Collider Signatures of the Left-Right Higgs Sector

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$B-L$ breaking

- Natural way to generate neutrino mass.
- Local $B-L$ symmetry.
- Associated Higgs field leaves a physical neutral scalar component.
- Important to find this $B-L$ counterpart to the SM Higgs.
- Experimentally realistic only if $B-L$ breaking scale is within multi-TeV.
- Mass of the new Higgs field is still largely unrestricted.
- Important to scan over the entire allowed range (leave no stone unturned).

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- Distinct signatures depending on whether the scale is above or below m_h.
- For masses $\gg m_h$, production is (typically) kinematically suppressed at the LHC. (Many studies on heavy Higgs searches)
- For masses $\sim m_h$, potentially large mixing with the SM Higgs (disfavored by the LHC Higgs data).
- Mass range $\ll m_h$ largely unexplored so far.

Left-Right Symmetric Model

- Provides a natural framework for type-I seesaw embedding.
- Based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. [Pati, Salam (PRD '74); Mohapatra, Pati (PRD '75); Senjanović, Mohapatra (PRD '75)]
- The main ingredients of seesaw (right-handed neutrinos with Majorana mass) are an essential part of the theory (and not put in 'by hand'):

$$
\begin{aligned}
Q_L &= \begin{pmatrix} u_L \\ d_L \end{pmatrix} \in \left(\mathbf{2}, \mathbf{1}, \frac{1}{3}\right) \overset{\mathcal{P}}{\longleftrightarrow} Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \in \left(\mathbf{1}, \mathbf{2}, \frac{1}{3}\right) \\
\Psi_L &= \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \in (\mathbf{2}, \mathbf{1}, -1) \overset{\mathcal{P}}{\longleftrightarrow} \Psi_R = \begin{pmatrix} N_R \\ e_R \end{pmatrix} \in (\mathbf{1}, \mathbf{2}, -1)
\end{aligned}
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- Can be realized at $v_R \gtrsim 5$ TeV scale, with many observable effects.
- Heavy gauge bosons W_R with spectacular signals at the LHC (and beyond). [Keung, Senjanović (PRL '83)]
- New contributions to $0\nu\beta\beta$ and lepton flavor violation. [Riazuddin, Marshak, Mohapatra (PRD '81); Hirsch, Klapdor-Kleingrothaus, Panella (PLB '96); Tello, Nemevsek, Nesti, Senjanović, Vissani (PRL '10)]

Minimal scalar sector

$$
\begin{array}{c}
SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
\Big\Downarrow \Delta_R\,(\mathbf{1},\mathbf{3},2) \\
SU(2)_L \times U(1)_Y \\
\Big\Downarrow \Phi\,(\mathbf{2},\mathbf{2},0) \\
U(1)_{\rm EM}
\end{array}
$$

$$
\begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix} \Rightarrow H_3^0,\ H_2^{\pm\pm}
$$

$$
\begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow h,\ H_1^0,\ A_1^0,\ H_1^\pm
$$

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$$\begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix} \Rightarrow H_3^0,\ H_2^{\pm\pm}$$

$$\begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow h,\ H_1^0,\ A_1^0,\ H_1^\pm$$

- Eight physical scalars with rich phenomenology. [Gunion, Grifols, Mendez, Kayser, Olness (PRD '89); 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);...]
- Left-handed Δ_L can be decoupled from the TeV scale physics. [Chang, Mohapatra, Parida (PRL '84), Deshpande, Gunion, Kayser, Olness (PRD '91)]
- Allows gauge coupling $g_R \neq g_L$ at the TeV scale.
- Lower limit on $g_R/g_L \geq \tan\theta_w \simeq 0.55$. [Brehmer, Hewett, Kopp, Rizzo, Tattersall (JHEP '15); BD, Mohapatra, Zhang (JHEP '16)]

Scalar Potential

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

[More discussion in A. Patra's talk]

Physical scalar masses

Assume CP conservation and

$$\xi \equiv \langle \phi_2^0 \rangle / \langle \phi_1^0 \rangle = \kappa' / \kappa \simeq m_b / m_t \ll 1 \, ,$$
$$\epsilon \equiv v_{\rm EW} / v_R = \sqrt{\kappa^2 + \kappa'^2} / v_R \ll 1$$

scalars	components	mass squared
h	$\sim \phi_1^{0\,\rm Re}$	$\left(4\lambda_1 - \frac{\alpha_1^2}{\rho_1 - \lambda_1} \right) \kappa^2$
H_1^0	$\sim \phi_2^{0\,\rm Re}$	$\alpha_3 (1 + 2\xi^2) v_R^2 + 4 \left(2\lambda_2 + \lambda_3 + \frac{4\alpha_2^2}{\alpha_3 - 4\rho_1} \right) \kappa^2$
A_1^0	$\sim \phi_2^{0\,\rm Im}$	$\alpha_3 (1 + 2\xi^2) v_R^2 + 4 \left(\lambda_3 - 2\lambda_2 \right) \kappa^2$
$H_1^\pm$	$\sim \phi_2^\pm$	$\alpha_3 (1 + 2\xi^2) v_R^2 + \frac{1}{2} \alpha_3 \kappa^2$
H_3^0	$\sim \Delta_R^{0\,\rm Re}$	$4\rho_1 v_R^2 + \left(\frac{\alpha_1^2}{\rho_1} - \frac{16\alpha_2^2}{\alpha_3 - 4\rho_1} \right) \kappa^2$
$H_2^{\pm\pm}$	$\sim \Delta_R^{\pm\pm}$	$4\rho_2 v_R^2 + \alpha_3 \kappa^2$

Bidoublet scalars

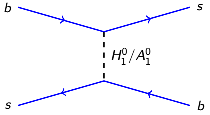
Almost degenerate masses

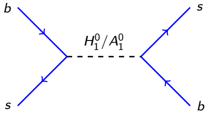
Triplet scalars

Couple to quarks only through mixings: Hadrophobic states

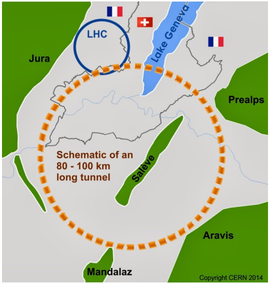
Constraints on the Bidoublet Scalars

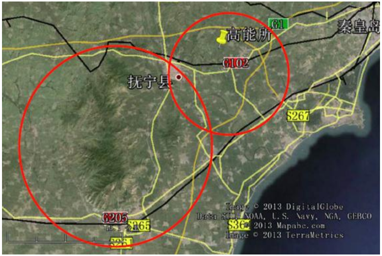
- Contribute to tree-level FCNCs.



