(Selected) phenos of left-right symmetric models

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3rd Neutrino Theories and Phenos in JUNO

Parity violation

Figure: C. N. Yang, T. D. Lee & C. S. Wu

Left $\neq$ Right

Parity restoration?

- Why (only) the weak interaction is left-handed?
- Parity conserved theory?
- GUT?
- Observable at LHC, future 100 TeV collider, or high-intensity experiments?

- very very rich pheno...

Minimal left-right symmetric model:

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

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

Minimal Left-Right Symmetric Model (LRSM)

- RHNs are added automatically to the SM:

$$
\begin{aligned}
Q_L &= \begin{pmatrix} u_L \\ d_L \end{pmatrix} \in \left(\mathbf{2}, \mathbf{1}, \frac{1}{3}\right) \overset{\mathcal{P}}{\longleftrightarrow} Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \in \left(\mathbf{1}, \mathbf{2}, \frac{1}{3}\right) \\
\Psi_L &= \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \in (\mathbf{2}, \mathbf{1}, -1) \overset{\mathcal{P}}{\longleftrightarrow} \Psi_R = \begin{pmatrix} N_R \\ e_R \end{pmatrix} \in (\mathbf{1}, \mathbf{2}, -1)
\end{aligned}
$$

- Electric charge and the hypercharge

$$
Q = I_{3L} + I_{3R} + \frac{1}{2}(B - L)
$$

- Tiny neutrino masses via seesaw mechanism(s) & heavy RHNs N

$$
m_\nu \simeq -m_D M_N m_D^{\mathsf{T}}
$$

- Heavy gauge bosons W_R and Z_R from the $SU(2)_R \times U(1)_{B-L}$ sector.
- Heavy (and light) beyond SM scalars.

Minimal scalar sector: canonical case

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

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

$$\Delta_R = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^+ & \Delta_R^{++} \\ \Delta_R^0 & -\frac{1}{\sqrt{2}}\Delta_R^+ \end{pmatrix} \Rightarrow \begin{pmatrix} 0 & 0 \\ \langle \Delta_R^0 \rangle & 0 \end{pmatrix}$$

$\Rightarrow H_3^0,\ H_2^{\pm\pm}$

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \Rightarrow \begin{pmatrix} \langle \phi_1^0 \rangle & 0 \\ 0 & \langle \phi_2^0 \rangle \end{pmatrix}$$

$\Rightarrow h,\ H_1^0,\ A_1^0,\ H_1^\pm$

Parity- & $SU(2)_R$-breaking

Chang, Mohapatra & Parida '84, Deshpande, Gunion, Kayser & Olness '91

- Decoupling parity- & $SU(2)_R$-breaking scales:
  $\Rightarrow$ left-handed Δ_L decoupling from the TeV-scale physics.

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

- *D*-parity breaking in SO(10) leads to parity nonconservation at low energies in LRSM.
- All Higgs couplings are real:

$$D\text{-parity in SO(10)} = \text{parity in LRSM}$$

Scalar potential

Most general potential of $\Phi(\mathbf{2},\mathbf{2},0)$ & $\Delta_R(\mathbf{1},\mathbf{3},2)$:

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

(3 mass parameters) + (9 real quartic couplings) + (CP phase δ_2)
Minimization conditions $\Rightarrow$ -4; SM Higgs mass $\Rightarrow$ -1.

small parameters:

$$\xi \equiv \frac{\kappa'}{\kappa} = \frac{\langle\phi_2^0\rangle}{\langle\phi_1^0\rangle}, \quad \epsilon \equiv \frac{\kappa}{v_R} \simeq \frac{v_{\rm EW}}{v_R}, \quad \alpha \sim \delta_2$$

Physical scalars

Table: Nomenclature: CP-even scalars $H^0_{1,2,3}$ predominantly from respectively Φ & $\Delta_{L,R}$; CP-odd scalars $A^0_{1,2}$ ($H^\pm_{1,2}$) from Φ & Δ_L; and $H^{\pm\pm}_{1,2}$ from $\Delta_{L,R}$.

scalars	components	mass squared
h	$\sim \phi_1^{0\,\mathrm{Re}}$	$\left(4\lambda_1 - \frac{\alpha_1^2}{\lvert\rho_1-\lambda_1\rvert}\right)\kappa^2$
H^0_1	$\sim \phi_2^{0\,\mathrm{Re}}$	$\alpha_3(1+2\xi^2)v_R^2 + 4\left(2\lambda_2+\lambda_3+\frac{4\alpha_2^2}{\alpha_3-4\rho_1}\right)\kappa^2$
A^0_1	$\sim \phi_2^{0\,\mathrm{Im}}$	$\alpha_3(1+2\xi^2)v_R^2 + 4(\lambda_3-2\lambda_2)\kappa^2$
$H^\pm_1$	$\sim \phi_2^\pm$	$\alpha_3(1+2\xi^2)v_R^2 + \frac{1}{2}\alpha_3\kappa^2$
H^0_3	$\sim \Delta_R^{0\,\mathrm{Re}}$	$4\rho_1 v_R^2 + \left(\frac{\alpha_1^2}{\rho_1} - \frac{16\alpha_2^2}{\alpha_3-4\rho_1}\right)\kappa^2$
$H^{\pm\pm}_2$	$\sim \Delta_R^{\pm\pm}$	$4\rho_2 v_R^2 + \alpha_3\kappa^2$

