Long-lived light scalars as probe of seesaw

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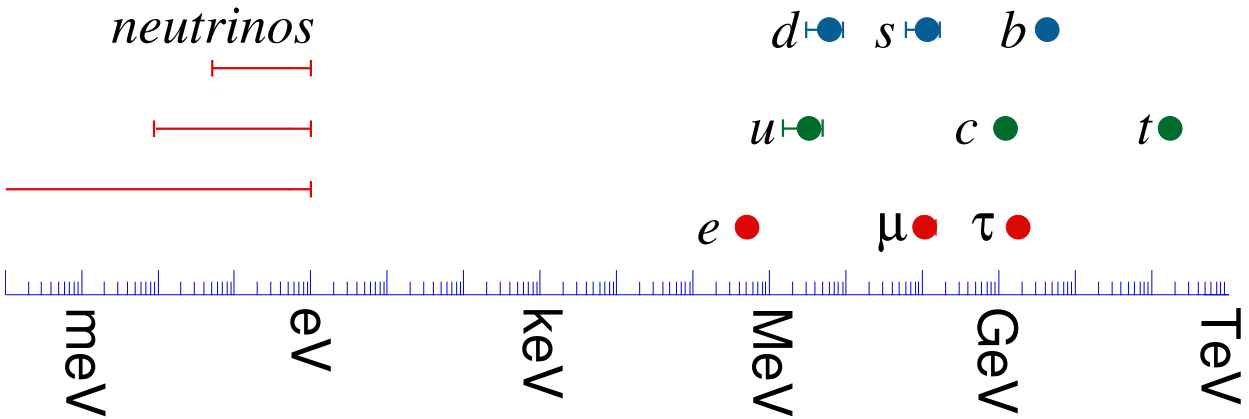
BD, R. N. Mohapatra (Maryland) and Yongchao Zhang (Brussels),
arXiv:1612.09587 [hep-ph], arXiv:1703.02471 [hep-ph].

Harbinger of New Physics

Non-zero neutrino mass $\Longrightarrow$ physics beyond the SM



- Something beyond the EW Higgs mechanism?
- A natural way is by breaking the $(B-L)$-symmetry of the SM.
- Dimension-5 operator $(LLHH)/\Lambda$. [Weinberg (PRL '79)]
- Tree-level realization: **Seesaw mechanism**

Can the seesaw mechanism be ever tested experimentally?

- Look for *all* possible signatures *(leave no stone unturned)*.

Origin of $B - L$ breaking

Local $B - L$ symmetry

- The corresponding Higgs field will have a physical neutral scalar component.
- Could provide important clues to the physics of neutrino mass.
- 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.

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- Mass of the new Higgs field is still largely unrestricted.
- Important to scan over the entire allowed range.
- For mass $\gg m_h$, production at colliders is (typically) kinematically suppressed. (Many studies on heavy Higgs searches)
- For masses $\sim m_h$, potentially large mixing with the SM Higgs (disfavored by the LHC Higgs data).
- Our focus here will be on the 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)]
- Minimal scalar sector:

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

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

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

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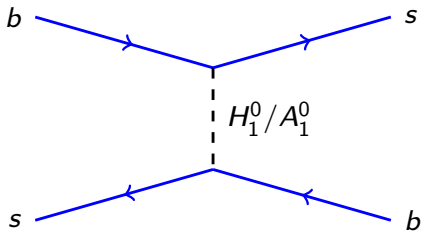
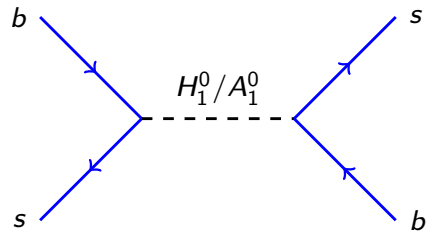
- Eight physical scalars with rich phenomenology. [Gunion, Grifols, Mendez, Kayser, Olness (PRD '89); Bambhaniya, Chakrabortty, Gluza, Jeliński, Kordiaczyńska (PRD '14, '15); Dutta, Eusebi, Gao, Ghosh, Kamon (PRD '14); BD, Mohapatra, Zhang (JHEP '16);...]
- Left-handed Δ_L is decoupled from the TeV scale physics. [Chang, Mohapatra, Parida (PRL '84), Deshpande, Gunion, Kayser, Olness (PRD '91)]
- Allows gauge coupling $g_R \neq g_L$ at the TeV scale.

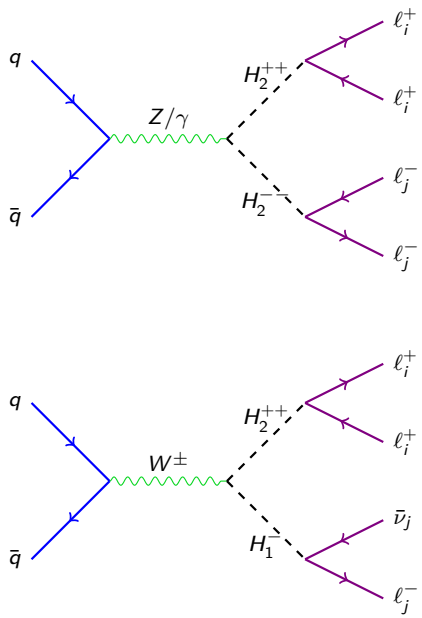
Constraints on the scalars

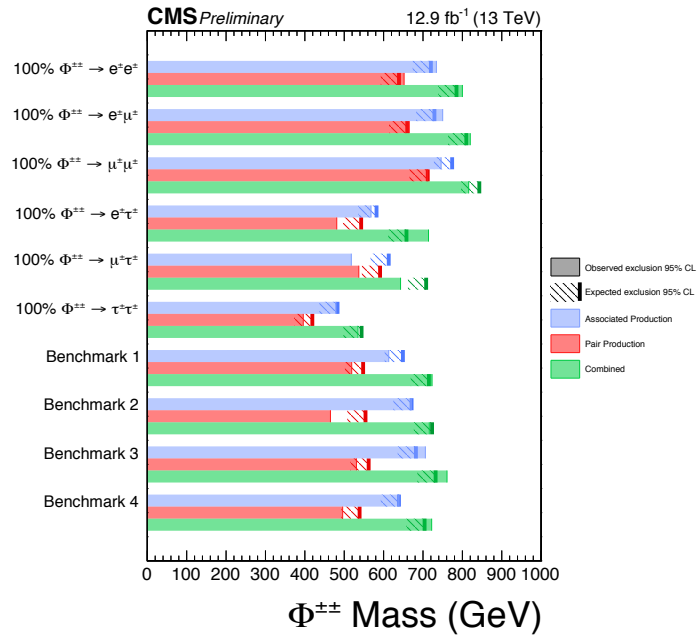
- FCNC limits on bidoublet mass: $M_{H_1^0, A_1^0, H_1^\pm} \gtrsim 10\,\text{TeV}$ [Zhang, An, Ji, Mohapatra (NPB '07); Bertolini, Maiezza, Nesti (PRD '14)]





- LHC limits on doubly-charged scalar: $M_{H_2 \pm\pm} \gtrsim 500\,\text{GeV}$





- Almost no limit on the neutral scalar H_3 (before our work).