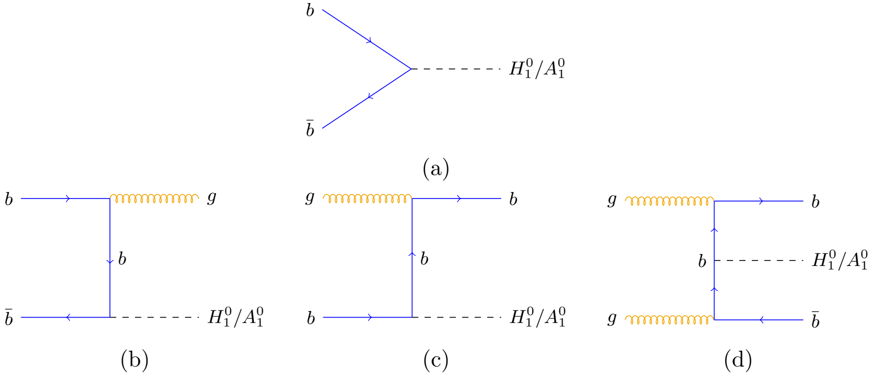


- Severe limits on bidoublet mass: $M_{H_1^0, A_1^0, H_1^\pm} \gtrsim 10\,\mathrm{TeV}$ [Zhang, An, Ji, Mohapatra (NPB '07); Bertolini, Maiezza, Nesti (PRD '14)]
- No hope of finding them at the LHC.
- A good motivation for FCC-hh.

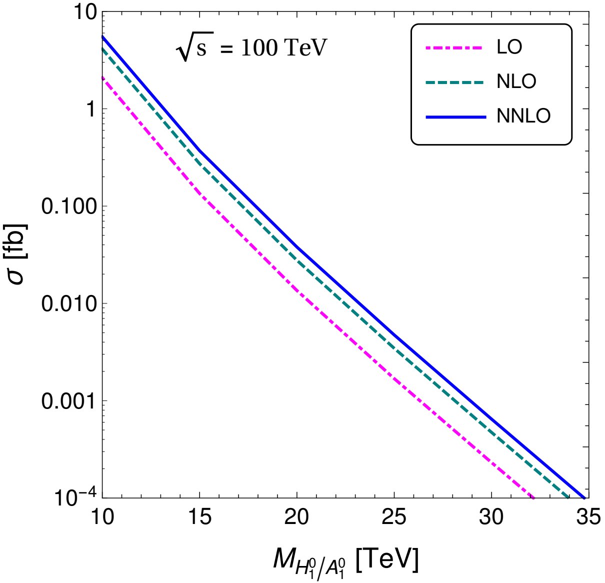




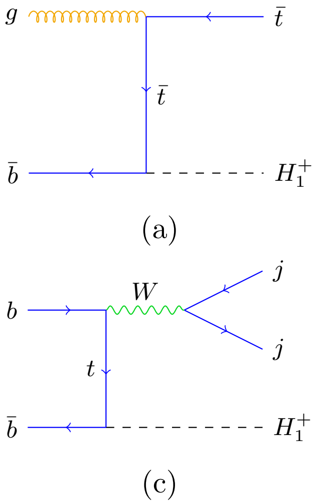
Production of H_1^0, A_1^0



Cross Section for H_1^0, A_1^0



Production of $H_1^{\pm}$



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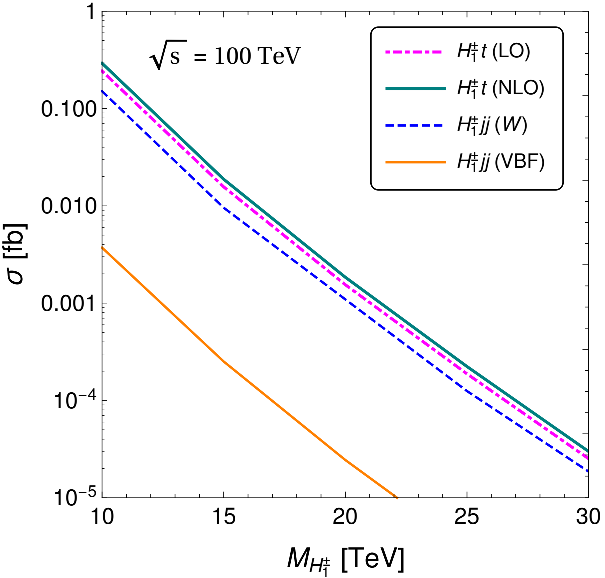
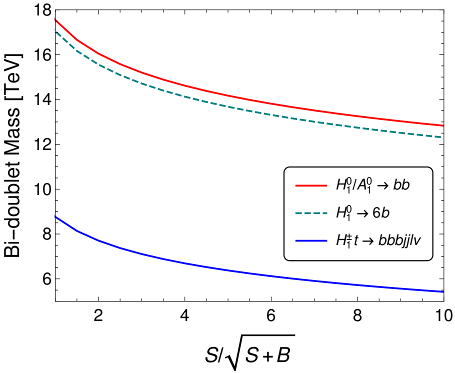


Discovery Channel for H_1^0/A_1^0

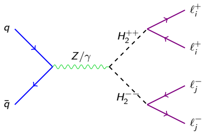
scalar	discovery channel	SM background	$\sigma_{\rm SM}$ [fb]
H_1^0/A_1^0	$H_1^0/A_1^0 \to b\bar{b}$	$b\bar{b}$	1500
	$H_1^0 \to hH_3^0 \to hhh$	$hhh \to 6b$	0.038
		$ZZZ \to 6b$	0.19
$H_1^\pm$	$H^\pm t \to ttb$	$ttb \to bbbjj\ell\nu$	984

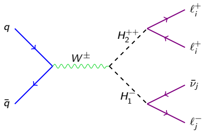


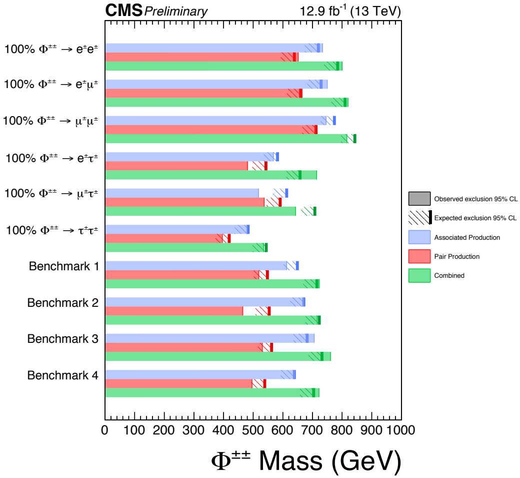
For $H_1^\pm$, another alternative: $pp \to H_2^{\pm\pm} H_1^\mp \to$tri-lepton+MET.

