Light scalar at the high energy and intensity frontiers: example in the minimal left-right model

Yongchao Zhang
(張永超)

Université Libre de Bruxelles
(→ Washington University in St. Louis)

Aug 11, 2017, Columbus Ohio
TeVPA 2017

based on
Bhupal Dev, Mohapatra & YCZ, NPB [1703.02471]
Bhupal Dev, Mohapatra & YCZ, PRD**95**, 115001 [1612.09587]
Bhupal Dev, Mohapatra & YCZ, JHEP**05**(2016)174 [1602.05947]

Long-lived particle & the HEP frontiers

- LLPs are intimately related to the frontiers of HEP:
  [see the MATHUSLA white paper 17xx.abcde]

neutrino masses, DM, baryon asymmetry, naturalness,
supersymmetry, composite models, leptogenesis ...

- The world is *chiral*: weak interaction is left-handed.
  since the era of C.N.Yang, T.D.Lee & C.S.Wu...

EW theory ⇒ LRSM ⇒ light scalar: unique LLP candidate

Minimal Left-Right Symmetric Model

- Minimal left-right symmetric extension:

$$SU(2)_L \times U(1)_Y \to SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- Matter fields are parity symmetric

left-handed	right-handed
$\begin{pmatrix} u_L \\ d_L \end{pmatrix} = Q_L$	$Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}$
$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = \Psi_L$	$\Psi_R = \begin{pmatrix} N_R \\ e_R \end{pmatrix}$

There are three different classes of LR models (private communication with Mohapatra), here is the best-known scenario

Minimal scalar sector

Pati & Salam '74; Mohapatra & Pati '75; Senjonavić & Mohapatra '75

$$\begin{tikzcd}
SU(2)_L \times SU(2)_R \times U(1)_{B-L} \arrow[d, Rightarrow, "\Delta_R\,(\mathbf{1},\mathbf{3},2)"] \\
SU(2)_L \times U(1)_Y \arrow[d, Rightarrow, "\Phi\,(\mathbf{2},\mathbf{2},0)"] \\
U(1)_{\rm EM}
\end{tikzcd}$$

$$\begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix} \Rightarrow H_3 \text{ (CP-even)}$$

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

- Left-handed triplet Δ_L decouples from the TeV scale physics.

  [Chang, Mohapatra & Parida '84, Deshpande, Gunion, Kayser & Olness '91]
- Gauge coupling $g_R \neq g_L$ at the TeV scale.
- Assuming CP conservation and the parameters small:

  [Zhang, An, Ji & Mohapatra '07, Dev, Mohapatra & YCZ '16]

$$\xi \equiv \langle \phi_2^0 \rangle / \langle \phi_1^0 \rangle = \kappa'/\kappa \simeq m_b/m_t \ll 1\,,$$

$$\epsilon \equiv v_{\rm EW}/v_R = \sqrt{\kappa^2 + \kappa'^2}/v_R \ll 1$$

Physical scalars

- Bidoublet scalar Φ

$$\mathcal{L}_Y = h\bar{Q}_L\Phi Q_R + \tilde{h}\bar{Q}_L\tilde{\Phi}Q_R \quad (\tilde{\Phi} = \sigma_2\Phi^*\sigma_2)$$

$\Rightarrow$ EW symmetry breaking, generating fermion masses

  - SM-like Higgs: $h \sim \mathrm{Re}\,\phi_1^0$
  - Heavy doublet $H_1^0,\ A_1^0,\ H_1^+ \sim (\phi_2^0,\ \phi_2^+)$ [Mohapatra et al, '83; Ecker et al, '83; Pospelov, '97; Zhang et al, '07; Maiezza et al, '10; Chakrabortty et al, '12; Bertolini et al, '14]

tree level FCNC couplings to the quarks $\Rightarrow M_{\phi_2} \gtrsim 15\,\mathrm{TeV}$