Scalar Potential

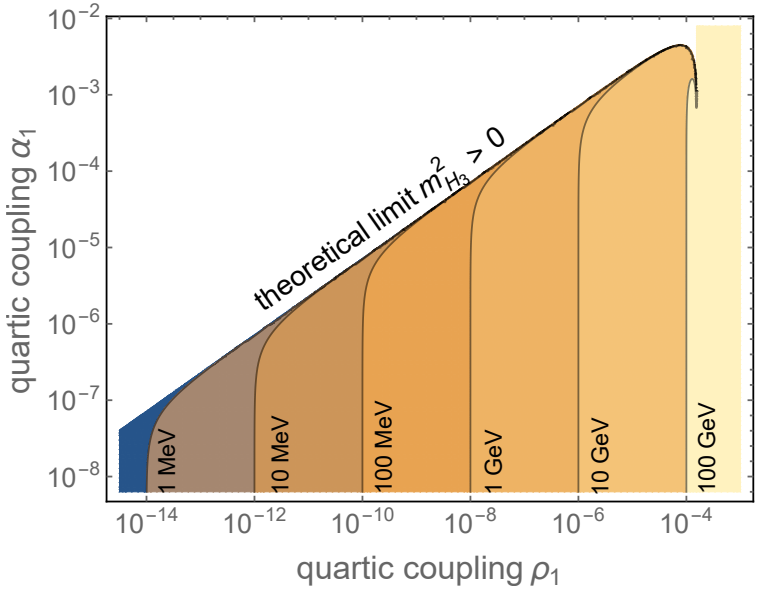
$$
\begin{aligned}
V(\Phi, \Delta_R) \;=\; & -\mu_1^2\,\mathrm{Tr}(\Phi^\dagger\Phi) - \mu_2^2\left[\mathrm{Tr}(\tilde{\Phi}\Phi^\dagger) + \mathrm{Tr}(\tilde{\Phi}^\dagger\Phi)\right] - \mu_3^2\,\mathrm{Tr}(\Delta_R\Delta_R^\dagger) \\
& + \lambda_1\left[\mathrm{Tr}(\Phi^\dagger\Phi)\right]^2 + \lambda_2\left\{\left[\mathrm{Tr}(\tilde{\Phi}\Phi^\dagger)\right]^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

Light neutral scalar H_3

- Mixing with the SM Higgs

$$\mathcal{M}^2_{h,H_3} = \begin{pmatrix} 4\lambda_1\epsilon^2 & 2\alpha_1\epsilon \\ 2\alpha_1\epsilon & 4\rho_1 \end{pmatrix} v_R^2 \quad \Longrightarrow \quad \sin\theta_1 \simeq \frac{\alpha_1}{2\lambda_1}\frac{v_R}{v_{\rm EW}}$$

- Tree-level mass: $m^2_{H_3} \simeq 4\rho_1 v_R^2 - \sin^2\theta_1\, m_h^2$.

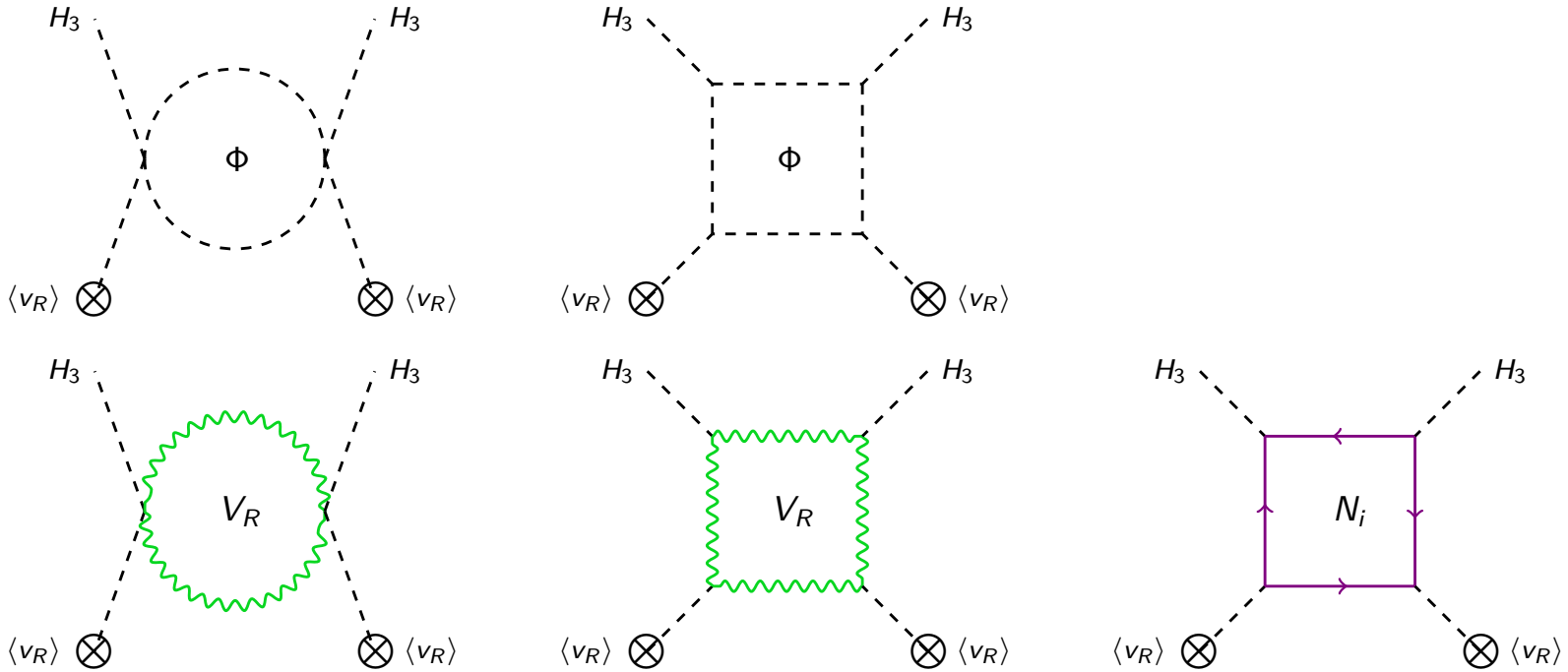


- Mixing with the heavy doublet scalar H_1: $\sin\theta_2 \simeq \frac{4\alpha_2}{\alpha_3}\frac{v_{\rm EW}}{v_R}$.
- H_3 talks to the SM particles via
  - mixing angles $\sin\theta_{1,2}$: hadrons, $\ell^+\ell^-$, $\gamma\gamma$;
  - RH gauge (and scalar) coupling: $\gamma\gamma$ [through the W_R (also $H_1^\pm$, $H_2^{\pm\pm}$) loop].