Bidoublet scalars

Almost degenerate masses

Triplet scalars

Couple to quarks only through mixings: *Hadrophobic states*

Corrections to the SM Higgs

- SM Higgs and cubic scalar coupling

$$
\begin{aligned}
m_h^2 &\simeq \left(4\lambda_1 - \frac{\alpha_1^2}{|\rho_1 - \lambda_1|}\right) v_{\rm EW}^2 \\
\lambda_{hhh} &\simeq \frac{1}{2\sqrt{2}}\left(4\lambda_1 - \frac{\alpha_1^2}{|\rho_1 - \lambda_1|}\right) v_{\rm EW} = \frac{m_h^2}{2\sqrt{2}\, v_{\rm EW}}
\end{aligned}
$$

- The α_1 term is from mixing with the neutral component H_3 of Δ_R.

$$
\alpha_1 \to 0 \quad \Rightarrow \quad \lambda_1 \to \lambda_{\rm SM}
$$

The $h - H_3$ mixing is *naturally* small.

important to push a light H_3 to be long-lived

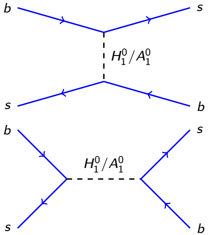
FCNC limits on the heavy doublet H_1^0, A_1^0 & $H_1^\pm$

Flavor-changing neutral currents of H_1^0 and A_1^0 contribute to $K^0 - \bar{K}^0$ and $B_{d,s} - \bar{B}_{d,s}$ mixings [Mohapatra, Senjanovic, Tran, '83; Ecker, Grimus, Neufeld, '83; Pospelov, '97; Zhang, An, Ji, Mohapatra, '07; Maiezza, Nemevsek, Nesti, Senjanovic, '10; Chakrabortty, Gluza, Sevillano, Szafron, '12; Bertolini, Maiezza, Nesti, '14]

$$M_{H_1^0, A_1^0, H_1^\pm} \gtrsim 10\,\mathrm{TeV}$$

$$
\begin{aligned}
-\mathcal{L}_Y &= h_q \bar{Q}_L \Phi Q_R + \tilde{h}_q \bar{Q}_L \tilde{\Phi} Q_R + \mathrm{h.c.} \\
\Rightarrow & \begin{cases} H_1^0 \bar{u}_i u_j : \; -\sqrt{2}\xi \widehat{Y}_U + \frac{1}{\sqrt{2}} \left(V_L \widehat{Y}_D V_R^\dagger \right) \\ H_1^0 \bar{d}_i d_j : \; \frac{1}{\sqrt{2}} \left(V_L^\dagger \widehat{Y}_U V_R \right) - \sqrt{2}\xi \widehat{Y}_D \end{cases}
\end{aligned}
$$

$\Rightarrow$



Left-right symmetry

Maiezza, Nemevsek, Nesti & Senjanovic '10

	$\mathcal{P}$	$\mathcal{C}$
quarks	$Q_L \leftrightarrow Q_R$	$Q_L \leftrightarrow Q_R^C$
bidoublet	$\Phi \to \Phi^\dagger$	$\Phi \to \Phi^T$
Yukawa couplings	$Y = Y^\dagger$	$Y = Y^T$
RH mixing	$V_R = S_u V_L S_d$	$V_R = K_u V_L^* K_d$

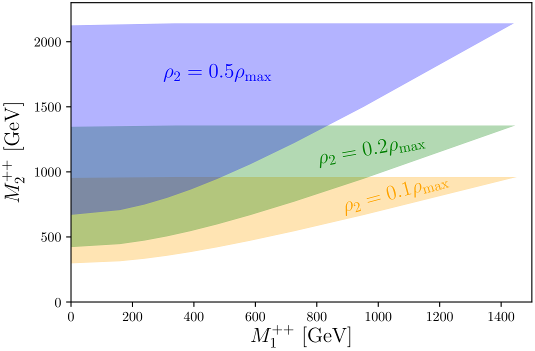
- $S_{u,\,d}$ are diagonal matrices of signs;
- $K_{u,\,d}$ are diagonal matrices of phases.