Constraints on Doubly-charged Scalars

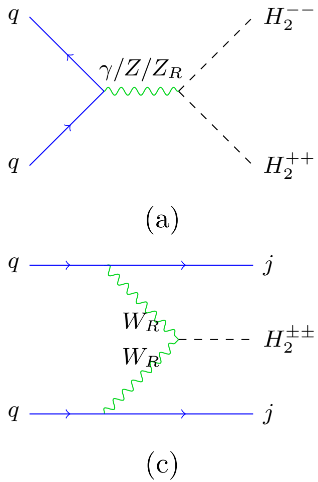
LHC multilepton search limits on doubly-charged scalar: $M_{H_2^{\pm\pm}} \gtrsim 500 - 700\,\mathrm{GeV}$



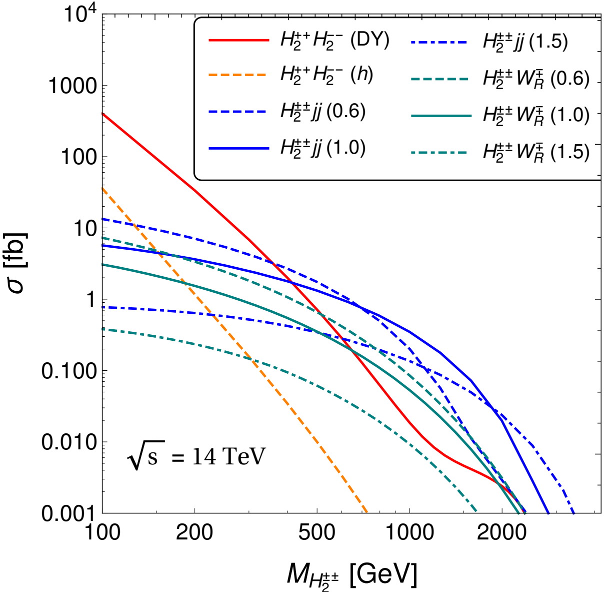




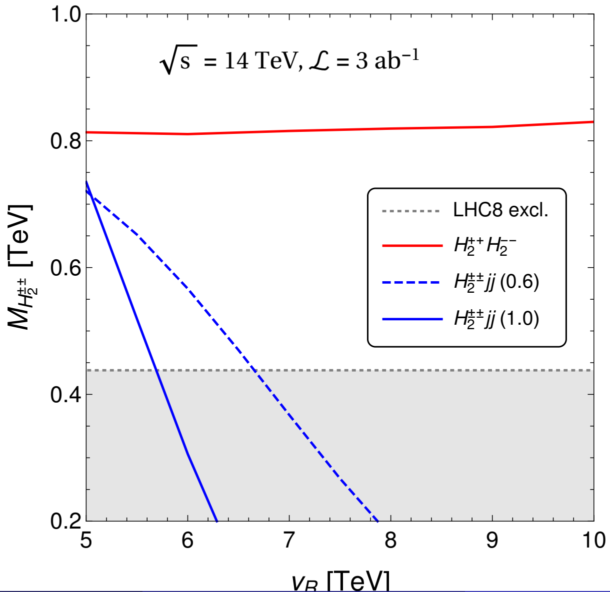
Production of $H_2^{\pm\pm}$



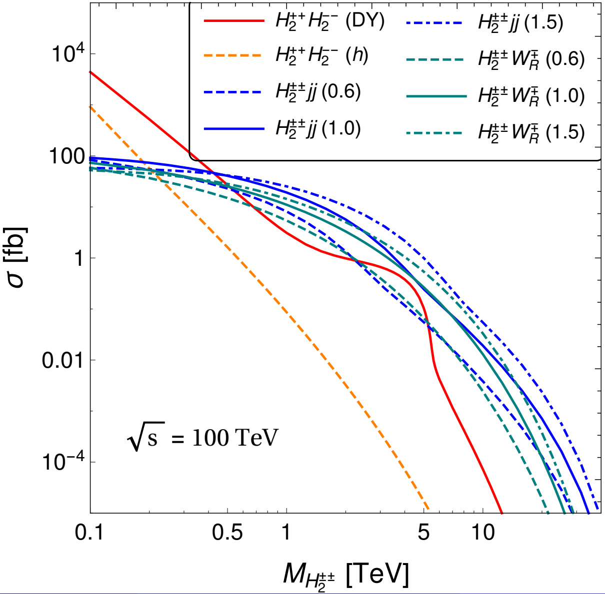
Cross Section for $H_2^{\pm\pm}$ at LHC



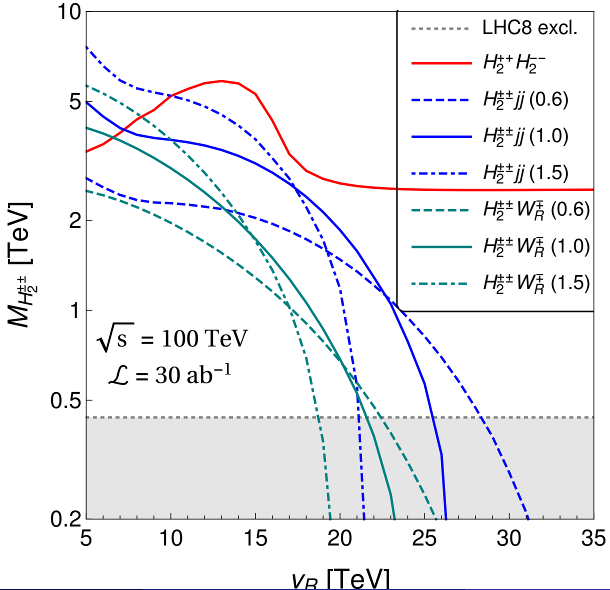
3σ Sensitivity for $H_2^{\pm\pm}$ at 14 TeV



Cross Section for $H_2^{\pm\pm}$ at 100 TeV



3σ Sensitivity for $H_2^{\pm\pm}$ at 100 TeV



Distinction from MSSM Higgs Sector

Field	MSSM	LR model
H_1^0, A_1^0	$b\bar{b}$, $\tau^+\tau^-$ (high $\tan\beta$)	$b\bar{b}$
	tt (low $\tan\beta$)	$W_R^+ W^- \to \ell^+\ell^+ 4j$
H^+	$t\bar{b}t\bar{b}$, $t\bar{b}\bar{\tau}\nu$	$\bar{t}_L b_R$

- $H_1^0/A_1^0 \to \tau^-\tau^-$ mode is suppressed by either the Dirac Yukawa coupling or the left-right mixing.
- New decay modes (absent/suppressed in MSSM): $H_1^0 \to W_R^+ W^-$, $H_1^+ \to W_R^+ Z$, $H_3^0 \to hh$.
- Doubly-charged scalar.