Radiative Effects

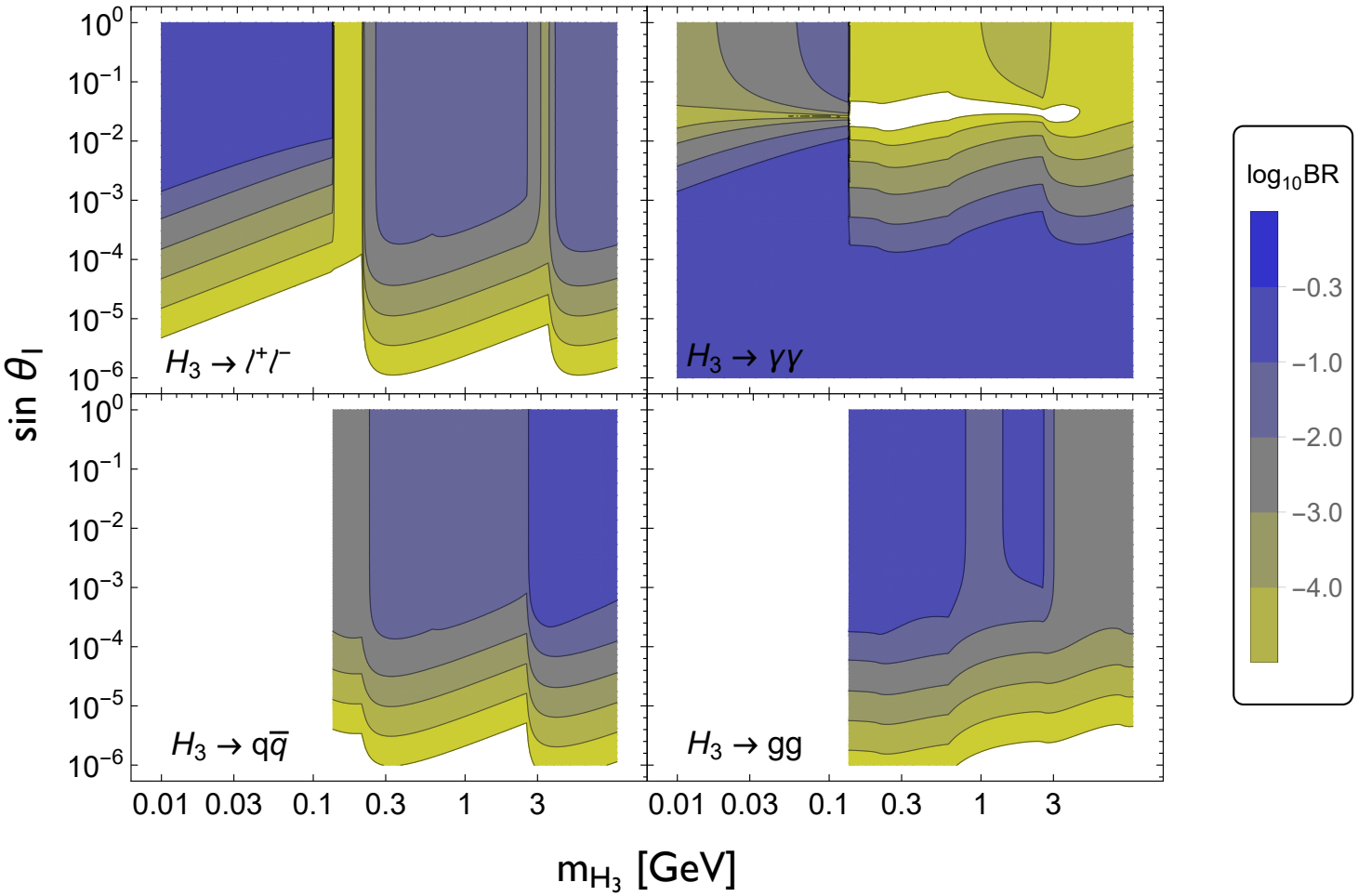
- Mass dependence on the parameters at the 1-loop level

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

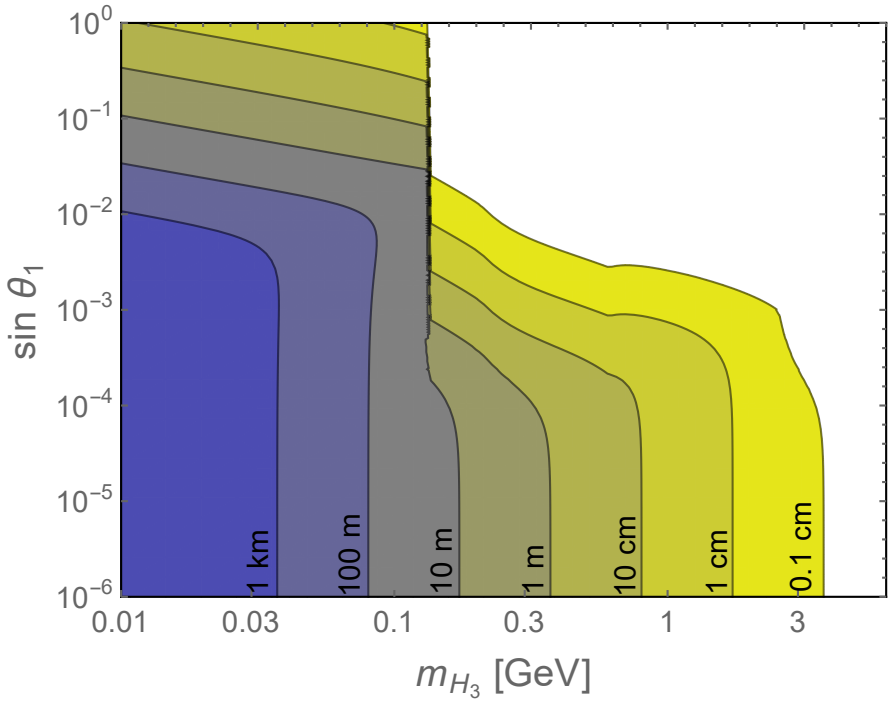


For $m_{H_3} \sim$ GeV and $v_R \simeq$ few TeV, the parameters above are tuned at the level of $\sim \text{GeV}/\frac{v_R}{4\pi} \simeq 10^{-2}$.

