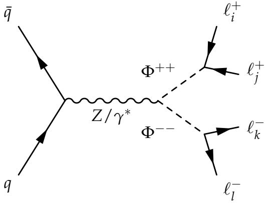
Constraints on Masses

- Bidoublet scalars (H_1^0, A_1^0, $H_1^\pm$) are quasi-degenerate with mass $\sqrt{\alpha_3} v_R \gtrsim 10$ TeV. [An, Ji, Mohapatra, Zhang (NPB '08); Bertolini, Maiezza, Nesti (PRD '14)]





- $M_{H_2^{\pm\pm}} \gtrsim 500$ GeV from LHC searches for same-sign dilepton pair.



- No available constraints (before our paper) on H_3^0 and it can be much lighter, depending on the scalar quartic couplings.

Light Scalar

- Decoupling H_1^0, A_1^0 from the neutral scalar mass matrix, we are left with $\{h, H_3^0\}$ (where h is the SM Higgs):

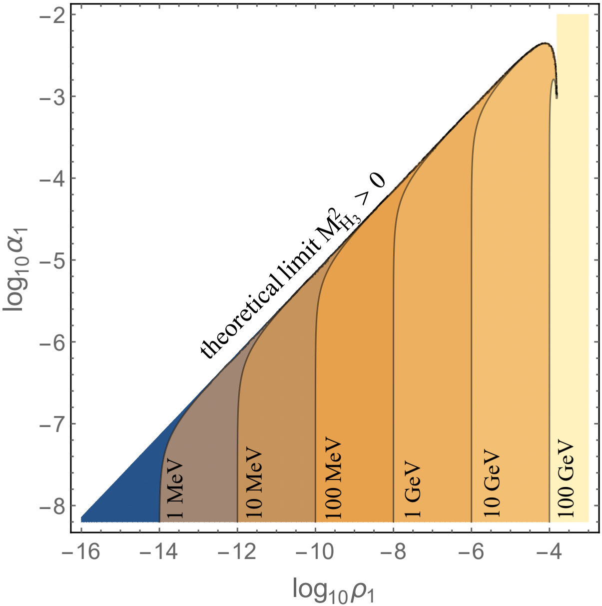
$$\mathcal{M}_{\rm neutral} \; = \; \left(\begin{array}{cc} 4\lambda_1\epsilon^2 & 2\alpha_1\epsilon \\ 2\alpha_1\epsilon & 4\rho_1 \end{array} \right) v_R^2 \, .$$

- In the limit of $m^2_{H_3^0} \ll m_h^2$, we get

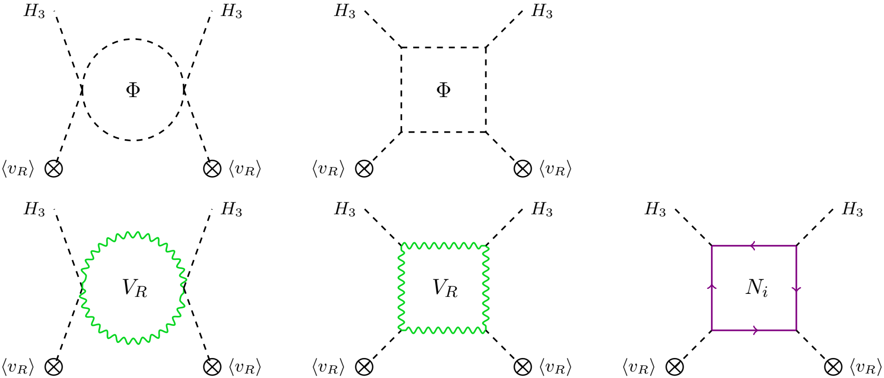
$$\begin{aligned} m_h^2 \; & \simeq \; 4\lambda_1\epsilon^2 v_R^2 = 4\lambda v_{\rm ew}^2 \, , \\ m_{H_3}^2 \; & \simeq \; 4\rho_1 v_R^2 - \sin^2\theta_1 \, m_h^2 \, , \end{aligned}$$

  with the $h - H_3^0$ mixing angle $\sin\theta_1 \simeq \frac{\alpha_1}{2\lambda_1\epsilon}$, which is required to be small.
- The $H_3^0 - H_1^0$ mixing is also suppressed: $\sin\theta_2 \simeq \frac{4\alpha_2\epsilon}{\alpha_3}$.
- H_3^0 talks to the SM sector only through these two mixings.

