

# Testing Type II Radiative Seesaw Model

## – from Dark Matter Detection to LHC Signatures

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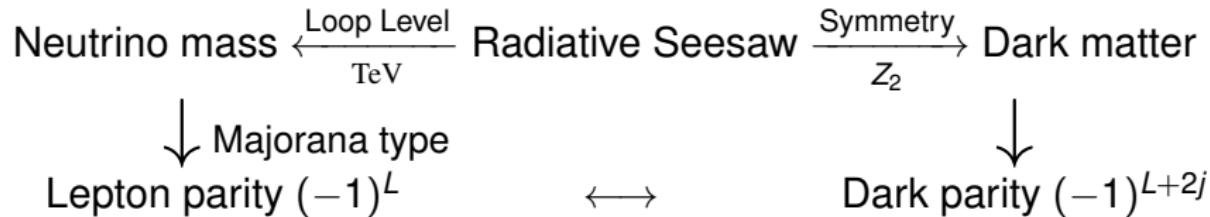
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Collaboration with Shu-Yuan Guo and Yi Liao



# Introduction



- ◊ Two important roles of the imposed symmetry:
  - Stable dark matter
  - Forbid lower order  $m_\nu$
- ◊ The difficulty for a type II radiative seesaw with DM:  
the **exact symmetry** used to forbid the tree-level coupling  $\overline{F_L^C} \xi F_L$  will also forbid any loop realization of it.
- ◊ Solution: the symmetry (**lepton parity**) used to forbid the hard term  $\overline{F_L^C} \xi F_L$  must be **softly broken** in the loop for neutrino mass.  
E. Ma, PRL **115**, no.1, 011801(2015)

# Model

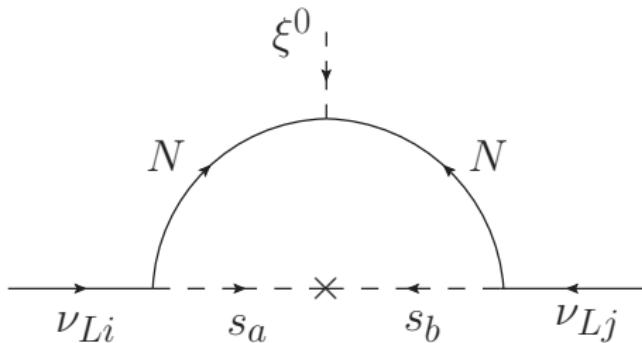


Figure: Radiative neutrino mass.

Particles	$\Phi$	$F_{iL}$	$\ell_{iR}$	$\xi$	$s_a$	$\chi$
Dark $Z_2$	+	+	+	+	-	-
$L$	0	1	1	0	1	0
$U(1)_Y$	1	-1	-2	2	0	-1
$SU(2)_L$	2	2	1	3	1	2

Table: Relevant fields and their charge assignments.

# Model

- ◇ The Yukawa couplings:

$$\begin{aligned}\mathcal{L}_Y = & -y'_{ij} \overline{F_{iL}} \Phi \ell_{jR} - M_\chi \bar{\chi}_L \chi_R - \frac{1}{2} z^L \overline{\chi_L^C} i\tau^2 \xi \chi_L \\ & - \frac{1}{2} z^R \overline{\chi_R^C} i\tau^2 \xi \chi_R - x'_{ai} s_a \overline{F_{iL}} \chi_R + \text{h.c.}\end{aligned}\quad (1)$$

- ◇ The complete scalar potential invariant under the dark  $Z_2$  :

$$\begin{aligned}V = & -m^2 \Phi^\dagger \Phi + M_\xi^2 \text{Tr} (\xi^\dagger \xi) + (m_s^2)_{ab} s_a^* s_b + (\kappa_{ab}^{i2} s_a s_b + \mu \Phi^\dagger \xi \tilde{\Phi} + \text{h.c.}) \\ & + \lambda (\Phi^\dagger \Phi)^2 + \lambda_1^\xi \left( \text{Tr} (\xi^\dagger \xi) \right)^2 + \lambda_2^\xi \text{Tr} (\xi^\dagger \xi)^2 + \lambda_{ab;cd}^{is} s_a^* s_b^* s_c s_d \\ & + \lambda_1^{\Phi\xi} (\Phi^\dagger \Phi) \text{Tr} (\xi^\dagger \xi) + \lambda_2^{\Phi\xi} \Phi^\dagger \xi \xi^\dagger \Phi + \lambda_{ab}^{is\Phi} s_a^* s_b \Phi^\dagger \Phi + \lambda_{ab}^{is\xi} s_a^* s_b \text{Tr} \xi^\dagger \xi\end{aligned}\quad (2)$$