Branching ratios

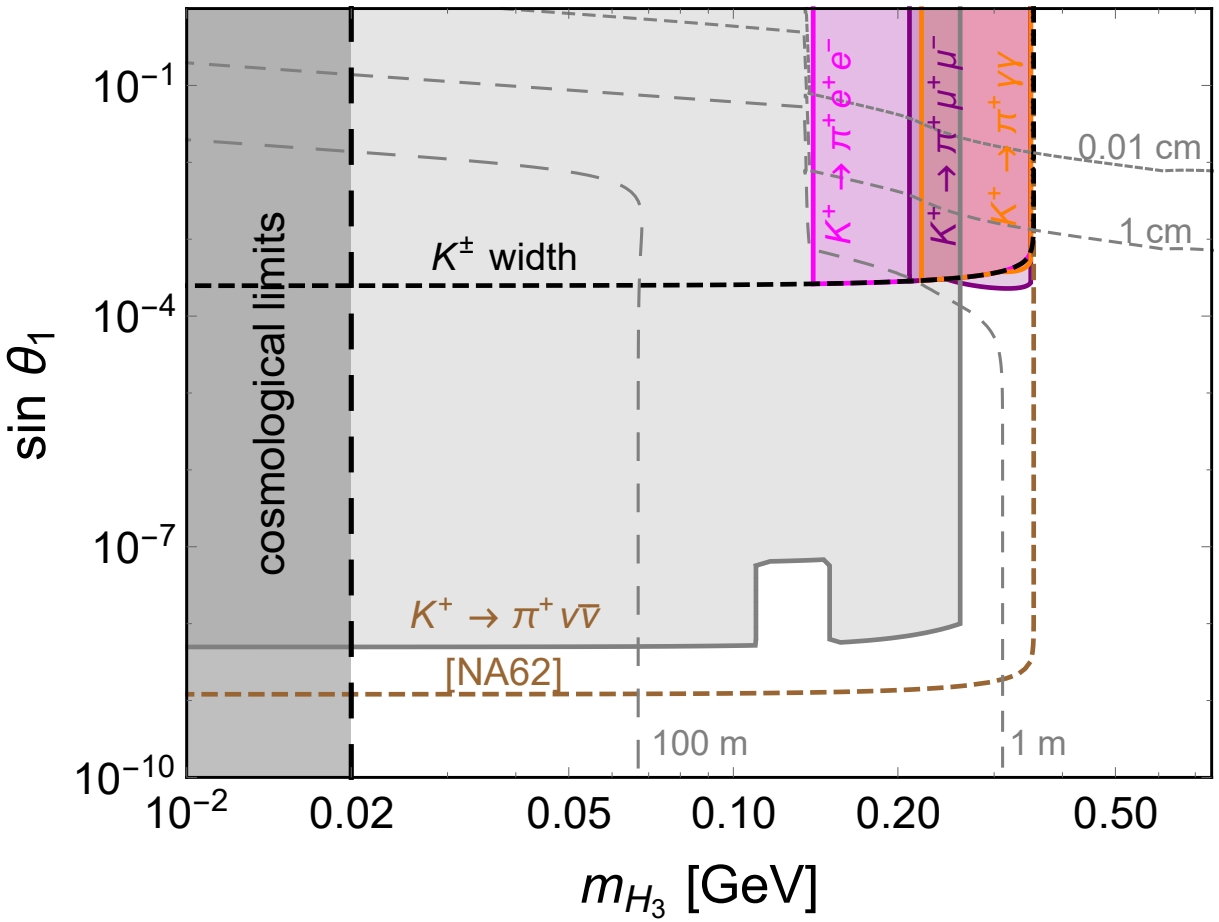


Decay Length



- The mixing angles $\sin\theta_{1,2}$ are required to be very small ($\lesssim 10^{-4}$) by the meson oscillation and rare decay constraints.
- Make H_3 long-lived with dominant decay mode as $H_3 \to \gamma\gamma$ (via W_R loop).
- Displaced diphoton signal at the LHC.
- For lower masses, sufficiently long-lived to escape the ECAL of LHC detectors.
- Suitable to search for at the lifetime frontier: **MATHUSLA** (MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles) [Chou, Curtin, Lubati (PLB '16)]

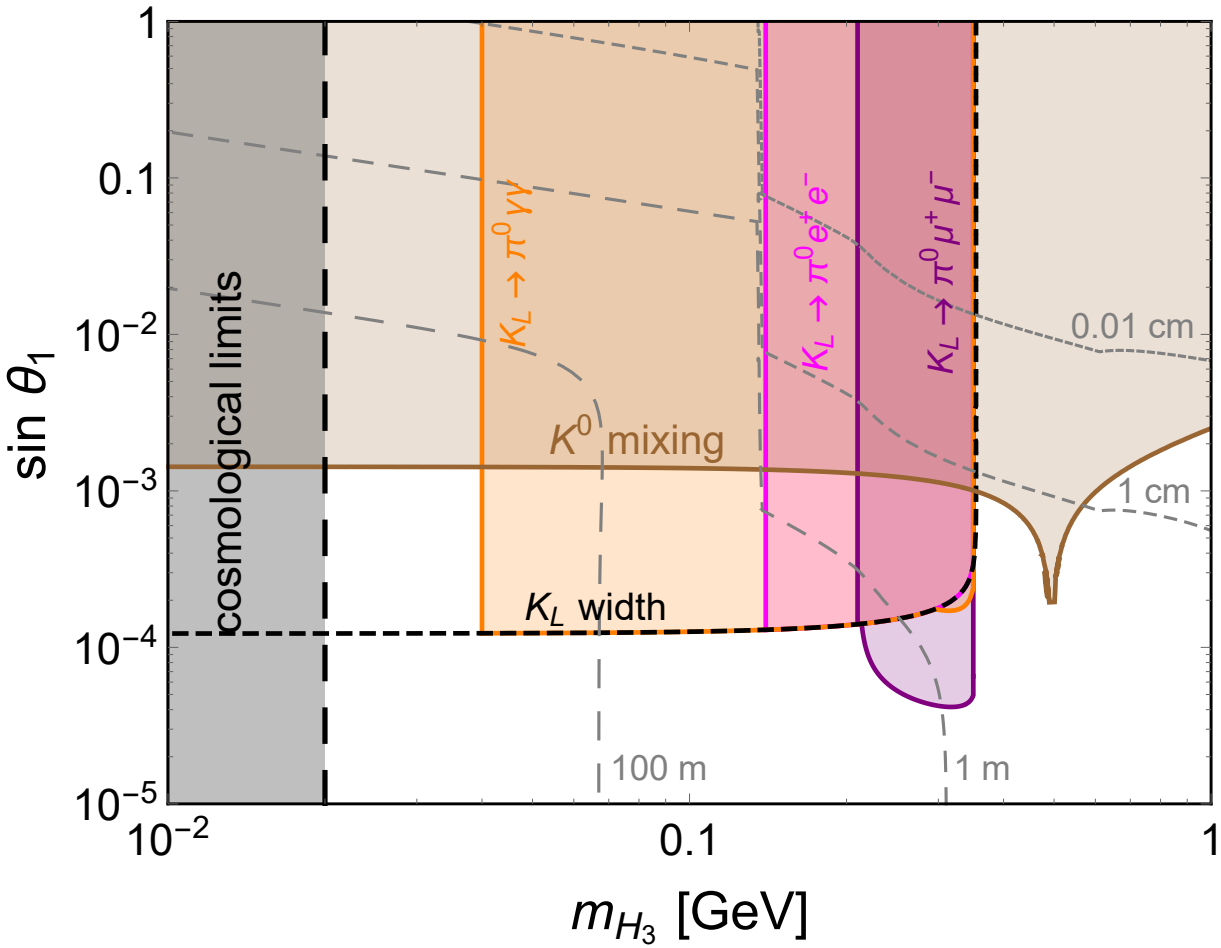
$K^{\pm}$ meson limits



$K^{\pm}$ 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]		