Possible Parameter Space



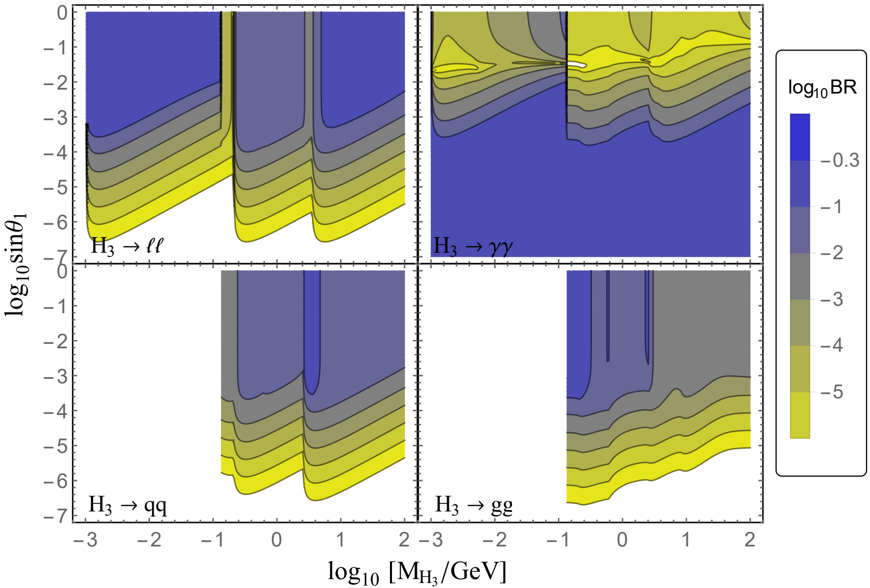
Radiative Corrections



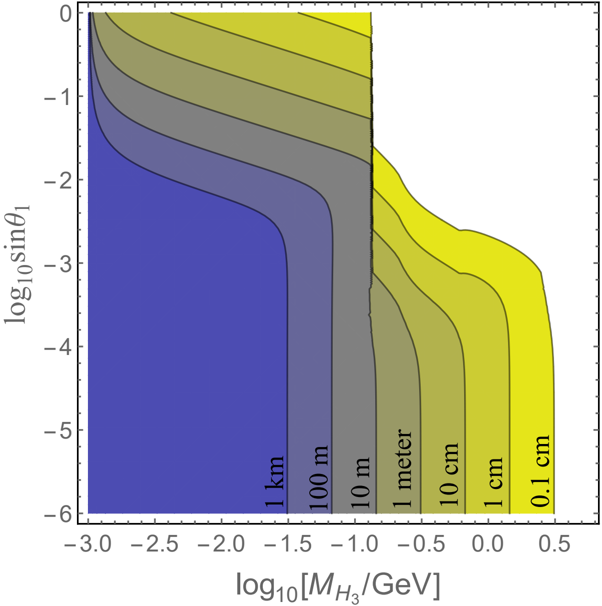
$$\left(m_{H_3}^2\right)^{\text{loop}} \simeq \frac{3}{8\pi^2}\left[\frac{16}{9}\alpha_3^2 + \frac{3}{2}\alpha_3^4 + (g_R^2 + g_{BL}^2)^2 + \frac{1}{2}g_R^4 - f^4\right] v_R^2 \,.$$

Fermion contribution can be canceled against the gauge and scalar terms to keep the scalar light.