# Neutrino Mass

- ◊ The one-loop induced neutrino masses:

$$m_\nu = \frac{ux^2\kappa^2}{8\sqrt{2}\pi^2 m_\chi^2} \left[ z^L F_L \left( \frac{m_s^2}{m_\chi^2} \right) + z^R F_R \left( \frac{m_s^2}{m_\chi^2} \right) \right], \quad (3)$$

where the loop functions  $F_L$  and  $F_R$  are given by:

$$F_L(x) = \frac{2}{(1-x)^2} + \frac{(1+x)\ln x}{(1-x)^3}, \quad (4)$$

$$F_R(x) = \frac{1+x}{(1-x)^2} + \frac{2x\ln x}{(1-x)^3}. \quad (5)$$

In order to obtain  $m_\nu \sim 0.01$  eV, we can take, for instance,  
 $u \sim 0.5$  GeV,  $x \sim 0.005$ ,  $\kappa \sim 3$  GeV,  $z^{L,R} \sim 1$  with both  $M_s$  and  $M_\chi$  around electroweak scale. ( $\langle \xi^0 \rangle = u/\sqrt{2}$ )

# Lepton Flavor Violation Constraints

- ◊ The branching ratio of the lepton radiative decay  $\ell_j \rightarrow \ell_i \gamma$

$$\text{BR}(\ell_j \rightarrow \ell_i \gamma) = \text{BR}(\ell_j \rightarrow \ell_i \bar{\nu}_i \nu_j) \frac{3\alpha}{16\pi G_F^2 M_\chi^4} \left| \sum_a x_{ai}^* x_{aj} F\left(\frac{M_{sa}^2}{M_\chi^2}\right) \right|^2, \quad (6)$$

with the loop function  $F(x)$  given by:

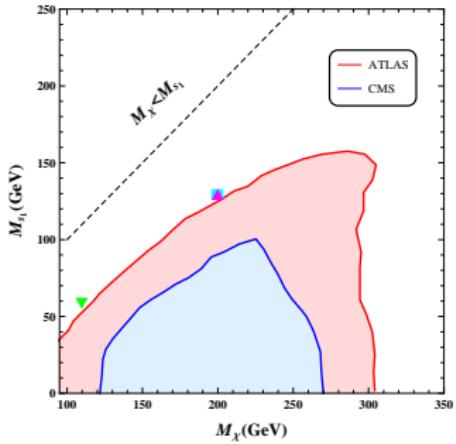
$$F(x) = -\frac{1}{12(1-x)^4} [1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x]. \quad (7)$$

- ◊ The MEG limit:  $\text{BR}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$  requires that

$$\left| x_{ae}^* x_{a\mu} \right| \lesssim 5 \times 10^{-5} \left( \frac{M_\chi}{100 \text{ GeV}} \right)^2 \quad (8)$$

- ◊ If  $M_\chi \sim 200 \text{ GeV}$ , then  $|x_{ai}| \lesssim 0.01$  without requiring a special flavor structure.

# LHC Constraints and Benchmark Points



**Figure:** Exclusion regions in the  $M_{S_1}$ – $M_\chi$  plane by ATLAS (1403.5294) and CMS (1405.7570) from slepton search.