- $\mathcal{C}$ is an automatic gauge symmetry in SO(10) GUT.

Vacuum structure

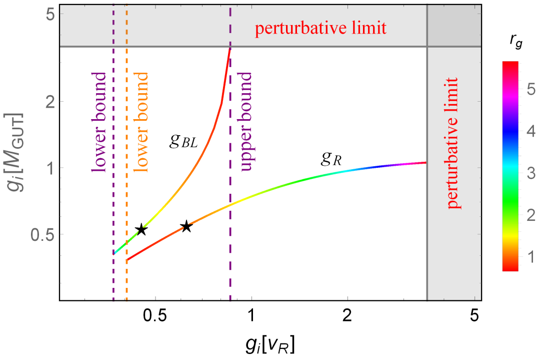
Chauhan '19; Dev, Mohapatra, Rodejohann & Xu '19

- Only a small fraction of parameter space can have good vacua.
- Limits can be set on some scalar masses.



Running of gauge couplings up to GUT scale

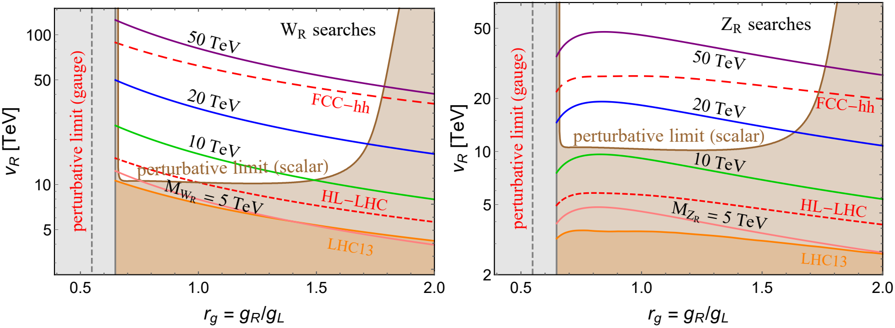
Chauhan, Dev, Mohapatra & YCZ '18



- gauge coupling ratio $r_g \equiv g_R/g_L$;
- perturbativity limit $g_i < \sqrt{4\pi}$;
- $v_R = 10$ TeV;
- stars $g_L = g_R$ in the figure.

Perturbativity limits

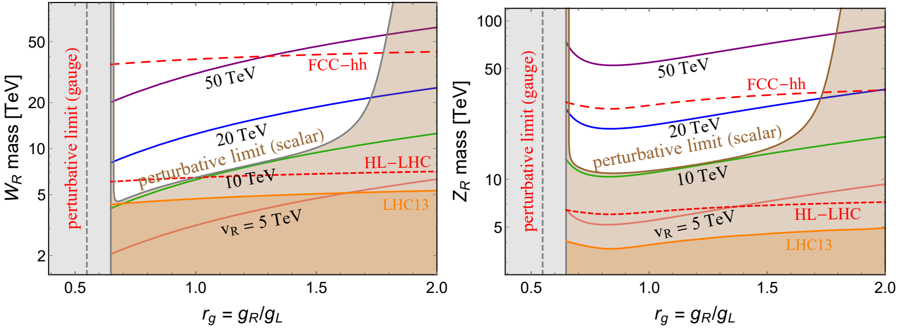
Chauhan, Dev, Mohapatra & YCZ '18



- masses we take: $m_{H_1,\,A_1,\,H_1^\pm} = 10$ TeV, $m_{H_3} = 100$ GeV, $m_{H_1^{\pm\pm}} = 1$ TeV;
- $\lambda_{2,3,4},\ \alpha_{1,2} = 0$ at v_R scale.

Heavy gauge boson prospects

Chauhan, Dev, Mohapatra & YCZ '18



- masses we take: $m_{H_1,\, A_1,\, H_1^\pm} = 10$ TeV, $m_{H_3} = 100$ GeV, $m_{H_1^{\pm\pm}} = 1$ TeV;
- $\lambda_{2,3,4},\ \alpha_{1,2} = 0$ at v_R scale.

$SU(2)_R$-breaking scalar H_3

Almost no limit on the neutral singlet-like scalar H_3.

[Nemevsek, Senjanovic, Yue Zhang, '12; Maiezza, Nemevsek, Nesti, '16; Nemevsek Nesti, Vasquez, '16]

H_3 could be very light

Mixing with h & H_1

Dev, Mahapatra & YCZ '16; '17

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

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

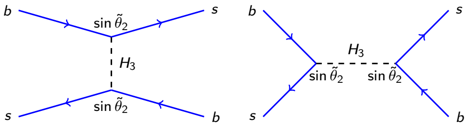
- Mixing with the heavy doublet scalar H_1 [inducing FCNC couplings]

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

- H_3 couples to the SM particles through:
  - the mixing angles $\sin\theta_{1,2}$: hadrons, $\ell^+\ell^-$, $\gamma\gamma$;
    All the couplings to SM quarks and leptons are proportional to the linear combinations of $\sin\theta_{1,2}$.
  - RH gauge coupling: $\gamma\gamma$, through the W_R (& $H_1^\pm$, $H_2^{\pm\pm}$) loop.
    Heavy particle loops for $H_3 \to \gamma\gamma$ suppressed by $v_{\rm EW}/v_R$.