- RH triplet: $H_3 \sim \mathrm{Re}\,\Delta_R^0$
  - $SU(2)_R$-breaking $\Rightarrow$ coupling to W_R
  - coupling to RHNs $\Rightarrow$ type-I seesaw mechanism

$$\mathcal{L}_Y = f\Phi_R^T\Delta_R\Phi_R$$

  - **(Almost) no *lower* limits on its mass $\Rightarrow$ can be very light!** [Nemevsek et al, '12; Maiezza et al, '16; Nemevsek et al, '16; Dev, Mohapatra & YCZ, 1703.02471, xxxx.yyyyy]

cosmological + supernova constraints $\Rightarrow m_{H_3} \gtrsim \mathrm{MeV}$

How could it be so light ($\sim$ GeV)?

At tree level...

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

$$V \supset \rho_1 [\mathrm{Tr}(\Delta_R \Delta_R^\dagger)]^2 \quad \Rightarrow \quad m_{H_3}^2 \simeq 4\rho_1 v_R^2$$

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

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

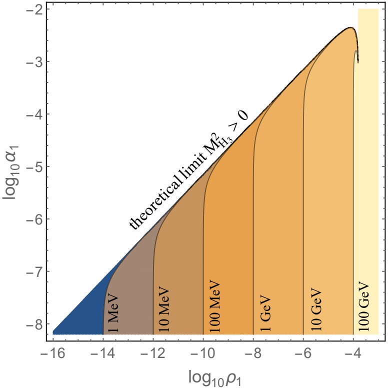
- Mixing with the heavy doublet scalar H_1 [inducing FCNC couplings]

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

How could it be so light ($\sim$ GeV)?
At tree level...

- Mass dependence on the quartic couplings at the tree level

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



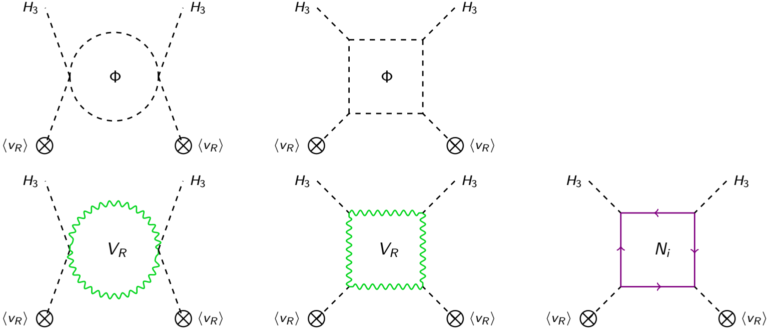
To have a $\sim$ GeV H_3, the parameter $\rho_1 \simeq \mathrm{GeV}^2/4v_R^2 \simeq 10^{-8}$ for $v_R = 5$ TeV.

How could it be so light ($\sim$ GeV)?

At 1-loop level...

- 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 $\sim \mathrm{GeV}/\frac{v_R}{4\pi} \simeq 10^{-2}$.

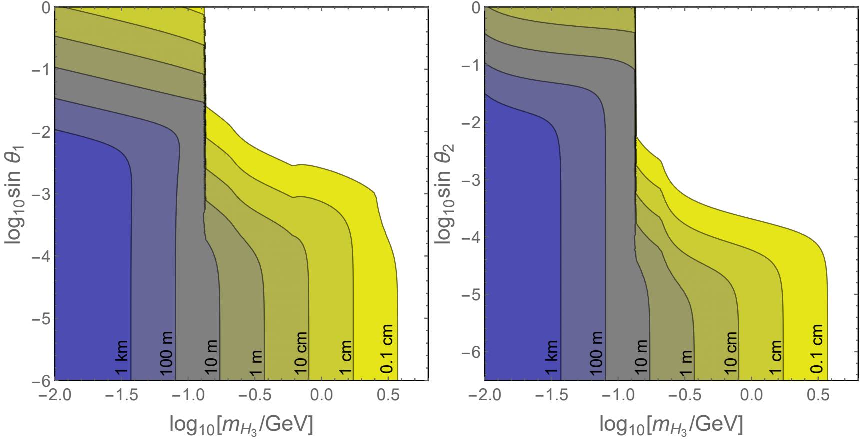
Decay $\Rightarrow$ LLP candidate!

