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Heavy Scalars in the Minimal Left-Right Symmetric Model @ FCC-hh

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Mainly based on the papers

- P. S. Bhupal Dev, R. N. Mohapatra & YCZ,
  Long Lived Light Scalars as Probe of Low Scale Seesaw Models,
  1701.abcde
- P. S. Bhupal Dev, R. N. Mohapatra & YCZ,
  Displaced Photon Signal from a Possible Light Scalar in Minimal Left-Right Seesaw Model,
  1612.09587
- P. S. Bhupal Dev, R. N. Mohapatra & YCZ,
  Probing the Higgs Sector of the Minimal Left-Right Symmetric Model at Future Hadron Colliders,
  JHEP**05**(2016)174 [1602.05947]

Minimal Left-Right Symmetric Model

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

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

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

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

- Left-handed Δ_L decouples from the TeV scale physics;

  [Chang, Mohapatra & Parida '84, Deshpande, Gunion, Kayser & Olness '91]
- Allowing 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

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

Bidoublet scalars

Almost degenerate masses

Triplet scalars

Couple to quarks only through mixings: Hadrophobic states

FCNC constraints on bidoublet scalars

Due to the flavor-changing neutral currents and precision meson data ($\bar{K}^0 - \bar{K}^0$, $B_d - \bar{B}_d$ & $\bar{B}_s - \bar{B}_s$ mixings etc), the bi-doublet masses are stringently constrained

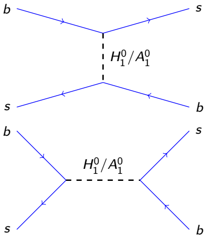
Mohapatra, Senjanovic, Tran, '83; Ecker, Grimus, Neufeld, '83; Pospelov, '97; Zhang, An, Ji, Mohapatra, '07; Maiezza, Nemevsek, Nesti, Senjanovic, '10; Chakrabortty, Gluza, Sevillano, Szafron, '12

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

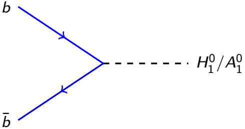
$$-\mathcal{L}_Y = h_q \bar{Q}_L \Phi Q_R + \tilde{h}_q \bar{Q}_L \tilde{\Phi} Q_R + \mathrm{h.c.}$$

$$\Rightarrow \begin{cases} H_1^0 \bar{u}u : \; -\sqrt{2}\xi \widehat{Y}_U + \frac{1}{\sqrt{2}} \left(V_L \widehat{Y}_D V_R^\dagger \right) \\ H_1^0 \bar{d}d : \; \frac{1}{\sqrt{2}} \left(V_L^\dagger \widehat{Y}_U V_R \right) - \sqrt{2}\xi \widehat{Y}_D \end{cases}$$

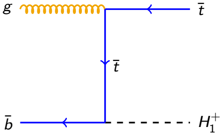
$\Longrightarrow$



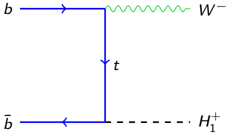
Dominant production modes



$$H_1^0(A_1^0)b\bar{b}: \left(\frac{1}{\sqrt{2}}y_t - \sqrt{2}\xi y_b\right) \simeq \frac{m_t}{\sqrt{2}\kappa}$$



$$H_1^+\bar{t}_L b_R: \left(\frac{1}{\sqrt{2}}y_t - \sqrt{2}\xi y_b\right) \simeq \frac{m_t}{\sqrt{2}\kappa}$$



associate production $H_1^\pm W^\mp$

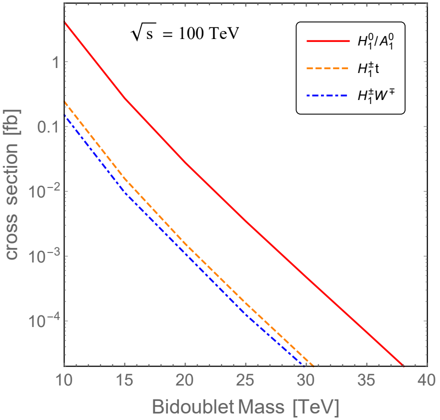
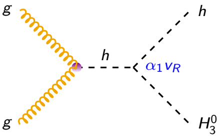