H_3 induced meson mixings

Dev, Mahapatra & YCZ '16; '17



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

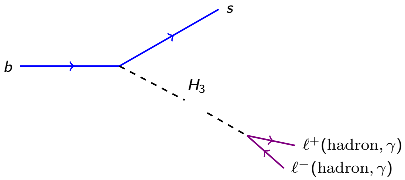
$$\sin\tilde{\theta}_2 \equiv \sin\theta_2 + \xi \sin\theta_1 \,, \quad \left[\xi = \langle \phi_2^0 \rangle / \langle \phi_1^0 \rangle, \quad h - H_1 \text{ mixing} \right]$$

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

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

Flavor-changing meson decay

Dev, Mahapatra & YCZ '16; '17



- 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**

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

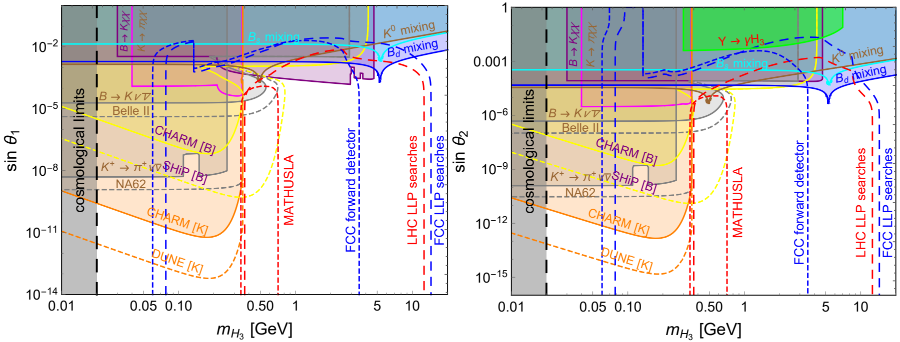
List of meson decay limits

	Expt.	meson decay	H_3 decay	E_{H_3}	L_{H_3}	$\mathrm{BR}/\underline{N_{\rm event}}$
	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}
†	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, † flavor-conserving couplings only

High-intensity Constraints

Dev, Mahapatra & YCZ '16; '17



The LLP searches at LHC and MATHUSLA (and future 100 TeV collider FCC-hh) 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 $\sin\theta_{1,2}$)

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

Dev, Mahapatra & YCZ '16; '17

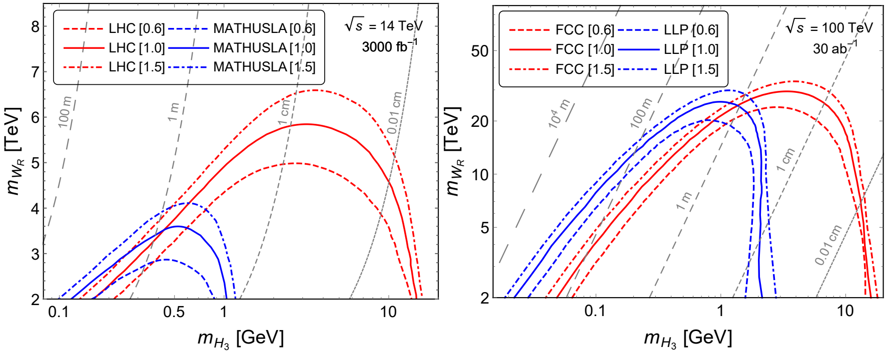


Figure: The grey contours indicate the proper lifetime of H_3 with $g_R = g_L$; for $g_R \neq g_L$, the lifetime has to be rescaled by the factor of $(g_R/g_L)^{-2}$.