K^0 meson limits

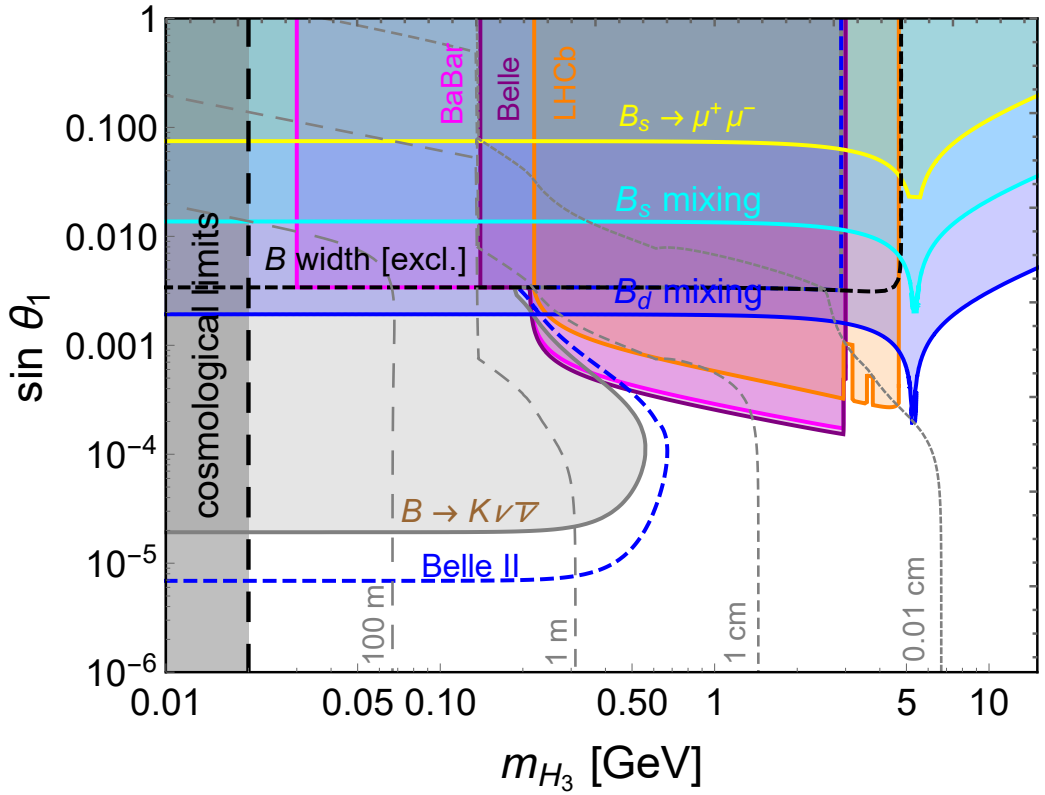


$K^0 - \bar{K}^0$ mixing limits from 50% of experimental central value [1.74×10^{-12} MeV]

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

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

B meson limits

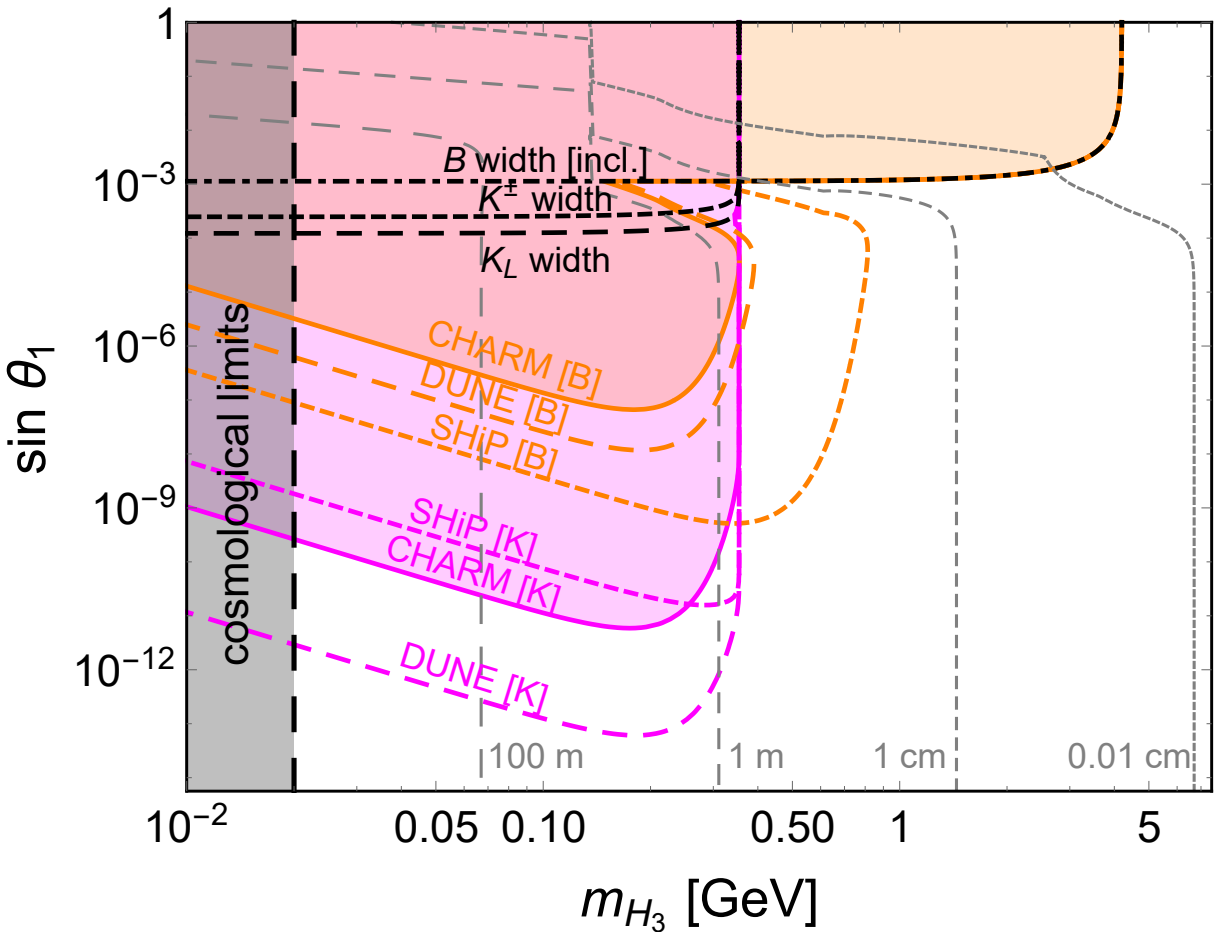


$B_{d(s)} - \bar{B}_{d(s)}$ mixing limits from CKM fitter [9.3 (2.7) $\times$ $10^{-11(9)}$ MeV]

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

$B \to K\ell^+\ell^-$:	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]

Beam dump experiments



$$\text{CHARM}: \quad N_{\text{PoT}} = 2.4 \times 10^{18} \implies 1.2 \times 10^{17}\, K, \quad 2.6 \times 10^{10}\, B$$

$$\text{SHiP}: \quad N_{\text{PoT}} = 2 \times 10^{20} \implies 8 \times 10^{18}\, K, \quad 7 \times 10^{13}\, B$$

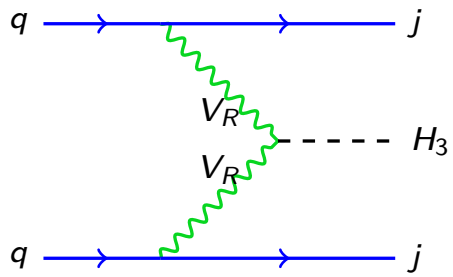
$$\text{DUNE}: \quad N_{\text{PoT}} = 5 \times 10^{21} \implies 7.8 \times 10^{21}\, K, \quad 5.5 \times 10^{12}\, B$$