- Couplings to SM quarks and leptons are proportional to $\sin\theta_{1,2}$.
- $H_3 \to \gamma\gamma$ suppressed by the heavy particle masses, effectively by v_R scale.

$$\begin{aligned}
\Gamma(H_3 \to q\bar{q}) &\propto \sin\theta_{1,2}^2, \\
\Gamma(H_3 \to \ell^+\ell^-) &\propto \sin\theta_{1,2}^2, \\
\Gamma(H_3 \to gg) &\propto \sin\theta_{1,2}^2 \times (\text{loop factor}),
\end{aligned}$$

$$\Gamma(H_3 \to \gamma\gamma) = \frac{\alpha^2 m_{H_3}^3}{512 v_R^2 \pi^3} \left| \underbrace{-7}_{W_R\ \text{loop}} + \underbrace{\frac{1}{3}}_{H_1^\pm\ \text{loop}} + \underbrace{\frac{4}{3}}_{H_2^{\pm\pm}\ \text{loop}} \right|^2 .$$

proper Lifetime



$v_R = 5$ **TeV**, $m_{H_3} = 1$ **GeV** $\Rightarrow c\tau_0 \simeq$ **cm**

FCNC couplins
$\Rightarrow K, B$ meson mixing

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

from mixing with heavy doublet scalar H_1 and SM Higgs h

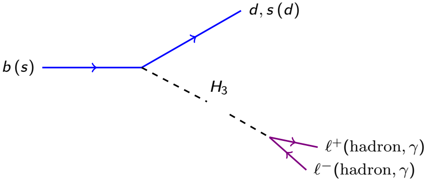
$$
\begin{aligned}
\mathcal{L}_{H_3} \quad = \quad & \frac{G_F}{4\sqrt{2}} \frac{\sin^2 \tilde{\theta}_2}{m_K^2 - m_{H_3}^2 + i m_{H_3} \Gamma_{H_3}} \\
& \times \left[\left(\sum_i m_i \lambda_i^{RL} \right)^2 \mathcal{O}_2 + \left(\sum_i m_i \lambda_i^{LR} \right)^2 \tilde{\mathcal{O}}_2 + 2 \left(\sum_i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

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

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

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

FCNC couplins
$\Rightarrow K$, B meson flavor-changing decay



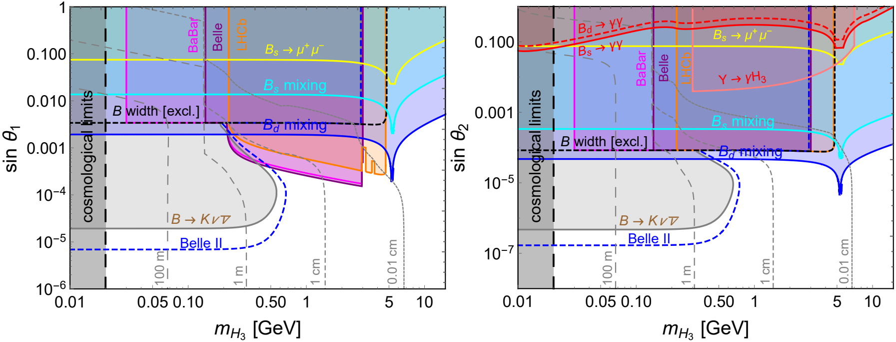
H_3 decaying **inside detector spatial resolution** or **outside detector size**

flavor limits: **high intensity frontier**

	Expt.	meson decay	H_3 decay	E_{H_3}	L_{H_3}	BR/$\underline{N_{\text{event}}}$
	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

Example: 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]