BPs for GW signals in LRSM

Brdar, Graf, Helmboldt & Xu '19; Li, Yan, YCZ & Zhao '21

	BP1	BP2	BP3	BP4
v/GeV	246	246	246	246
v_R/GeV	10^4	10^6	10^4	5×10^4
$\tan\beta$	10^{-3}	10^{-3}	0	0
λ_1	0.13	0.13	0.13	0.13
λ_2	0	0	0	0
λ_3	1.2040	0.88814	0.6	0.6
λ_4	0	0	0	0
ρ_1	0.13414	0.11146	0.001	0.002
ρ_2	1.2613	1.4109	0.900218	0.401126
ρ_3	1.5140	1.5489	0.900215	0.401126
ρ_4	0	0	0	0.040113
α_1	0	0	0	0
α_2	0.30246	0.15557	0	0
α_3	0.10765	0.11185	1.14815	0.378138
$\beta_{1,2,3}$	0	0	0	0
g	0.65	0.65	0.65	0.65
g_{B-L}	0.4324	0.4324	0.4324	0.4324
y_t	0.95	0.95	0.95	0.95
y_M	1	1	0.78595	0.52404

GW signals in LRSM

Brdar, Graf, Helmboldt & Xu '19; Li, Yan, YCZ & Zhao '21

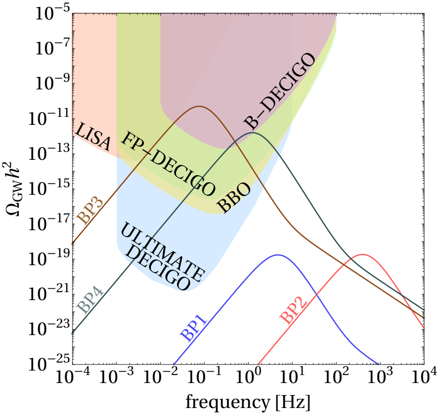


Figure: GW spectra for BPs in the LRSM

Alternative symmetry breaking pattern

Alternative way to break the gauge symmetry:

$$
\begin{array}{c}
SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
\Big\Downarrow \chi_R\,(\mathbf{1},\mathbf{2},1) \\
SU(2)_L \times U(1)_Y \\
\Big\Downarrow \chi_L\,(\mathbf{2},\mathbf{1},1) \\
U(1)_{\mathrm{EM}}
\end{array}
$$

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SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
\Big\Downarrow \chi_R\,(\mathbf{1},\mathbf{2},1) \\
SU(2)_L \times U(1)_Y \\
\Big\Downarrow \chi_L\,(\mathbf{2},\mathbf{1},1) \\
U(1)_{\mathrm{EM}}
\end{array}
$$

- The Higgs pheno in these two classes of LR models are completely different.

  numbers of d.o.f, couplings, constraints, production & decay

Framework

Berezhiani, PLB**129**(1983)99; Rajpoot, MPLA**2**(1987)307;
Davidson & Wali, PRL**59**(1987)393; Babu & Mohapatra, PRL**62**(1989)1079; PRD**41**(1990)1286

- Only two doublets to break gauge symmetry

$$\chi_L = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix} \in (2,\, 1,\, 1) \,, \quad \chi_R = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix} \in (1,\, 2,\, 1)$$

- Doublets $\chi_{L,R}$ can not connect directly the LH and RH components of SM quark and lepton fermions.
- Three generations of heavy vector-like fermions P, N and E are introduced to generate SM fermion masses via generalized seesaw mechanism, alleviating the large hierarchy of SM Yukawa couplings:*

$$\begin{aligned}
& Q_L \in (2,\, 1,\, 1/3) \,, \quad Q_R \in (1,\, 2,\, 1/3) \,, \\
& \Psi_L \in (2,\, 1,\, -1) \,, \quad \Psi_R \in (1,\, 2,\, -1) \,, \\
& P_{L,\,R} \in (1,\, 1,\, 4/3) \,, \quad N_{L,\,R} \in (1,\, 1,\, -2/3) \,, \quad E_{L,\,R} \in (1,\, 1,\, -2)
\end{aligned}$$

*The neutrino partners $\mathcal{N}$ are not necessary; without them active neutrino masses can be generated at 2-loop level via $W - W_R$ mixing [Chang & Mohapatra, '87; Babu & He, '89].

Universal seesaw mechanism

- Yukawa couplings:

$$
\begin{aligned}
-\mathcal{L}_Y &= \bar{Q}_L Y_u \tilde{\chi}_L P_R + \bar{Q}_L Y_d \chi_L N_R + \bar{\Psi}_L Y_e \chi_L E_R + (L \leftrightarrow R) \\
&\quad + \bar{P}_L M_P P_R + \bar{N}_L M_N N_R + \bar{E}_L M_E E_R + \mathrm{h.c.}
\end{aligned}
$$

- SM quarks and charged leptons [all flavor information from Y_f],

$$
\begin{pmatrix} 0 & \frac{1}{\sqrt{2}} Y_f v_L \\ \frac{1}{\sqrt{2}} Y_f v_R & M_F \end{pmatrix} \Longrightarrow m_f \simeq \frac{Y_f^2 v_L v_R}{2 M_F}
$$

- Due to the large Yukawa coupling, the RH $t - T$ mixing ($\simeq y_t v_R / \sqrt{2} M_F$) is potentially large:
  - Important for determination of y_t in LR model and vacuum stability problem.
  - Important for constraints on T mass.
  - Important for production of H via T loop and decaying into $t\bar{t}$.