[BD, Mohapatra, Zhang (JHEP '16)]

Light neutral scalar H_3

- At the leading order [mixing constrained to be very small]

$$m_{H_3}^2 \simeq 4\rho_1 v_R^2$$

- Mixing with the SM Higgs [note the inverse dependence on the VEV ratio]

$$\begin{pmatrix} 4\lambda_1\epsilon^2 & 2\alpha_1\epsilon \\ 2\alpha_1\epsilon & 4\rho_1 \end{pmatrix} v_R^2 \quad \Longrightarrow \quad \sin\theta_1 \simeq \frac{\alpha_1}{2\lambda_1}\frac{v_R}{v_{\rm EW}}$$

- Mixing with the heavy doublet scalar H_1 [inducing FCNC couplings]

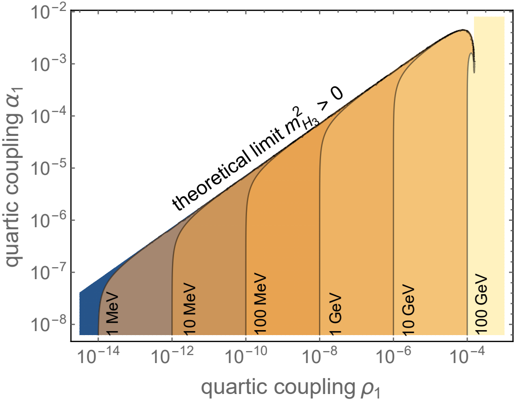
$$\sin\theta_2 \simeq \frac{4\alpha_2}{\alpha_3}\frac{v_{\rm EW}}{v_R}$$

- H_3 talks to the SM particles through:
  - the mixing angles $\sin\theta_{1,2}$: hadrons, $\ell^+\ell^-$, $\gamma\gamma$;
  - RH gauge coupling: $\gamma\gamma$, through the W_R (and $H_1^\pm$, $H_2^{\pm\pm}$) loop.

Mass dependence

- Mass dependence on the quartic couplings at the tree level

$$m_{H_3}^2 \quad \simeq \quad 4\rho_1 v_R^2 - \sin^2\theta_1\, m_h^2\,,$$

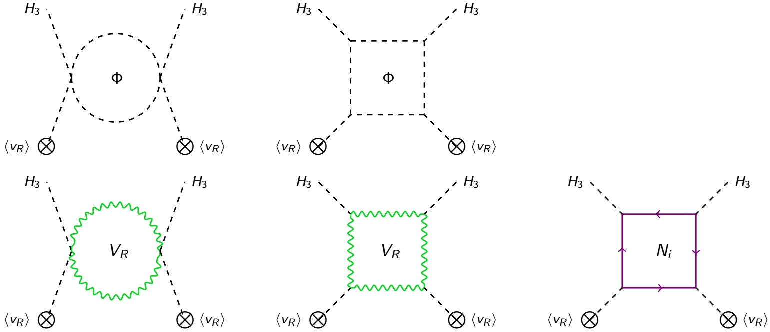


To have a $\sim$ GeV H_3, the parameter $\rho_1 \simeq \mathrm{GeV}^2/4v_R^2 \simeq 10^{-8}$ for $v_R = 5$ TeV.

Radiative Effects

- Mass dependence on the parameters at the 1-loop level

$$\left(m_{H_3}^2\right)^{\rm loop} \simeq \frac{3}{2\pi^2}\left[\frac{1}{3}\alpha_3^2 + \frac{8}{3}\rho_2^2 - 8f^4 + \frac{1}{2}g_R^4 + (g_R^2 + g_{BL}^2)^2\right] v_R^2$$



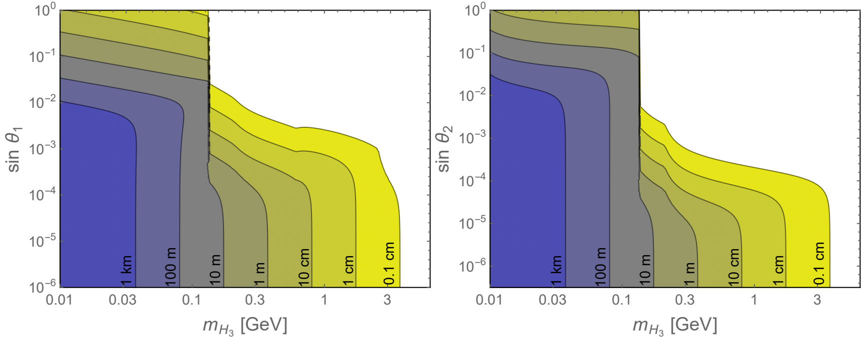
For $m_{H_3} \sim$ GeV and $v_R \simeq$ few TeV, the parameters above are tuned at the level of $\sim {\rm GeV}/\frac{v_R}{4\pi} \simeq 10^{-2}$.

Decay

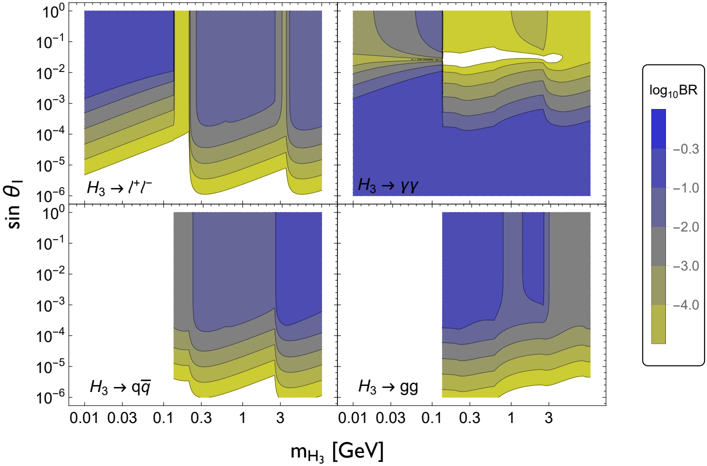
- All the couplings to SM quarks and leptons are proportional to the linear combinations of $\sin\theta_{1,2}$.
- Heavy particle loops for $H_3 \to \gamma\gamma$ suppressed by $v_{\rm EW}/v_R$.

$$\Gamma(H_3 \to q\bar{q}) = \frac{3m_{H_3}}{16\pi}\left[\sum_{i,j}|\mathcal{Y}_{u,\,ij}|^2\,\beta_2^3(m_{H_3}, m_{u_i}, m_{u_j})\Theta(m_{H_3} - m_{u_i} - m_{u_j})\right.$$
$$\left. + \sum_{i,j}|\mathcal{Y}_{d,\,ij}|^2\,\beta_2^3(m_{H_3}, m_{d_i}, m_{d_j})\Theta(m_{H_3} - m_{d_i} - m_{d_j})\right],$$
$$\Gamma(H_3 \to \ell^+\ell^-) = \frac{m_{H_3}}{16\pi}\sum_{i,j}|\mathcal{Y}_{e,\,ij}|^2\,\beta_2^3(m_{H_3}, m_{e_i}, m_{e_j})\Theta(m_{H_3} - m_{e_i} - m_{e_j}),$$
$$\Gamma(H_3 \to \gamma\gamma) = \frac{\alpha^2 m_{H_3}^3}{1024\pi^3}\left|\frac{\sqrt{2}}{v_R}A_0(\tau_{H_1^\pm}) + \frac{4\sqrt{2}}{v_R}A_0(\tau_{H_2^{\pm\pm}})\right.$$
$$\left. + \frac{\sqrt{2}}{v_{\rm EW}}\sum_{f=q,\ell} f_f N_C^f Q_f A_{1/2}(\tau_f) + \frac{\sqrt{2}}{v_R}A_1(\tau_{W_R})\right|^2, \quad \begin{bmatrix} A_0(0) = 1/3 \\ A_1(0) = -7 \end{bmatrix}$$
$$\Gamma(H_3 \to gg) = \frac{G_F\alpha_s^2(m_{H_3})m_{H_3}^3}{36\sqrt{2}\pi^3}\left|\frac{3}{4}\sum_{f=q} f_f A_{1/2}(\tau_f)\right|^2,$$