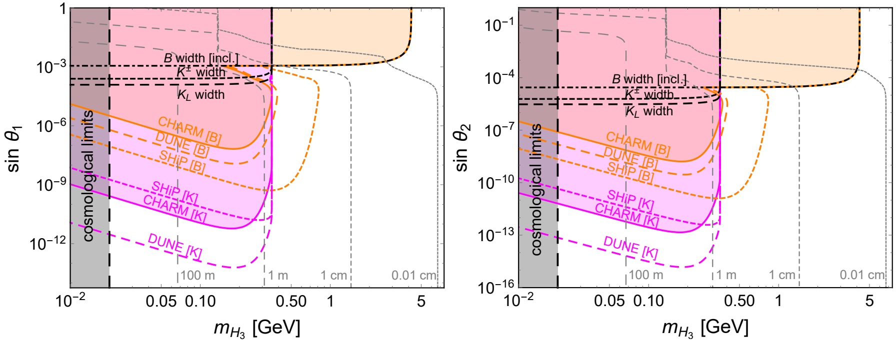
B width limits from 20% of $\Gamma_{\rm total}(B)$

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

(dashed gray lines indicate the proper lifetime of H_3)

Beam dump experiments

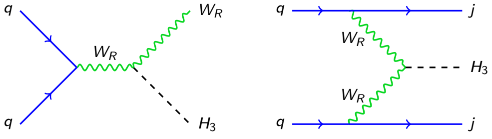
high intensity frontier



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

Production @ LHC
high energy frontier

- SM Higgs portal, highly suppressed by $\sin\theta_1$.
- Gauge portal, associate production with W_R:

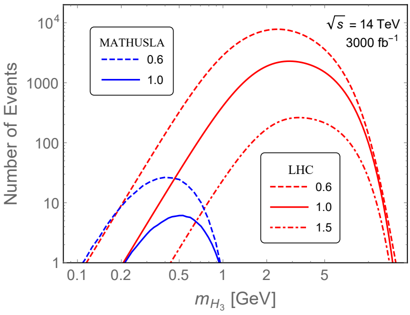


(subleading)

- For light scalar $m_{H_3} \lesssim 10$ GeV, the production cross section is almost a constant

$$\sigma(pp \to H_3 jj) = (7.2)1.6[0.15]\,\mathrm{fb}\,, \quad \text{for } g_R/g_L = (0.6)1.0[1.5]$$

Unique displaced photon signal



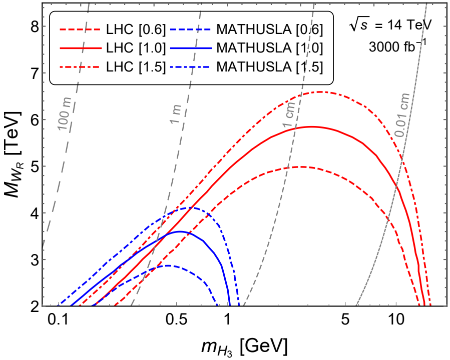
- The mixing angles $\sin\theta_{1,2}$ are constrained to be very small ($\lesssim 10^{-4}$) by the meson data.
- $H_3 \to \gamma\gamma$, highly collimated diphoton signal, dominated by the W_R loop, suppressed by v_R.
- H_3 tends to be long-lived if it is light.
- Decaying inside the ECAL of ATLAS, with $1\,\mathrm{cm} < bc\tau_0 < 1.5\,\mathrm{m}$ (boost factor $b \sim 10^2$).
- MATHUSLA is senstive to lighter and longer-lived H_3.
  [see the talk by David Curtin]

Unique (smoking-gun?) signal of the LR model:

In generic models the extra light scalar decays mostly into the SM fermions through mixing with the SM Higgs

$$\text{displaced photon} + \underbrace{\text{high-}p_T\text{ jets}}_{\text{from } W_R \text{ decay}} \text{ without large } \not{E}_T$$