Physical scalars

- Simple scalar potential with soft parity breaking terms $\mu^2_{L,R}$:

$$\begin{aligned} \mathcal{V} &= -\mu_L^2 \chi_L^\dagger \chi_L - \mu_R^2 \chi_R^\dagger \chi_R \\ &\quad +\lambda_1 \left[(\chi_L^\dagger \chi_L)^2 + (\chi_R^\dagger \chi_R)^2 \right] + \lambda_2 (\chi_L^\dagger \chi_L)(\chi_R^\dagger \chi_R) \end{aligned}$$

- In the limit of exact parity symmetry, at tree level $v_L = 0$ [original; Kobakhidze & Spencer-Smith, JHEP**08**(2013)036];
- One has to add radiative corrections or soft breaking terms.

$$\chi_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_L \end{pmatrix}, \quad \chi_R = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_R \end{pmatrix}$$

- Only two physical scalars [$v_L = v_{\rm EW}$]:

$$\begin{pmatrix} 2\lambda_1 v_L^2 & \lambda_2 v_L v_R \\ \lambda_2 v_L v_R & 2\lambda_1 v_R^2 \end{pmatrix} \Longrightarrow \begin{cases} M_h^2 = 2\lambda_1 \left(1 - \frac{\lambda_2^2}{4\lambda_1^2}\right) v_L^2 \\ M_H^2 = 2\lambda_1 v_R^2 \end{cases}$$

Parameter space scan

Mahapatra & YCZ '14

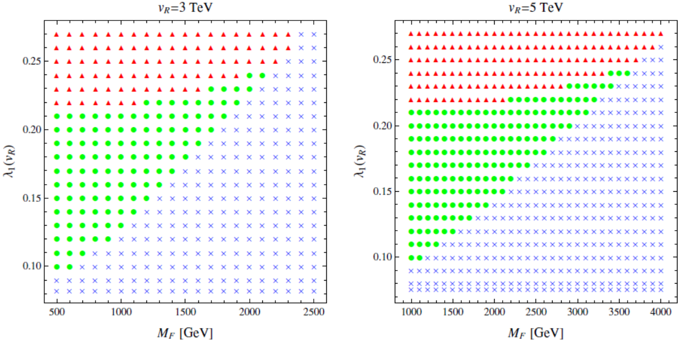
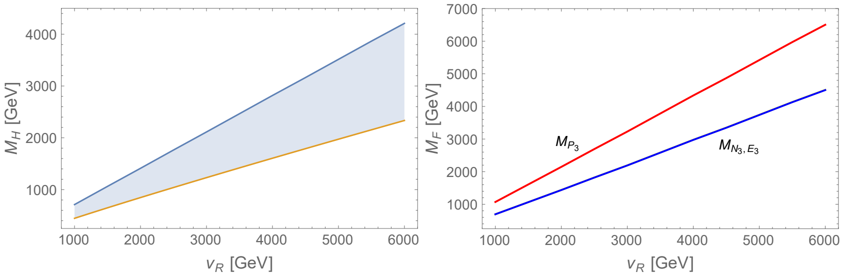


Figure 3. Scanning the parameter space of SLRM with $v_R = 3$ TeV (left) and 5 TeV (right). The green circles denote the allowed points in the parameter space, blue crosses are excluded by vacuum stability and red triangles excluded by the requirement of perturbativity.

Heavy Higgs & fermions @ TeV scale

Mahapatra & YCZ '14

- TeV scale Higgs:
  - Lower bound from vacuum stability: the coupling $\lambda_1 > \lambda^{\rm SM}$
  - Upper bound from perturbativity: the coupling $\lambda_1 \lesssim 0.25$
- TeV scale vector-like fermions ($3^{\rm rd}$ generation)
  - Upper bound from vacuum stability: $M_F < v_R$
  - Large y_t contributes significantly to M_T.



Solution to strong CP problem

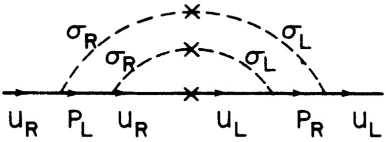
Babu & Mohapatra, PRL**62**(1989)1079; PRD**41**(1990)1286

- Strong CP parameter:

$$\bar{\theta} = \theta + \arg\det(M_u M_d)$$

- Contribution from 2-loop diagram below:
  (sin θ being typical mixing involving 3rd generation)

$$\bar{\theta} \simeq \left(\frac{y_t^2}{16\pi^2}\right)^2 \left(\frac{\lambda_2 v_L}{v_R}\right)^2 \sin^2\theta$$