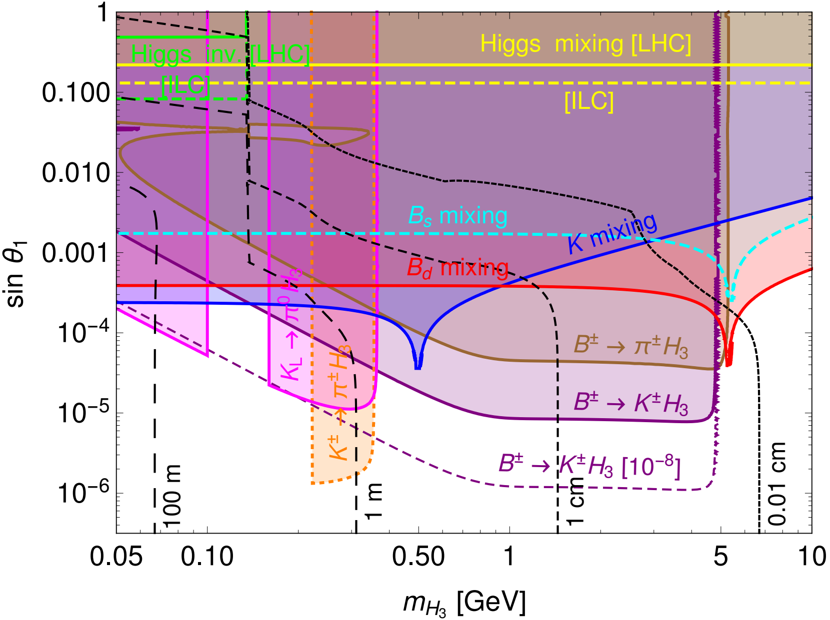
Decays to SM particles



Decay Lifetime



Experimental Constraints



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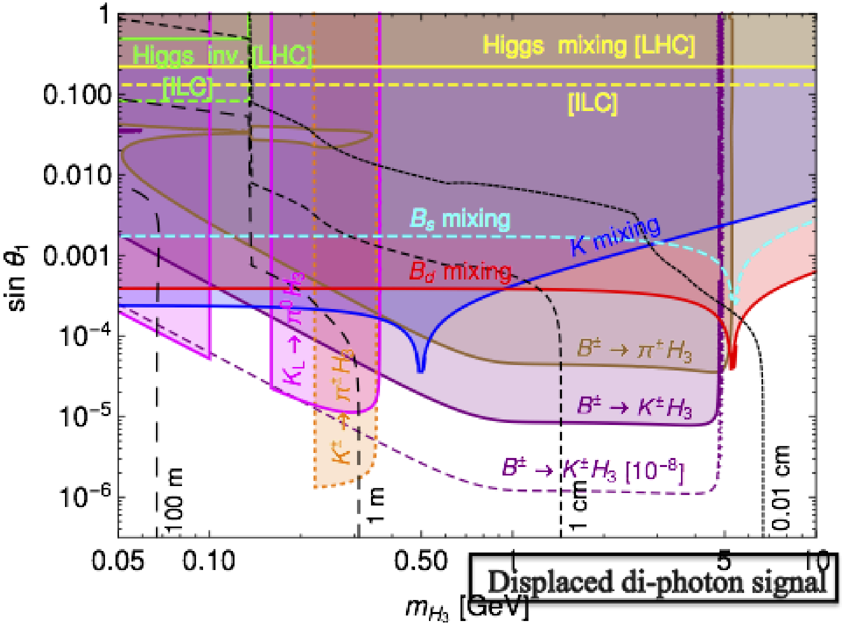
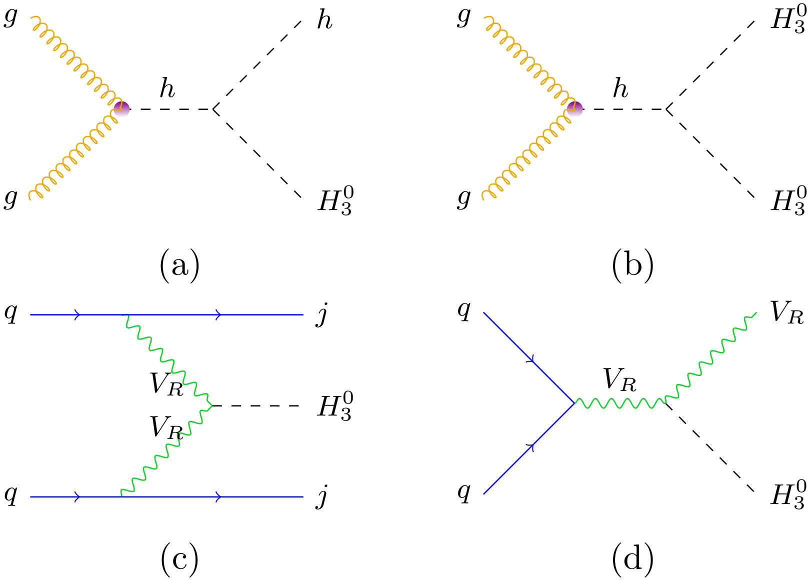
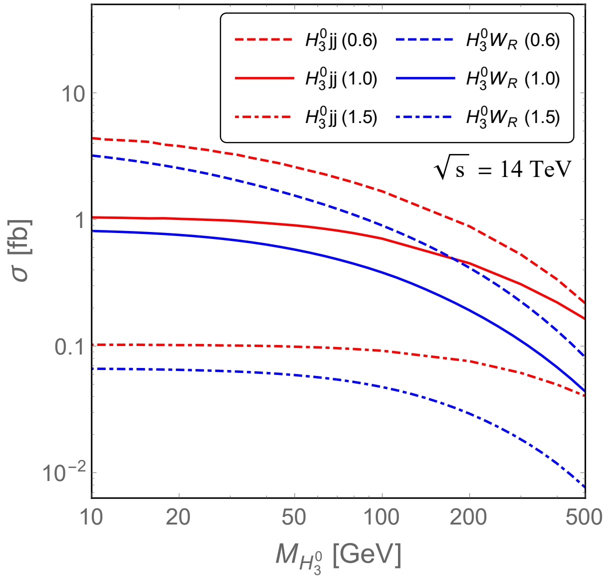