	$M_{S_1}$ (GeV)	$M_{S_2}$ (GeV)	$M_\chi$ (GeV)	$M_\xi$ (GeV)	$\lambda_{11}^{S\Phi}$	$\lambda_{12}^{S\Phi}$	$\Omega_{DM} h^2$	$\sigma^{SI}$ (pb)	Marker
BP-A	60	200	110	400	0.00095	0.05	0.1177	$2.1 \times 10^{-12}$	▼
BP-B	130	250	200	410	0.010	0.34	0.1186	$5.1 \times 10^{-11}$	▲
BP-C	130	300	200	500	0.005	0.40	0.1172	$1.3 \times 10^{-11}$	■

**Table:** Benchmark points for the study of dark matter and collider signatures.

# Annihilation Channels

- ◊ The annihilation channels, which can be classified
  - $s_1^* s_1 \xrightarrow{E,N} \ell^+ \ell^-, \nu \bar{\nu}$  suppressed by small  $x_{ai}$
  - $s_1^* s_1 \rightarrow H^{++} H^{--}, H^+ H^-$ , ... kinematically forbidden
  - $s_1^* s_1 \xrightarrow{h} W^+ W^-, b\bar{b}, \dots$  Higgs portal
  - $s_1^* s_1 \xrightarrow[t-channel]{s_2} hh$  important for light  $s_1$
  - $s_1^* s_2, s_2^* s_1 \xrightarrow{h} W^+ W^-, b\bar{b}, \dots$ , coannihilation

◊ We fix the following input parameters as

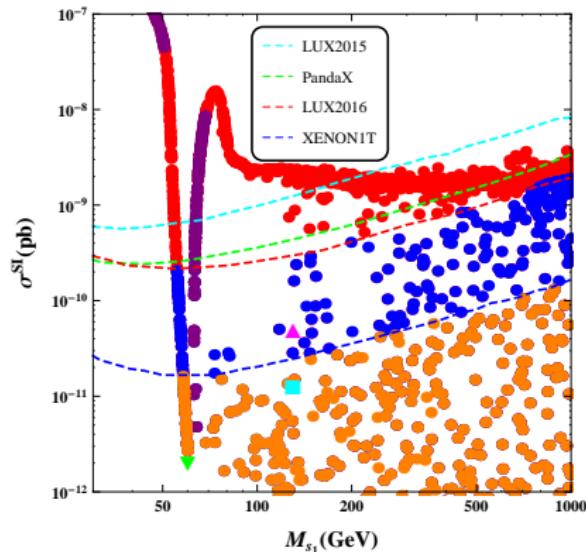
$$x_{ai} = 0.005, M_\xi = 500 \text{ GeV}, \lambda^{s\xi} = 0, \lambda_{22}^{s\Phi} = 0.01, \quad (9)$$

and also vary the parameters as

$$\begin{aligned} M_{s_1} &\in [10, 1000] \text{ GeV}, & M_{s_2} - M_{s_1} &\in [1, 1000] \text{ GeV}, \\ \lambda_{11}^{s\Phi} &\in [0.001, 1], & \lambda_{12}^{s\Phi} &\in [0.001, 1]. \end{aligned} \quad (10)$$

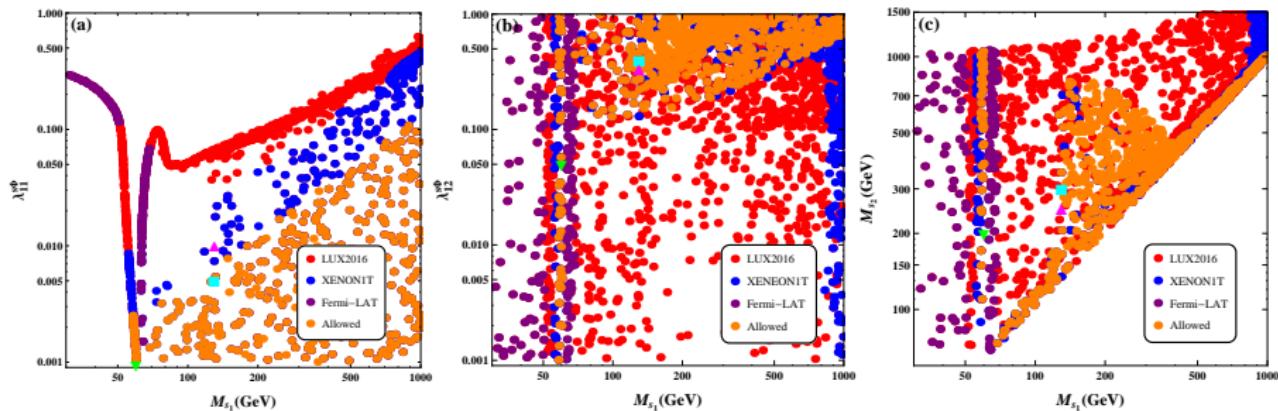
# Direct Detection

- ◇ We require that the relic density in  $2\sigma$  range, i.e.,  $0.1153 < \Omega_{\text{DM}} h^2 < 0.1221$  (1303.5076).