Embedding in GUTs

Deppisch, Gonzalo & Graf '17; Chakrabortty, Maji, Patra & Srivastava '17;

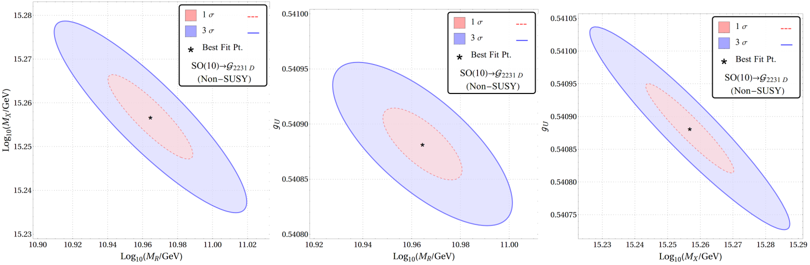


Figure: Correlations among intermediate scale M_R, unification scale M_X and the unified coupling g_U in the gauge breaking pattern $SO(10) \to G_{2231}$ for D-parity conserved case.

Topological effects

Deppisch, Gonzalo & Graf '17; Chakrabortty, Maji, Patra & Srivastava '17;

Intermediate Symmetry		Topological defects
$\mathcal{G}_{224}$	D-broken	monopoles
	D-conserved	domain wall + monopoles + Z_2-strings
$\mathcal{G}_{2231}$	D-broken	monopoles + embedded strings
	D-conserved	domain wall + monopoles + embedded strings
$\mathcal{G}_{2241}$	D-broken	monopoles + embedded strings
	D-conserved	domain walls + monopoles + embedded strings
$\mathcal{G}_{333}$	D-broken	textures
	D-conserved	domain walls + textures

Proton decay and cosmological constraints

Deppisch, Gonzalo & Graf '17; Chakrabortty, Maji, Patra & Srivastava '17;

Intermediate Symmetry (Non-SUSY)		**Topological defects** $M_R \gtrsim 10^{12}$ GeV		**Proton life time** $M_X \gtrsim 10^{16}$ GeV	
		No dim-5	dim-5	No dim-5	dim-5
$\mathcal{G}_{224}$	D-conserved	✓	✓	×	✓
	D-broken	×	×	×	✓
$\mathcal{G}_{2231}$	D-conserved	×	×	×	✓
	D-broken	×	×	✓	✓
$\mathcal{G}_{2241}$	D-conserved	✓	✓	×	✓
	D-broken	✓	✓	✓	✓
$\mathcal{G}_{333}$	D-conserved	—	✓	—	✓
	D-broken	—	✓	—	✓

The proton decay limit can be used to constrain the lower limit of the unification scale.

More topics (& some refs)

- probing seesaw mechanism in LRSM:
  Nemevsek, Senjanovic & Tello '13
- matching to low-energy SMEFT:
  Dekens, Andreoli, de Vries, Mereghetti & Oosterhof '21
- $0\nu\beta\beta$ in LRSM:
  Tello, Nemevsek, Nesti, Senjanovic & Vissani '10; Li, Ramsey-Musolf & Vasquez '20
- pheno of doubly-charged scalars in LRSM:
  Dev, Ramsey-Musolf & Dev '18; Dev & YCZ '18
- LNV & LFV signals in LRSM
  Awasthi, Parida, Patra '13; Deppisch, Gonzalo, Patra, Sahu, Sarkar '14;
  Mandal, Mitra & Sinha '17
- cold DM in extended LRSM
  Heeck & Patra '15; Garcia-Cely & Heeck '16
- warm DM in LRSM
  Nemevsek, Senjanovic & Zhang '12
- EDM in LRSM
  Frere, Galand, Le Yaouanc, Oliver, Pene & Raynal '90, '92, '92;
  Haba, Umeeda & Yamada '18; Bertolini, Maiezza & Nesti '18;
  Nieves, Chang & Pal '86; Lavoura '03
- leptogenesis
  Frere, Hambye & Vertongen '08
- ......

Conclusion

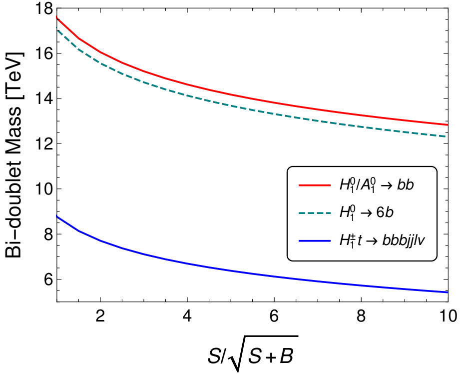
- LRSMs can have different variants.
- LRSMs are closely related to GUTs.
- The phenos of LRSM are very very... rich.