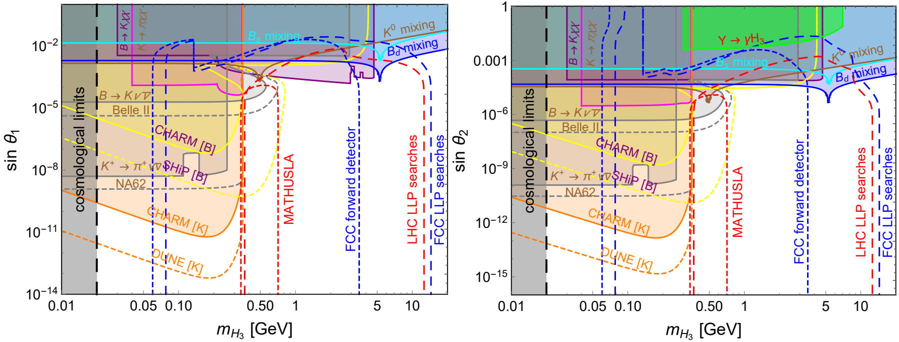
Probable $m_{H_3} - M_{W_R}$ regions



- LHC: Assuming 10 LLP signal events.
- MATHUSLA: Assuming 4 signal events.
  - 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 detectors therein.

Complementarity of the high energy/intensity experiments



The LLP searches at LHC & MATHUSLA are largely complementary to the meson limits

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

With the future 100 TeV collider we can do better...

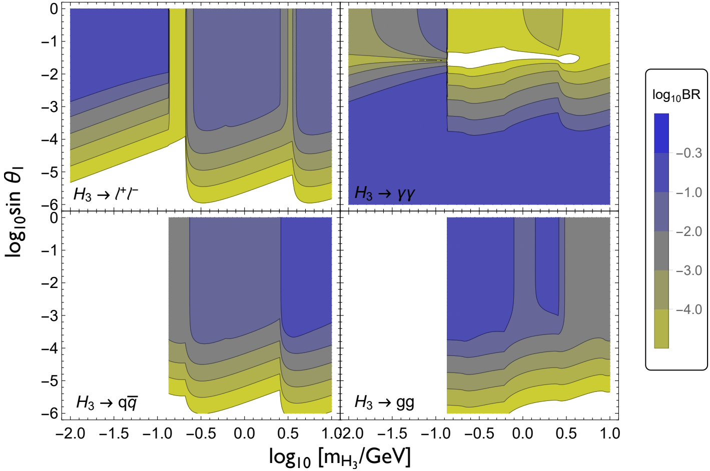
Conclusion: take-away messages

- In the minimal left-right symmetric model, the $SU(2)_R$-breaking scalar H_3 could be light and long-lived.
- The mixings with SM Higgs and heavy doublet scalar are constrained (mainly by meson data) to be very small, $\lesssim 10^{-4}$.
- The singlet-like scalar H_3 are produced at LHC from gauge interaction (associate production with W_R) and decays predominantly into $\gamma\gamma$.
- It could be tested at the high itensity experiments like DUNE and SHiP.
- It could also be probable via displaced photon searches at both ATLAS/CMS and MATHUSLA.
- The high-energy and high-intensity frontier of left-right models are largely complementary to each other, and provide us a new way to understand the neutrino masses, parity breaking etc.

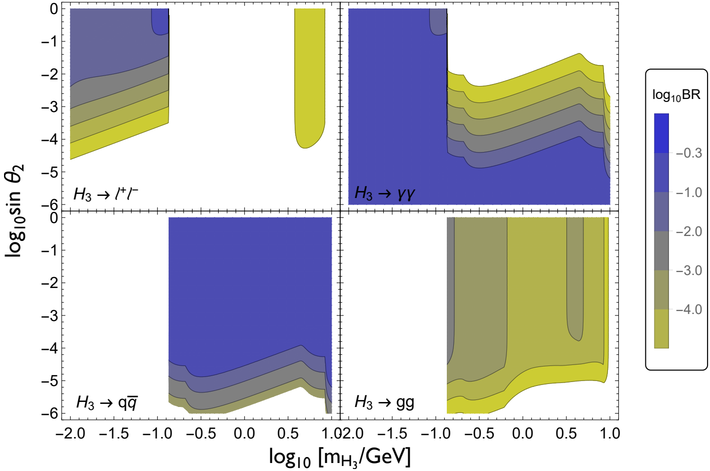
Thank you for your attention!