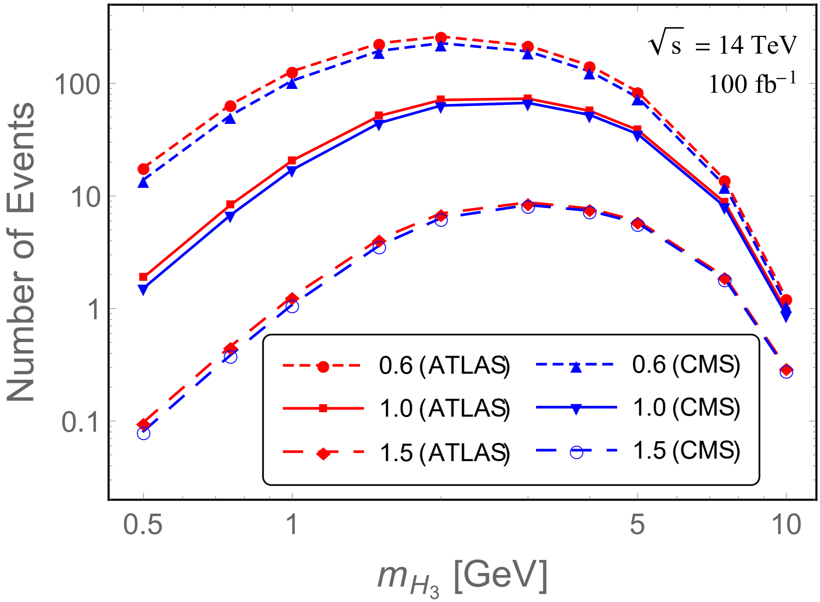
Production at the LHC



Production Cross Section



Displaced Photon Signal



Conclusion

- Discussed the possibility of a light neutral scalar field associated with the local $B - L$ breaking in a Left-Right seesaw framework.
- Low-energy constraints require the mixing of the light scalar with the SM Higgs sector to be small.
- Makes it necessarily long-lived at the LHC.
- Smoking gun signal: displaced, collimated di-photons.
- Good signal sensitivity at $\sqrt{s} = 14$ TeV LHC.