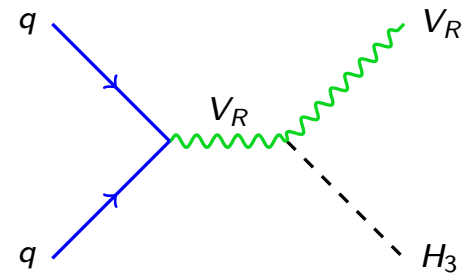
Production at LHC (and FCC-hh)

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

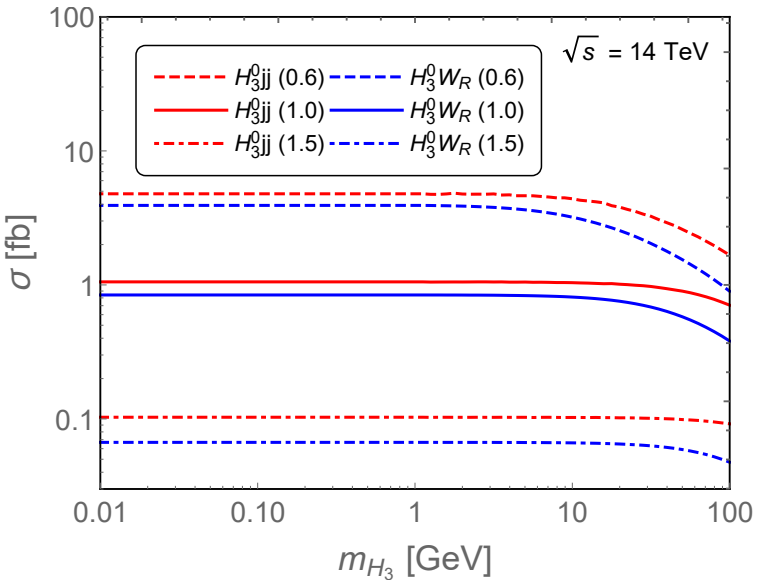
$$pp \to h^{(*)} \to hH_3/H_3H_3 \quad (\propto \sin\theta_1)$$

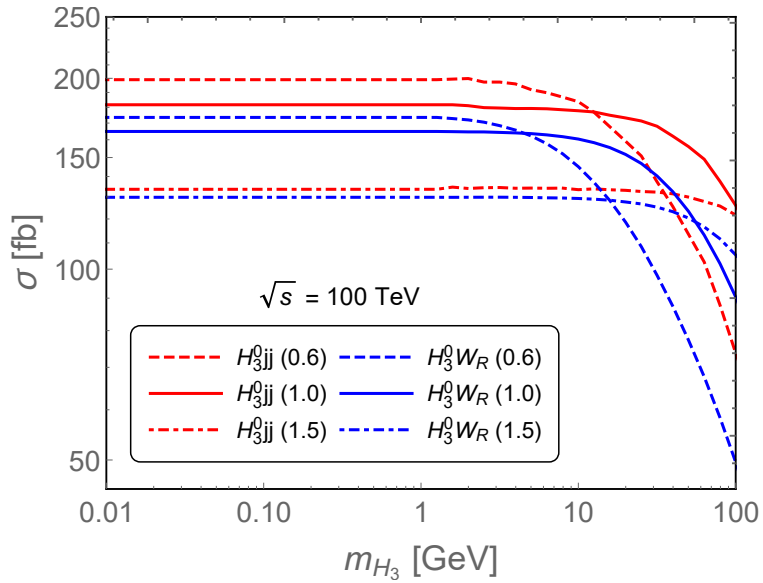
- Heavy VBF production & associated production:



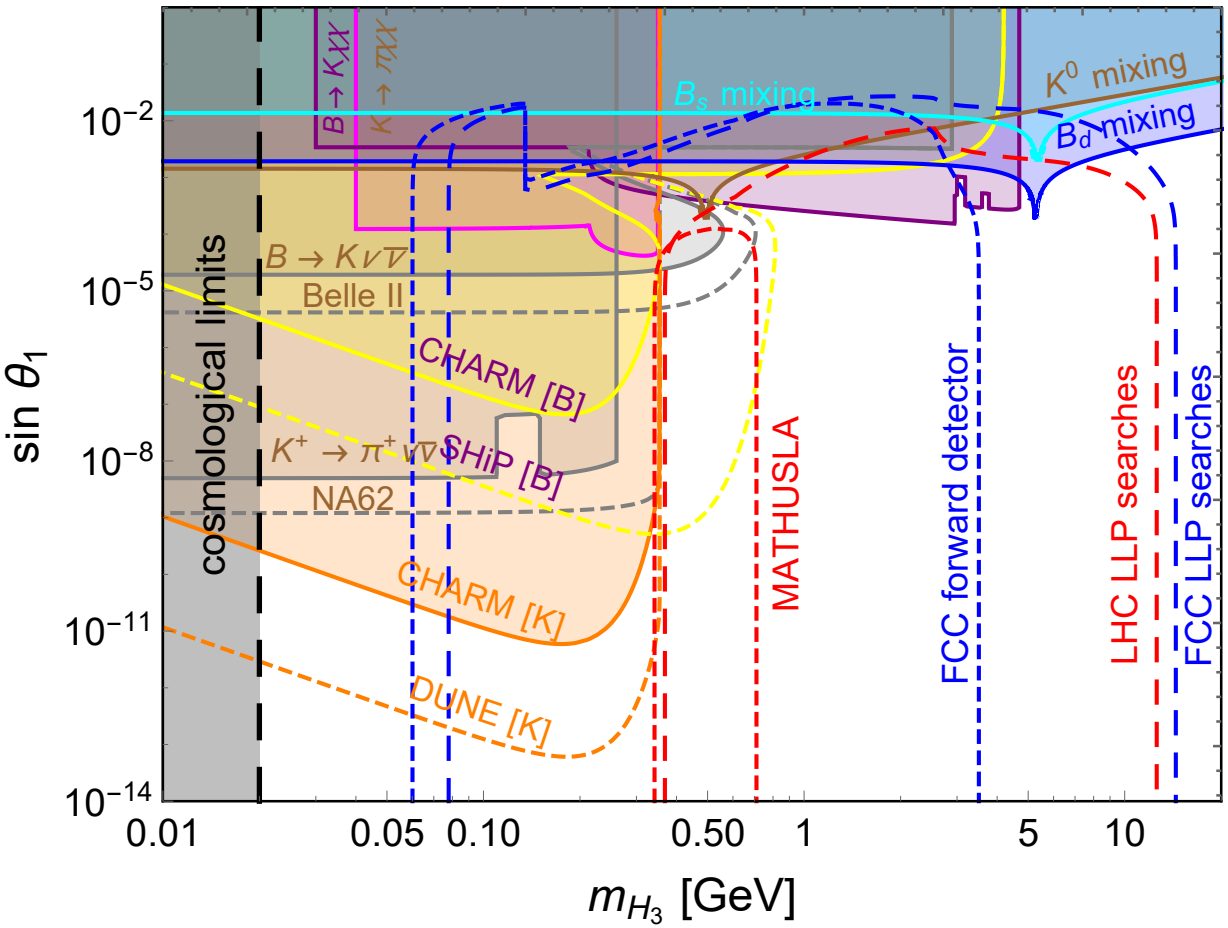


(subleading)