backup slides

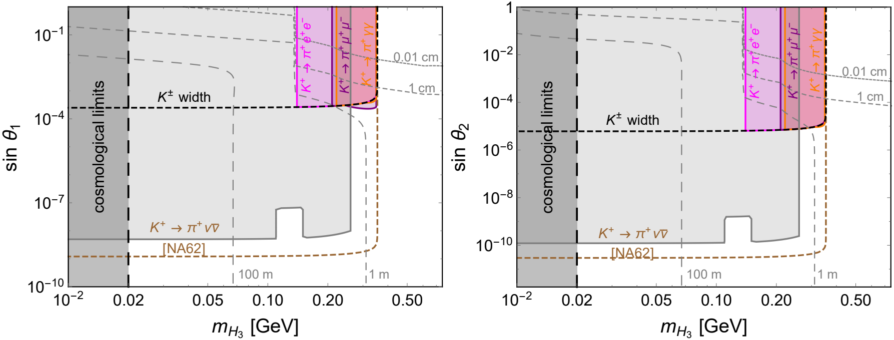
Branching ratios



Branching ratios



$K^\pm$ meson limits

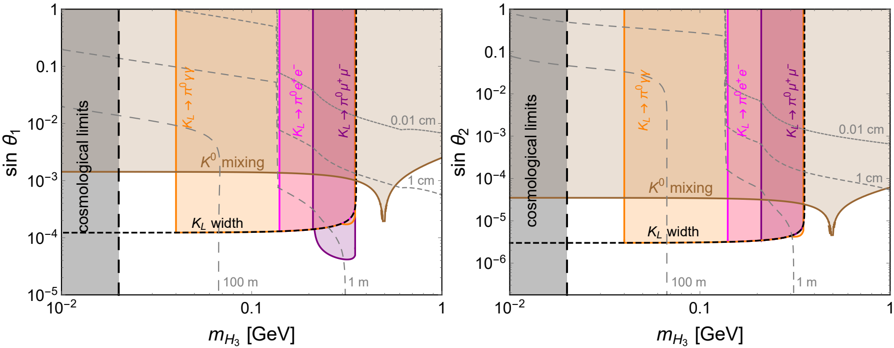


$K^\pm$ width limits from 20% of $\Gamma_{\rm total}(K^\pm)$

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

(dashed gray lines indicate the proper lifetime of H_3)

K^0 meson limits



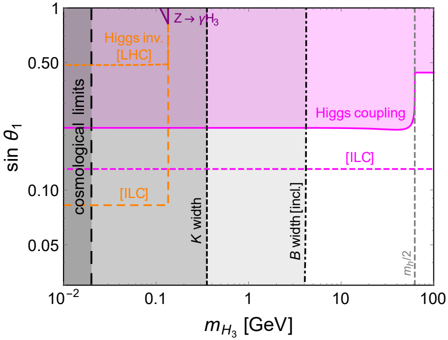
$K^0 - \bar{K}^0$ mixing limits from 50% of experimental central value [1.74×10^{-12} MeV]
(large theoretical uncertainties)

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

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

(dashed gray lines indicate the proper lifetime of H_3)

Higgs measurements and rare Z decay



- The $h - H_3$ mixing changes all the SM Higgs couplings by a factor of $\cos\theta_1$.
  Falkowski, Gross, Lebedev, '15; Profumo, Ramsey-Musolf, Wainwright, Winslow, '14
- Invisible decay $h \to H_3 H_3$ (H_3 decaying outside detector) opens when $m_{H_3} < m_h/2$.
  Peskin, '12; Baer, '13
- Rare decay $Z \to \gamma H_3$ ($H_3 \to \gamma\gamma$), induced by the SM fermion loops.
  Jaeckel, Spannowsky, '15

Expected LLP sensitivities @ LHC