Figure: LO production cross section

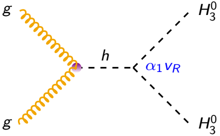
Hadrophobic scalar production

Couplings (w/o mixing)

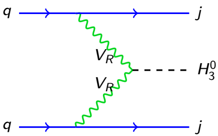
H_3^0: scalar (h), gauge (W_R & Z_R), Yukawa (N_i)
$H_2^{\pm\pm}$: scalar (h), gauge (γ, Z & Z_R), Yukawa ($\ell_i^\pm$)



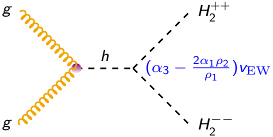
SM Higgs portal



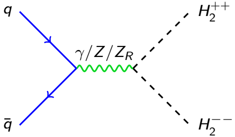
SM Higgs portal



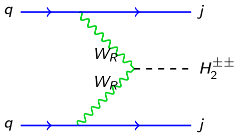
heavy VBF



SM Higgs portal



DY production



heavy VBF

Hadrophobic scalar production @ FCC-hh

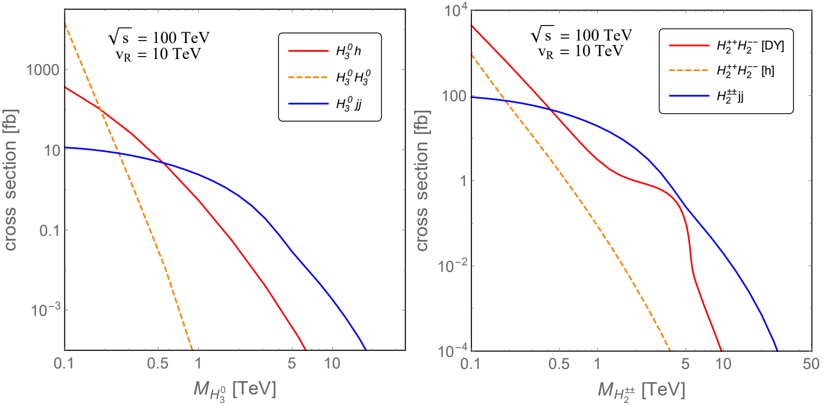


Figure: LO production cross section
$\alpha_1 = 0.01$, $\alpha_2 = 0$, $g_R = g_L$
$p_T(j) > 50$ GeV, $\Delta R(jj) > 0.4$

Bidoublet scalars: decay & sensitivity @ FCC-hh

Table: Dominant decay and search modes

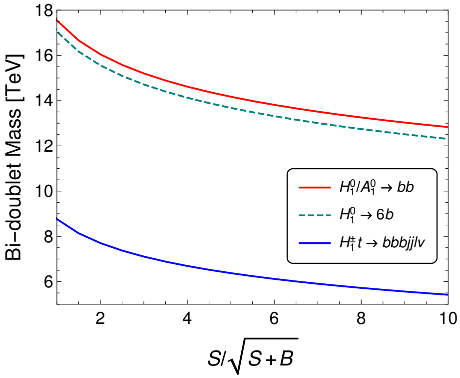
scalar	discovery channel	SM background	$\sigma_{\rm SM}$ [fb]
H_1^0/A_1^0	$H_1^0/A_1^0 \to b\bar{b}$	$b\bar{b}$	1500
	$H_1^0 \to hH_3^0 \to hhh$	$hhh \to 6b$	0.038
		$ZZZ \to 6b$	0.19
$H_1^\pm$	$H^\pm t \to ttb$	$ttb \to bbbjj\ell\nu$	984

- Bidoublet could decay also into the hadrophobic scalars and (heavy) gauge bosons, e.g. $H_1^0 \to hH_3^0$, $H_1^\pm \to ZW_R^\pm$.
- To suppress the SM background, taking into consideration of the FCNC constraints, we apply the special cuts

$$M_{bb} > 10 \text{ TeV for } H_1^0/A_1^0$$
$$M_{bb} > 5 \text{ TeV for } H_1^\pm$$