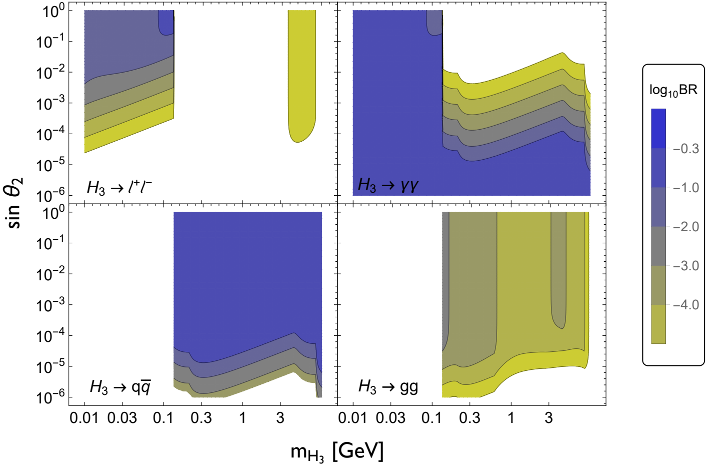
Decay Length



Branching ratios



Branching ratios



K (and B) meson mixing

- "Effective" FCNC coupling for $K^0 - \bar{K}^0$ mixing

  from mixing with heavy doublet scalar H_1 and SM Higgs h

$$\mathcal{L}_{H_3} = \frac{G_F}{4\sqrt{2}} \frac{\sin^2\tilde{\theta}_2}{m_K^2 - m_{H_3}^2 + i m_{H_3}\Gamma_{H_3}} \times \left[\left(\sum_i m_i \lambda_i^{RL} \right)^2 \mathcal{O}_2 + \left(\sum_i m_i \lambda_i^{LR} \right)^2 \tilde{\mathcal{O}}_2 + 2 \left(\sum_i m_i \lambda_i^{LR} \right) \left(\sum_i m_i \lambda_i^{RL} \right) \mathcal{O}_4 \right]$$

$$\sin\tilde{\theta}_2 \equiv \sin\theta_2 + \xi \sin\theta_1 \,, \quad \left[\xi = \langle \phi_2^0 \rangle / \langle \phi_1^0 \rangle, \quad h - H_1 \text{ mixing} \right]$$

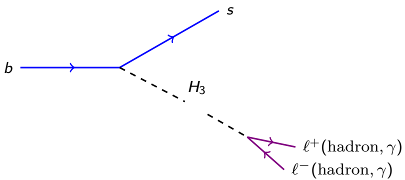
$$\begin{aligned} \mathcal{O}_2 &= [\bar{s}(1-\gamma_5)d][\bar{s}(1-\gamma_5)d] \,, \\ \tilde{\mathcal{O}}_2 &= [\bar{s}(1+\gamma_5)d][\bar{s}(1+\gamma_5)d] \,, \\ \mathcal{O}_4 &= [\bar{s}(1-\gamma_5)d][\bar{s}(1+\gamma_5)d] \,. \end{aligned}$$

$$m_i = \{m_u, m_c, m_t\} \,, \quad \lambda_i^{LR} = V_{L,i2}^* V_{R,i1} \,, \quad \lambda_i^{RL} = V_{R,i2}^* V_{L,i1}$$

- "Resonance" effect when m_{H_3} is close to the Kaon mass:

$$\frac{1}{q^2 - m_{H_3}^2 + i m_{H_3}\Gamma_{H_3}} \to \frac{1}{q^2} \simeq \frac{1}{m_K^2}$$

Flavor-changing meson decay



- Stringent limits from the down-type quark sector

$$K \to \pi\chi\chi\,, \quad B \to K\chi\chi\,, \quad [\chi = \text{hadron}, \ \ell, \ \gamma]$$

- "Visible decays": H_3 decaying **inside detector spatial resolution**

$$d_j \to d_i H_3\,, \quad H_3 \to \chi\chi$$

- "Invisible decays": H_3 decaying **outside detector size**

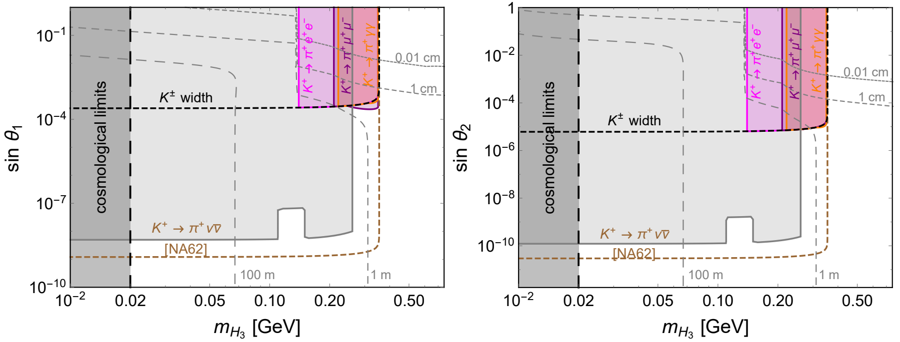
$$d_j \to d_i H_3\,, \quad H_3 \to \text{any}\,(L_{H_3} > R_{\rm detector})$$