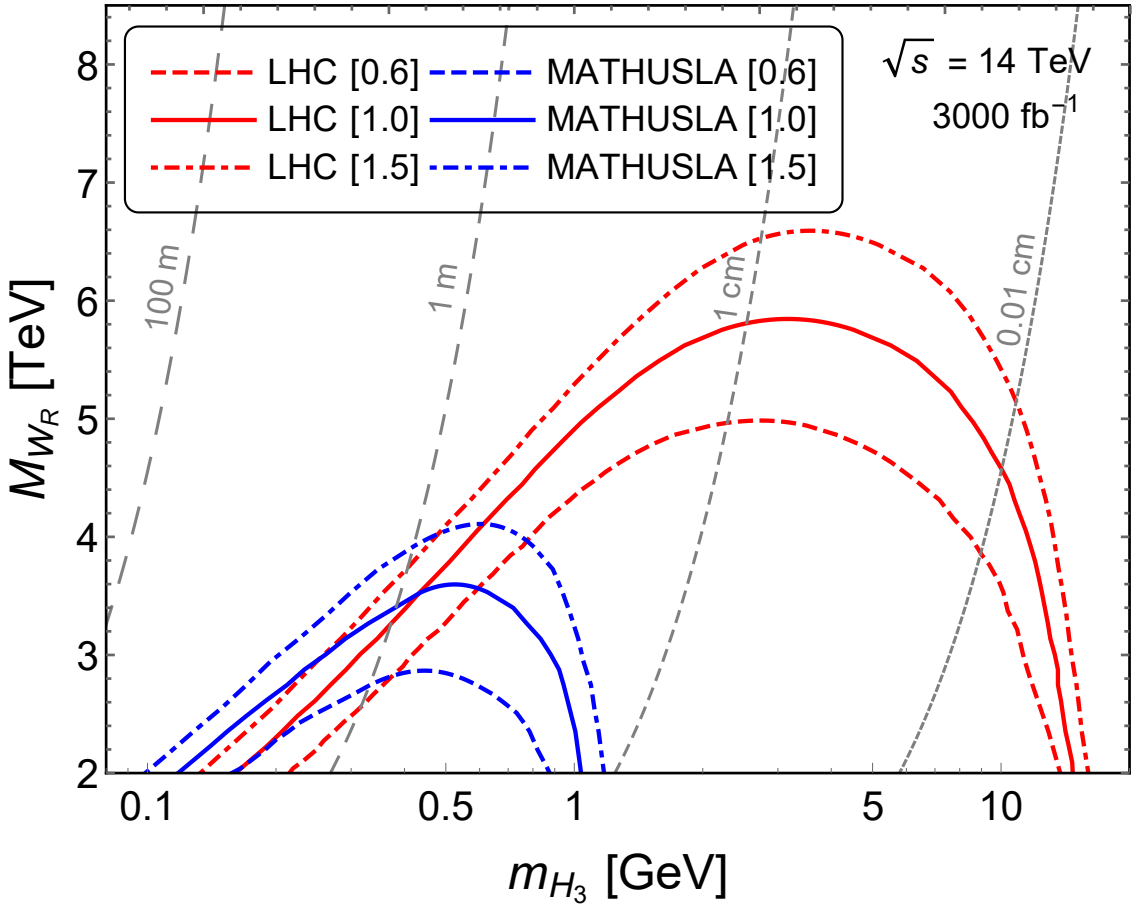


Energy-Intensity frontier complementarity



LLP searches at high-energy colliders are largely complementary to the meson decay and beam-dump experiments.

L-R seesaw sensitivity



Complementary to the like-sign dilepton searches, which constrain the $M_N - M_{W_R}$ parameter space.

Conclusion

- Light scalar (~ 0.1 to 10 GeV) in minimal left-right model: *neutral component from $SU(2)_R$-triplet (hadrophobic)*
- Mixings to SM Higgs and heavy doublet are constrained to be small (from FCNC).
- $H_3 \to \gamma\gamma$ is the dominant decay mode (via W_R loop).
- Necessarily long-lived particle with distinct diphoton signal.
- Unique to the L-R seesaw (though light H_3 can be long-lived in generic $U(1)_{B-L}$ models).
- Energy-intensity frontier complementarity.

A new probe of the origin of neutrino mass mechanism

Backup Slides

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

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 $v_{\rm EW}/v_R$.

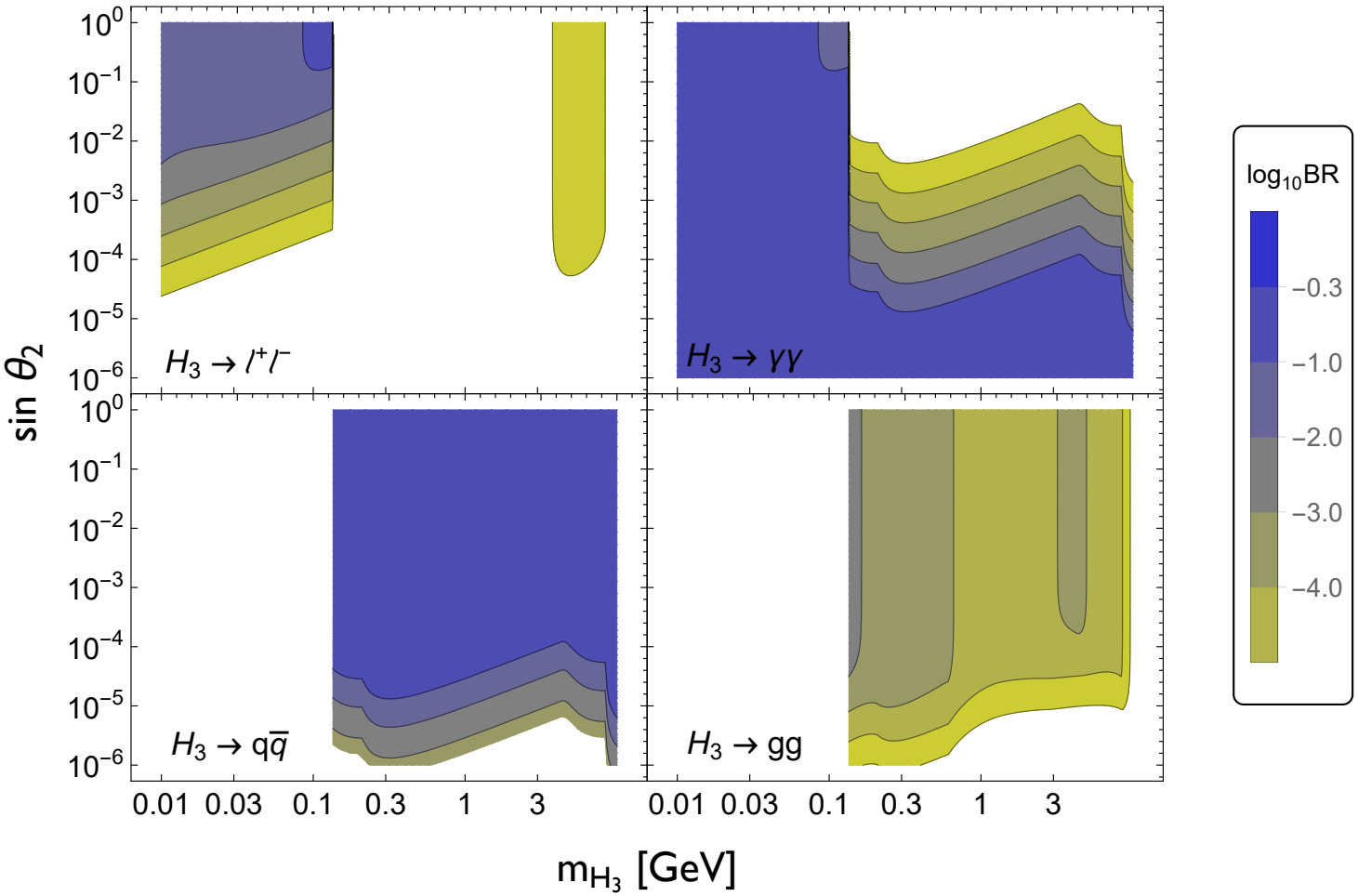
$$\Gamma(H_3 \to q\bar{q}) = \frac{3m_{H_3}}{16\pi}\left[\sum_{i,j} |\mathcal{Y}_{u,\,ij}|^2\, \beta_2^3(m_{H_3}, m_{u_i}, m_{u_j})\Theta(m_{H_3} - m_{u_i} - m_{u_j}) + \sum_{i,j} |\mathcal{Y}_{d,\,ij}|^2\, \beta_2^3(m_{H_3}, m_{d_i}, m_{d_j})\Theta(m_{H_3} - m_{d_i} - m_{d_j})\right],$$