Sensitivity @ FCC-hh: bidoublet scalars

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



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

Hadrophobic scalar decay

Dominant decay modes

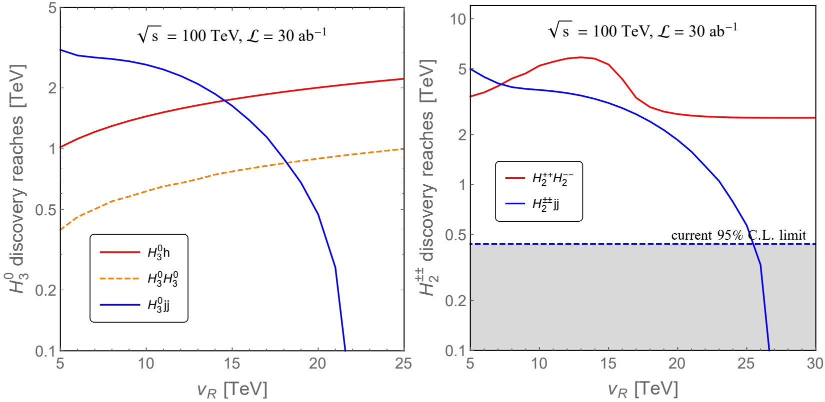
$$H_3^0 \to hh, \qquad H_2^{\pm\pm} \to \ell^\pm \ell^\pm$$

Table: Dominant decay and search modes

scalar	discovery channel	SM background	$\sigma_{\rm SM}$ [fb]
H_3^0	$H_3^0 h \to hhh$	$hhh \to 6b$	1.2
		$ZZZ \to 6b$	0.91
	$H_3^0 H_3^0 \to hhhh$	$ZZZZ \to 8b$	4.2×10^{-4}
	$H_3^0 jj \to hhjj$	$hhjj \to bbbbjj$	27
		$ZZW \to bbbbjj$	21
$H_2^{\pm\pm}$	$H_2^{++} H_2^{--} \to \ell^+\ell^+\ell^-\ell^-$	$ZZ \to \ell^+\ell^+\ell^-\ell^-$	2.1
	$H_2^{\pm\pm} jj \to \ell^\pm \ell^\pm jj$	WZ, ZZ, WW	1000

Sensitivity @ FCC-hh: hadrophobic scalars

ATLAS, 1412.0237



- 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.
- Bump structure in the right panel: $\Rightarrow$ Z_R resonance.

Light H_3^0 and displaced photon signal @ (LHC &) FCC-hh

Why light?

No **direct** interaction with the SM particles.

Why long-lived?

Mixing with h & H_1^0 $\Rightarrow$ stringent FCNC limits on $h - H_3^0$ mixing
Decaying predominantly into $\gamma\gamma$ through W_R (& $H_1^\pm$, $H_2^{\pm\pm}$) loop

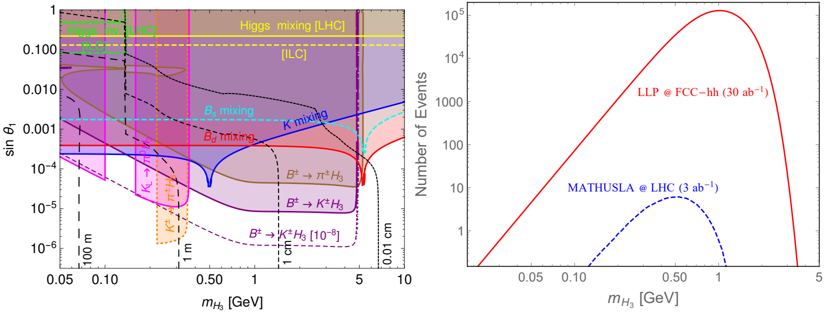


Figure: Current collider constraints on H_3, proper lifetime, and expected numbers of LLP events at LHC & FCC-hh [preliminary] 1612.09587, 1701.abcde

Conclusion: take-away messages

- In the minimal Left-Right Symmetric Model, the bidoublet scalars H_1^0, A_1^0, $H_1^\pm$ are stringently constrained by FCNC data, and can only be probed at future 100 TeV hadron collider such as FCC-hh.
- The bidoublet scalars can be probed up to $\simeq 15$ TeV at FCC-hh.
- The scalars H_3^0 & $H_2^{\pm\pm}$ from Δ_R are hadrophobic, and can be probed up to few-TeV scale, depending on v_R.
- The scalar H_3^0 can be possibly light, $\ll v_{\rm EW}$, long-lived, and searched for via displaced high energy photon signals, at both LHC and FCC-hh.

Thank you!