List of meson decay limits

	Expt.	meson decay	H_3 decay	E_{H_3}	L_{H_3}	BR/$\underline{N_{\rm event}}$
	NA48/2 ['09]	$K^+ \to \pi^+ H_3$	$H_3 \to e^+e^-$	~ 30 GeV	< 0.1 mm	2.63×10^{-7}
	NA48/2 ['11]	$K^+ \to \pi^+ H_3$	$H_3 \to \mu^+\mu^-$	~ 30 GeV	< 0.1 mm	8.88×10^{-8}
	NA62 ['14]	$K^+ \to \pi^+ H_3$	$H_3 \to \gamma\gamma$	~ 37 GeV	< 0.1 mm	4.70×10^{-7}
	E949 ['09]	$K^+ \to \pi^+ H_3$	any (inv.)	~ 355 MeV	> 4 m	4×10^{-10}
$*$	NA62 ['05]	$K^+ \to \pi^+ H_3$	any (inv.)	~ 37.5 GeV	> 2 m	2.4×10^{-11}
	KTeV ['03]	$K_L \to \pi^0 H_3$	$H_3 \to e^+e^-$	~ 30 GeV	< 0.1 mm	2.8×10^{-10}
	KTeV ['00]	$K_L \to \pi^0 H_3$	$H_3 \to \mu^+\mu^-$	~ 30 GeV	< 0.1 mm	4×10^{-10}
	KTeV ['08]	$K_L \to \pi^0 H_3$	$H_3 \to \gamma\gamma$	~ 40 GeV	< 0.1 mm	3.71×10^{-7}
	BaBar ['03]	$B \to K H_3$	$H_3 \to \ell^+\ell^-$	$\sim m_B/2$	< 0.1 mm	7.91×10^{-7}
	Belle ['09]	$B \to K H_3$	$H_3 \to \ell^+\ell^-$	$\sim m_B/2$	< 0.1 mm	4.87×10^{-7}
	LHCb ['12]	$B^+ \to K^+ H_3$	$H_3 \to \mu^+\mu^-$	~ 150 GeV	< 0.1 mm	4.61×10^{-7}
	BaBar ['13]	$B \to K H_3$	any (inv.)	$\sim m_B/2$	> 3.5 m	3.2×10^{-5}
$*$	Belle II ['10]	$B \to K H_3$	any (inv.)	$\sim m_B/2$	> 3 m	4.1×10^{-6}
	LHCb ['17]	$B_s \to \mu\mu$	–	–	–	2.51×10^{-9}
	BaBar ['10]	$B_d \to \gamma\gamma$	–	–	–	3.3×10^{-7}
	Belle ['14]	$B_s \to \gamma\gamma$	–	–	–	3.1×10^{-6}
$\dagger$	BaBar ['11]	$\Upsilon \to \gamma H_3$	$H_3 \to qq,\ gg$	$\sim m_\Upsilon/2$	< 3.5 m	$[1,\ 80] \times 10^{-6}$
	CHARM ['85]	$K \to \pi H_3$	$H_3 \to \gamma\gamma$	~ 10 GeV	$[480,\ 515]$ m	$\underline{< 2.3}$
	CHARM ['85]	$B \to X_s H_3$	$H_3 \to \gamma\gamma$	~ 10 GeV	$[480,\ 515]$ m	$\underline{< 2.3}$
$*$	SHiP ['15]	$K \to \pi H_3$	$H_3 \to \gamma\gamma$	~ 25 GeV	$[70,\ 125]$ m	$\underline{< 3}$
$*$	SHiP ['15]	$B \to X_s H_3$	$H_3 \to \gamma\gamma$	~ 25 GeV	$[70,\ 125]$ m	$\underline{< 3}$
$*$	DUNE ['13]	$K \to \pi H_3$	$H_3 \to \gamma\gamma$	~ 12 GeV	$[500,\ 507]$ m	$\underline{< 3}$
$*$	DUNE ['13]	$B \to X_s H_3$	$H_3 \to \gamma\gamma$	~ 12 GeV	$[500,\ 507]$ m	$\underline{< 3}$

$*$ future prospects, $\dagger$ flavor-conserving couplings only

$K^{\pm}$ meson limits

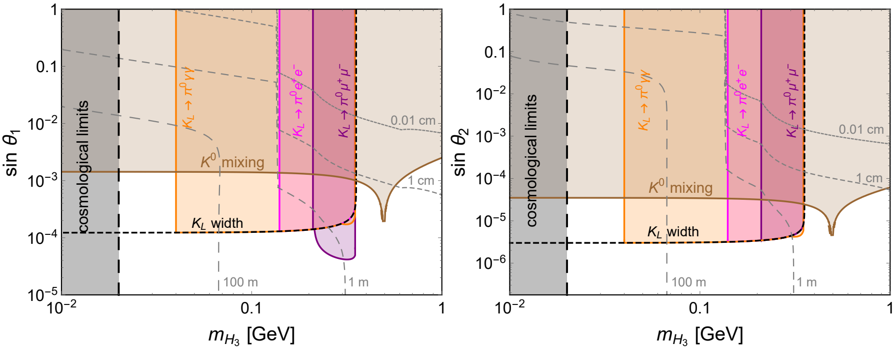


$K^{\pm}$ width limits from 20% of $\Gamma_{\rm total}(K^{\pm})$

$K^{\pm} \to \pi^{\pm} e^+ e^-$:	NA48/2 ['09]	$K^{\pm} \to \pi^{\pm} \nu\bar{\nu}$:	E949 ['09]
$K^{\pm} \to \pi^{\pm} \mu^+ \mu^-$:	NA48/2 ['11]	$K^{\pm} \to \pi^{\pm} \nu\bar{\nu}$:	NA62 (prosepcts)
$K^{\pm} \to \pi^{\pm} \gamma\gamma$:	NA62 ['14]		

(dashed gray lines indicate the proper lifetime of H_3)

K^0 meson limits



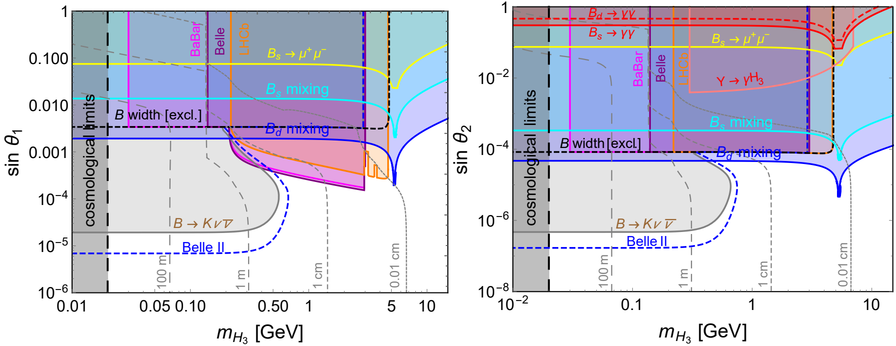
$K^0 - \bar{K}^0$ mixing limits from 50% of experimental central value [1.74×10^{-12} MeV]
(large theoretical uncertainties)

K_L width limits from 20% of $\Gamma_{\text{total}}(K_L)$

$K_L \to \pi^0 e^+ e^-$:	KTeV ['03]
$K_L \to \pi^0 \mu^+ \mu^-$:	KTeV ['00]
$K_L \to \pi^0 \gamma\gamma$:	KTeV ['08]

(dashed gray lines indicate the proper lifetime of H_3)

B meson limits



$B_{d(s)} - \bar{B}_{d(s)}$ mixing limits from CKM fitter $[9.3\,(2.7) \times 10^{-11(9)}$ MeV$]$

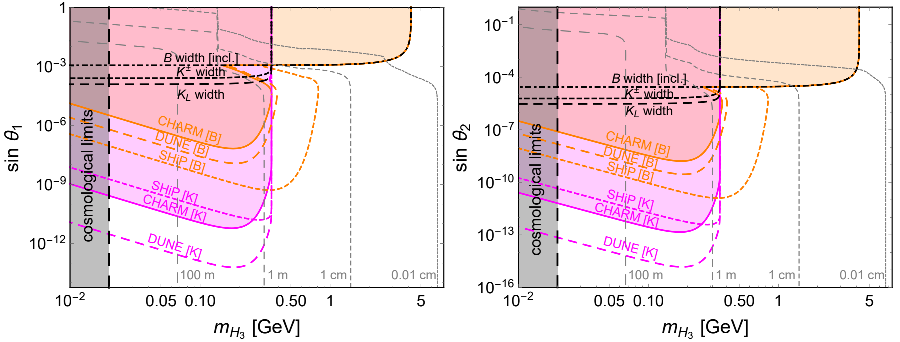
[Charles et al '15]