Thank you for your attention!

backup slides

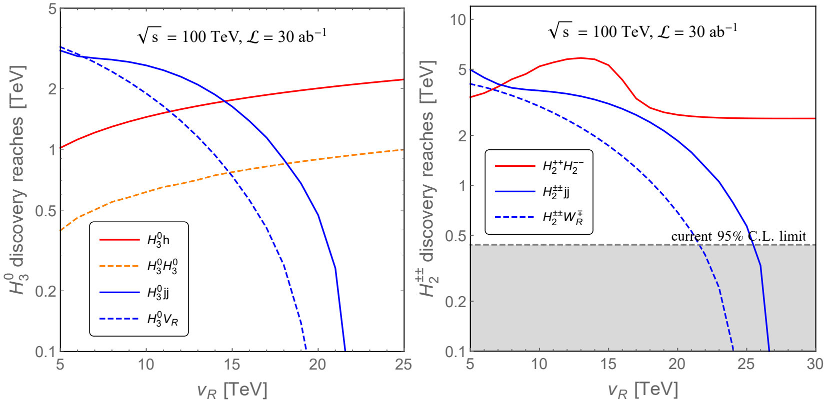
Sensitivity of heavy bidoublet scalars @ FCC-hh

$\sqrt{s} = 100$ TeV, $\mathcal{L} = 30$ ab^{-1}



3σ sensitivities: $\{15.2\,\mathrm{TeV},\ 14.7\,\mathrm{TeV},\ 7.1\,\mathrm{TeV}\}$

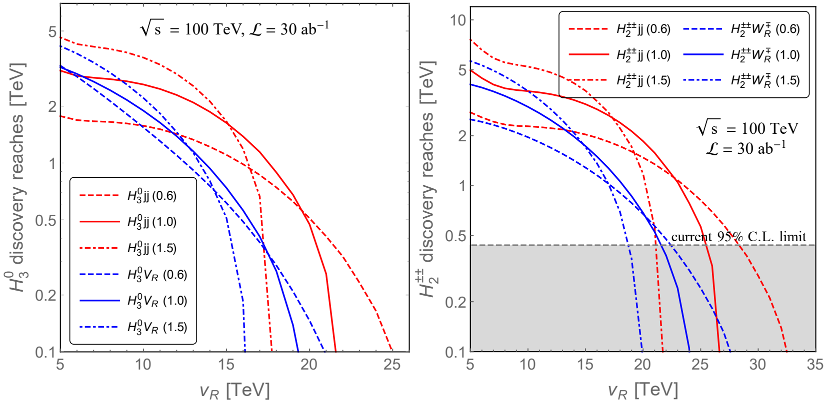
Hadrophobic scalar sensitivity @ FCC-hh



- Probable at the few-TeV scale, depending on the RH scale v_R.
- The SM Higgs portal production of H_3^0 depends also on the quartic couplings α_1 (& α_2 etc).
- "Bump"-structure in the right panel: $\Rightarrow$ Z_R resonance
- Associate production with heavy gauge boson are promising search channels at future 100 TeV collider

ATLAS, JHEP**03**(2015)041 for the 95% C.L. limit

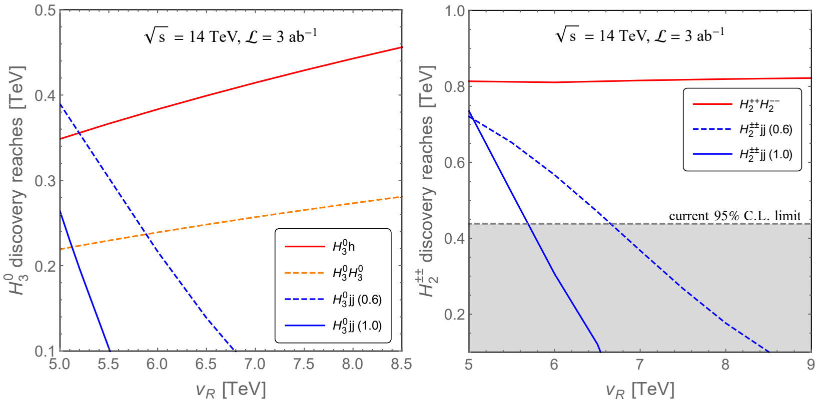
Hadrophobic scalar sensitivity @ FCC-hh, g_R effects



- Suppressed by the heavy gauge boson masses, the associate production modes are subdominant.
- When v_R small, the sensitivities benefit from larger g_R (large gauge coupling); When v_R large, benefit from small g_R (lighter V_R).

What realistic LR models accommodating $g_R > g_L$???

Hadrophobic scalar sensitivity @ LHC



- Only probable below the TeV scle.
- Rather sensitive to g_R at LHC in the VBF mode.
- Subleading contribution from associate production with V_R.