$$\Gamma(H_3 \to \ell^+\ell^-) = \frac{m_{H_3}}{16\pi}\sum_{i,j} |\mathcal{Y}_{e,\,ij}|^2\, \beta_2^3(m_{H_3}, m_{e_i}, m_{e_j})\Theta(m_{H_3} - m_{e_i} - m_{e_j}),$$

$$\Gamma(H_3 \to \gamma\gamma) = \frac{\alpha^2 m_{H_3}^3}{1024\pi^3}\left|\frac{\sqrt{2}}{v_R}A_0(\tau_{H_1^\pm}) + \frac{4\sqrt{2}}{v_R}A_0(\tau_{H_2^{\pm\pm}}) + \frac{\sqrt{2}}{v_{\rm EW}}\sum_{f=q,\ell} f_f N_C^f Q_f A_{1/2}(\tau_f) + \frac{\sqrt{2}}{v_R}A_1(\tau_{W_R})\right|^2, \quad \begin{bmatrix} A_0(0) = 1/3 \\ A_1(0) = -7 \end{bmatrix}$$

$$\Gamma(H_3 \to gg) = \frac{G_F \alpha_s^2(m_{H_3}) m_{H_3}^3}{36\sqrt{2}\pi^3}\left|\frac{3}{4}\sum_{f=q} f_f A_{1/2}(\tau_f)\right|^2,$$

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

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

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

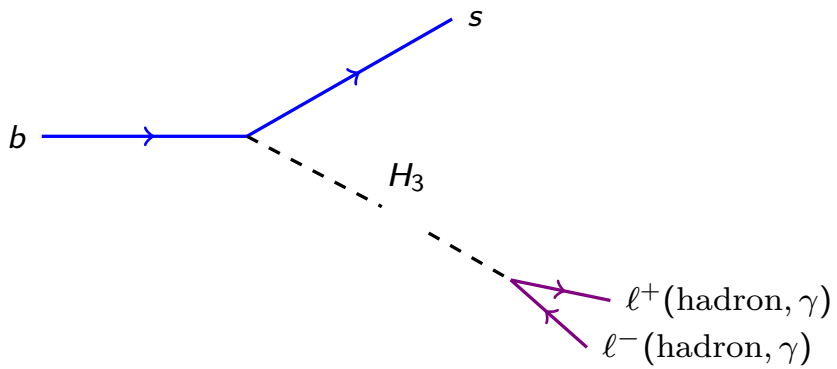
$$\begin{aligned} \mathcal{O}_2 &= [\bar{s}(1-\gamma_5)d][\bar{s}(1-\gamma_5)d] \,, \\ \tilde{\mathcal{O}}_2 &= [\bar{s}(1+\gamma_5)d][\bar{s}(1+\gamma_5)d] \,, \\ \mathcal{O}_4 &= [\bar{s}(1-\gamma_5)d][\bar{s}(1+\gamma_5)d] \,. \end{aligned}$$

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

- "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**

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

List of meson decay limits

	Expt.	meson decay	H_3 decay	E_{H_3}	L_{H_3}	BR/$N_{\rm event}$
	NA48/2 ['09]	$K^+ \to \pi^+ H_3$	$H_3 \to e^+e^-$	$\sim$ 30 GeV	$<$ 0.1 mm	2.63×10^{-7}
	NA48/2 ['11]	$K^+ \to \pi^+ H_3$	$H_3 \to \mu^+\mu^-$	$\sim$ 30 GeV	$<$ 0.1 mm	8.88×10^{-8}
	NA62 ['14]	$K^+ \to \pi^+ H_3$	$H_3 \to \gamma\gamma$	$\sim$ 37 GeV	$<$ 0.1 mm	4.70×10^{-7}
	E949 ['09]	$K^+ \to \pi^+ H_3$	any (inv.)	$\sim$ 355 MeV	$>$ 4 m	4×10^{-10}
$*$	NA62 ['05]	$K^+ \to \pi^+ H_3$	any (inv.)	$\sim$ 37.5 GeV	$>$ 2 m	2.4×10^{-11}
	KTeV ['03]	$K_L \to \pi^0 H_3$	$H_3 \to e^+e^-$	$\sim$ 30 GeV	$<$ 0.1 mm	2.8×10^{-10}
	KTeV ['00]	$K_L \to \pi^0 H_3$	$H_3 \to \mu^+\mu^-$	$\sim$ 30 GeV	$<$ 0.1 mm	4×10^{-10}
	KTeV ['08]	$K_L \to \pi^0 H_3$	$H_3 \to \gamma\gamma$	$\sim$ 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]	$B^+ \to K^+ H_3$	$H_3 \to \mu^+\mu^-$	$\sim$ 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}
†	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]	$K \to \pi H_3$	$H_3 \to \gamma\gamma$	$\sim$ 10 GeV	[480, 515] m	$\underline{< 2.3}$
	CHARM ['85]	$B \to X_s H_3$	$H_3 \to \gamma\gamma$	$\sim$ 10 GeV	[480, 515] m	$\underline{< 2.3}$
$*$	SHiP ['15]	$K \to \pi H_3$	$H_3 \to \gamma\gamma$	$\sim$ 25 GeV	[70, 125] m	$\underline{< 3}$
$*$	SHiP ['15]	$B \to X_s H_3$	$H_3 \to \gamma\gamma$	$\sim$ 25 GeV	[70, 125] m	$\underline{< 3}$
$*$	DUNE ['13]	$K \to \pi H_3$	$H_3 \to \gamma\gamma$	$\sim$ 12 GeV	[500, 507] m	$\underline{< 3}$
$*$	DUNE ['13]	$B \to X_s H_3$	$H_3 \to \gamma\gamma$	$\sim$ 12 GeV	[500, 507] m	$\underline{< 3}$

$*$ future prospects, † flavor-conserving couplings only