B width limits from 20% of $\Gamma_{\mathrm{total}}(B)$

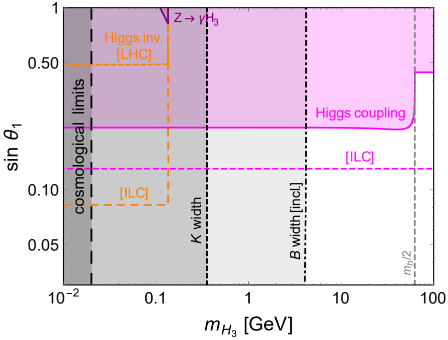
$B \to K\ell^+\ell^-$: BaBar ['03], Belle ['09], LHCb ['12]
$B \to K\nu\bar{\nu}$: BaBar ['13], Belle II (prospects)
$B_s \to \mu^+\mu^-$: LHCb ['17]
$B_{d(s)} \to \gamma\gamma$: BaBar (Belle) ['10 ('14)]
$\Upsilon \to \gamma H_3$: BaBar ['11]

(dashed gray lines indicate the proper lifetime of H_3)

Beam dump experiments

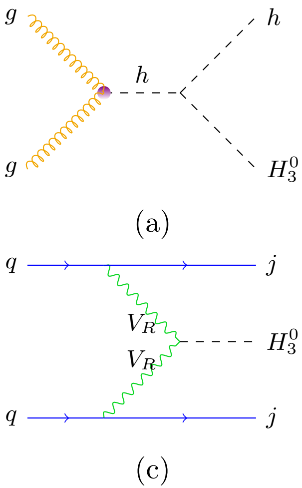


$$\begin{aligned}
\text{CHARM}: \quad & N_{\text{PoT}} = 2.4 \times 10^{18} & \Longrightarrow \quad & 1.2 \times 10^{17}\, K, \quad 2.6 \times 10^{10}\, B \\
\text{SHiP}: \quad & N_{\text{PoT}} = 2 \times 10^{20} & \Longrightarrow \quad & 8 \times 10^{18}\, K, \quad 7 \times 10^{13}\, B \\
\text{DUNE}: \quad & N_{\text{PoT}} = 5 \times 10^{21} & \Longrightarrow \quad & 7.8 \times 10^{21}\, K, \quad 5.5 \times 10^{12}\, B
\end{aligned}$$



- The $h - H_3$ mixing changes all the SM Higgs couplings by a factor of $\cos\theta_1$. [Falkowski, Gross, Lebedev (JHEP '15); Profumo, Ramsey-Musolf, Wainwright, Winslow (PRD '15)]
- Invisible decay $h \to H_3 H_3$ (H_3 decaying outside detector) opens when $m_{H_3} < m_h/2$. LHC limits and ILC prospects [Peskin '12; Baer *et al.* '13]
- Rare decay $Z \to \gamma H_3$ ($H_3 \to \gamma\gamma$), induced by the SM fermion loops. [Jaeckel, Spannowsky (PLB '15)]

Production of H_3^0

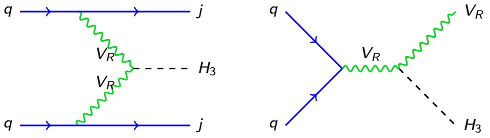


Production at LHC (and FCC-hh)

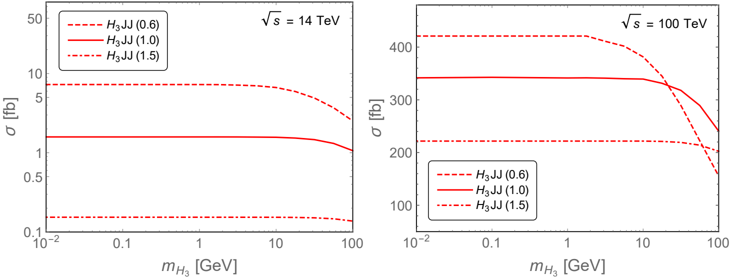
- SM Higgs portal is highly suppressed by $\sin\theta_1$

$$pp \to h^{(*)} \to hH_3/H_3H_3 \quad (\propto \sin\theta_1)$$

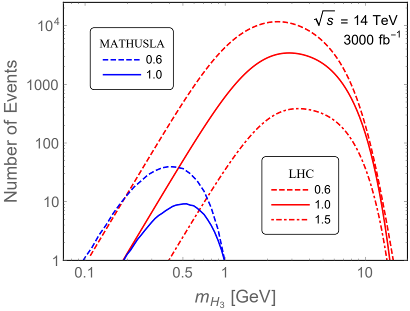
- Heavy VBF production & associated production:



(subleading)



Displaced photon signal



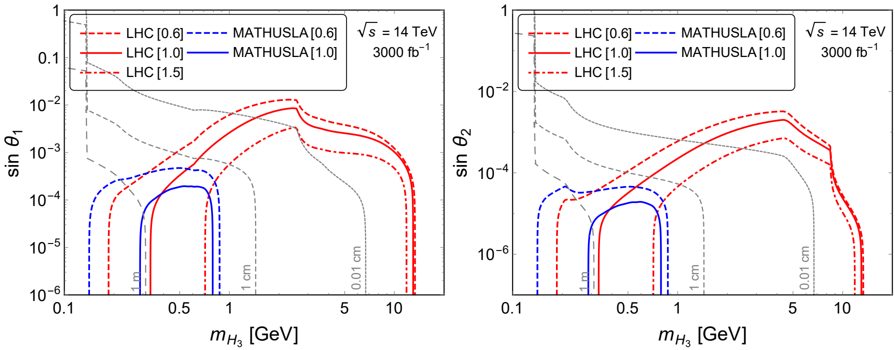
- Mixing angles $\sin\theta_{1,2}$ are constrained to be very small ($\lesssim 10^{-4}$) by the meson data.
- $H_3 \to \gamma\gamma$, highly collimated diphoton signal, dominated by the W_R loop, only suppressed by v_R.
- H_3 tends to be long-lived if it is light:

$$\text{GeV mass} \Longrightarrow L_0 \simeq \mathrm{cm}$$

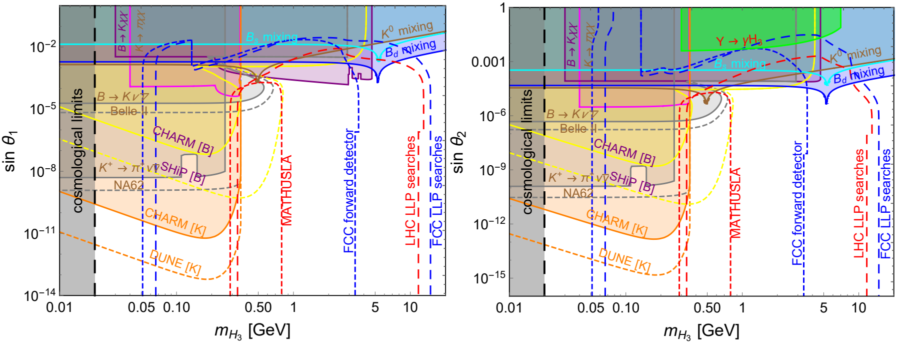
$$100\,\mathrm{cm} \lesssim \left(\frac{E_{H_3}}{m_{H_3}}\right) L_0 \lesssim 100\,\mathrm{m}$$

- Displaced vertex signal at the LHC.
- Lifetime frontier: **MATHUSLA** (MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles) [Chou, Curtin, Lubati (PLB '16)]

Expected LLP sensitivities



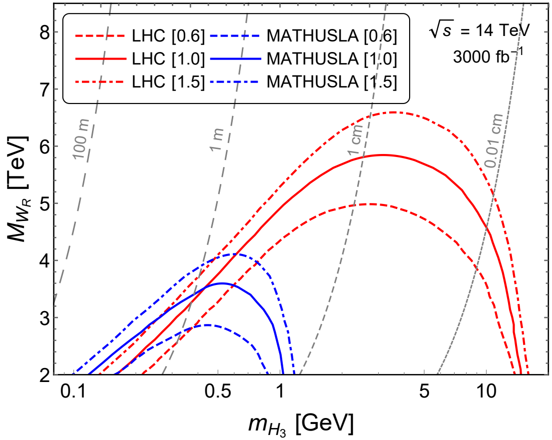
- LHC: Assuming 10 LLP signal events.
- MATHUSLA: Assuming 4 signal events (since virtually background-free).
  - Effective solid angle very small, $\lesssim 10\%$.
  - "Thin"-disk-like compared to the decay length of ~ 100 m.
- Larger regions probable at FCC-hh and forward LLP detector therein.



The LLP searches at LHC and MATHUSLA (and future 100 TeV collider FCC-hh) are largely complementary to the meson limits from beam-dump (including SHiP)

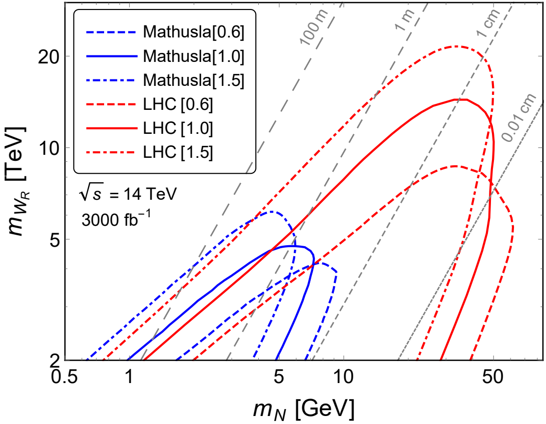
- H_3 mass ranges complementary.
- Mixing angles $\sin\theta_{1,2}$ complementary.
  ($H_3 \to \gamma\gamma$ does not depend on $\sin\theta_{1,2}$)

L-R seesaw sensitivity



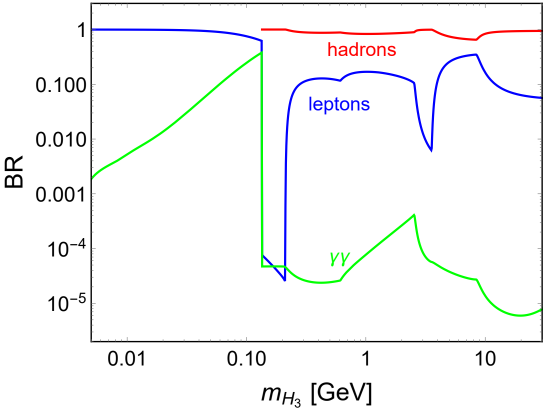
Larger regions probable at FCC-hh and forward LLP detectors therein.

L-R seesaw sensitivity



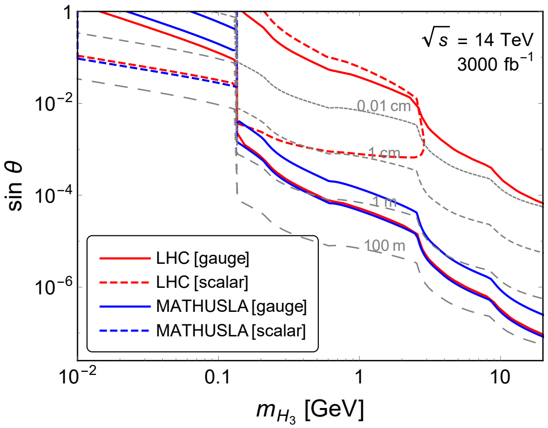
Larger regions probable at FCC-hh and forward LLP detectors therein.

$U(1)$ Case



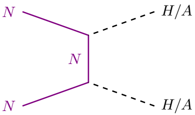
$\gamma\gamma$ is no longer the dominant decay mode.

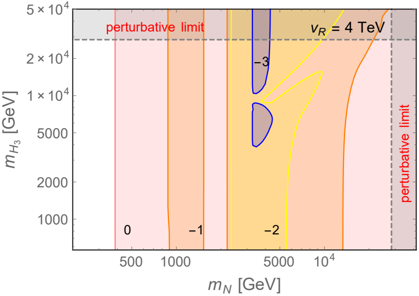
$U(1)$ Sensitivity

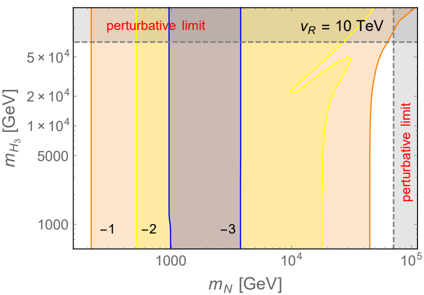


Production can be through Z' portal or Higgs portal.

Constraints from Leptogenesis







[BD, Mohapatra, Zhang (NPB '17)]

Conclusion

light scalar in minimal left-right model

neutral component from $SU(2)_R$-triplet

mixings to SM Higgs and flavor-changing heavy doublet
are constrained to be small

mostly decays into diphoton (through W_R loop)

long-lived particle ($\sim$ 0.1 to 10 GeV)

high intensity frontier

SHiP: $B \to KH_3$, $H_3 \to \gamma\gamma$

high energy frontier

LHC+MATHUSLA: LLP searches

$W_R^* \to H_3 W_R$, $H_3 \to \gamma\gamma$

Testing the seesaw mechanism via the LLP searches
(can be generalized to other $U(1)_{B-L}$ models)

A new probe of the origin of neutrino mass mechanism