**Figure:** Spin-independent DM-nucleon cross section  $\sigma^{\text{SI}}$  with constraints from LUX2015(1512.03506), PandaX-II (1607.07400), LUX2016 (IDM2016) and XENON1T (1206.6288).

# Direct Detection

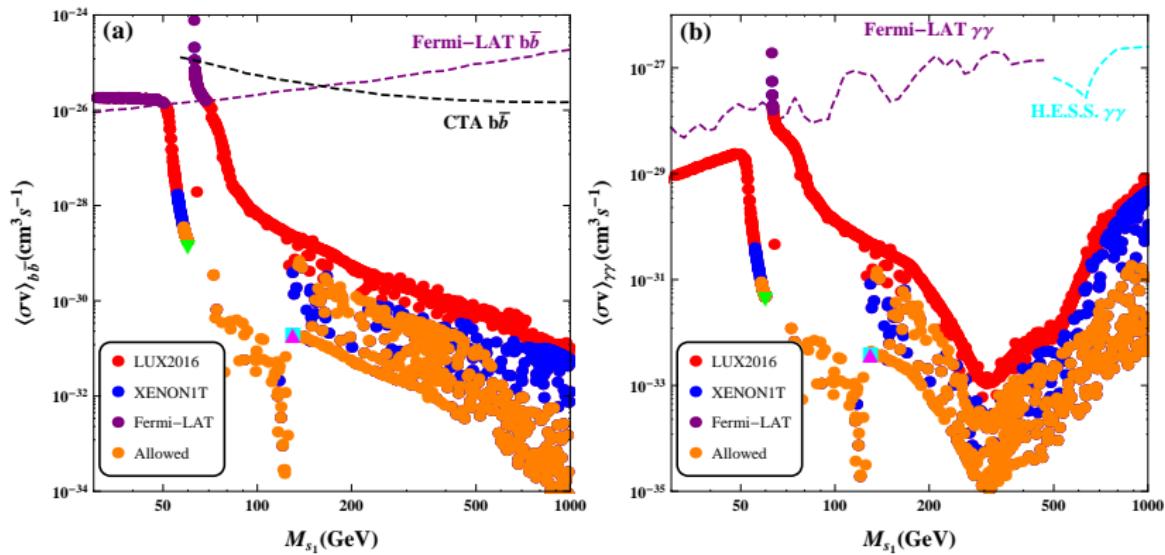


**Figure:** Excluded and allowed parameter space in the  $\lambda_{11}^{s\phi} - M_{S_1}$  (a),  $\lambda_{12}^{s\phi} - M_{S_1}$  (b), and  $M_{S_2} - M_{S_1}$  (c) planes.

◊ Some results:

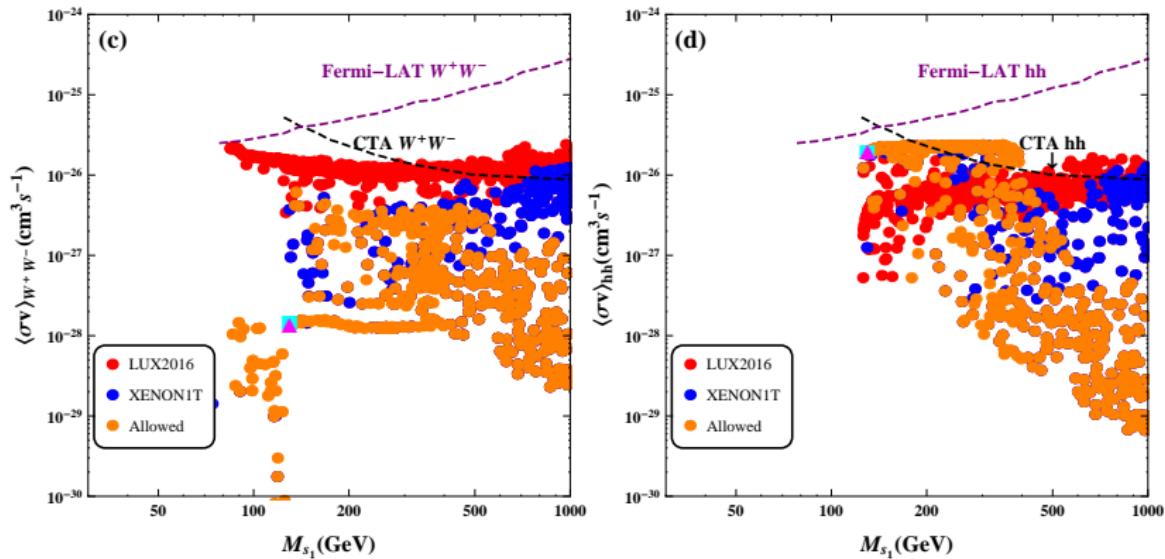
- 1.  $\lambda_{11}^{s\phi} \lesssim 0.05$ ,  $\lambda_{12}^{s\phi} \gtrsim 0.1$
- 2.  $s_1^* s_1 \xrightarrow{S_2} hh$  only happens when  $M_{S_1} < 400$  GeV
- 3. Coannihilation could always survive

# Indirect Detection



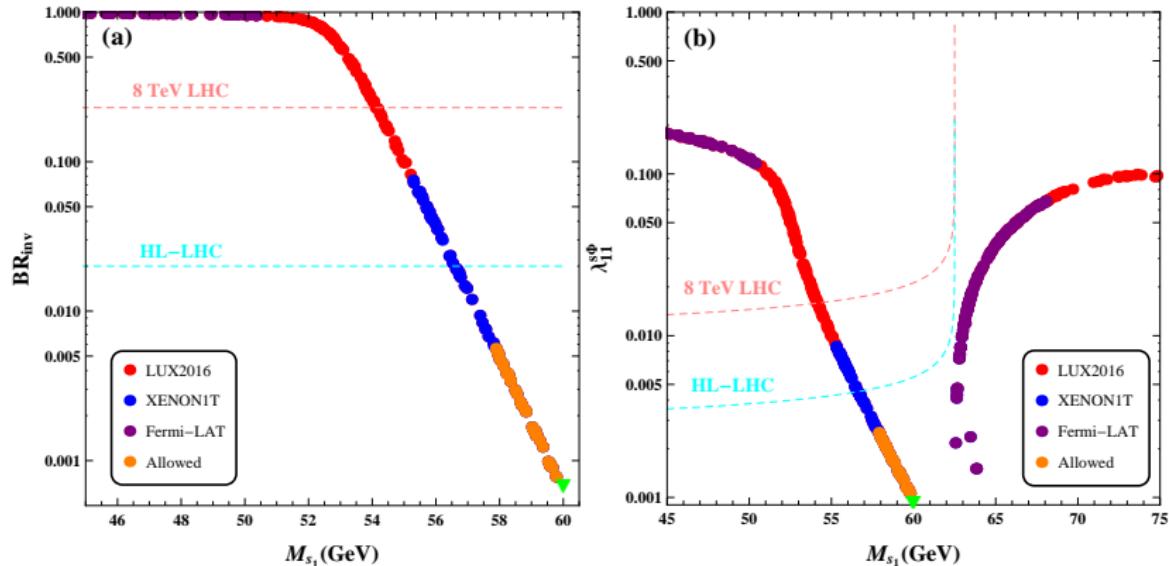
**Figure:** Velocity-averaged cross sections times velocity  $\langle \sigma v \rangle$  for the annihilation into  $b\bar{b}$  (a),  $\gamma\gamma$  (b),  $W^+ W^-$  (c), and  $hh$  (d) with bounds from Fermi-LAT , H. E. E. S. , and CTA .

# Indirect Detection



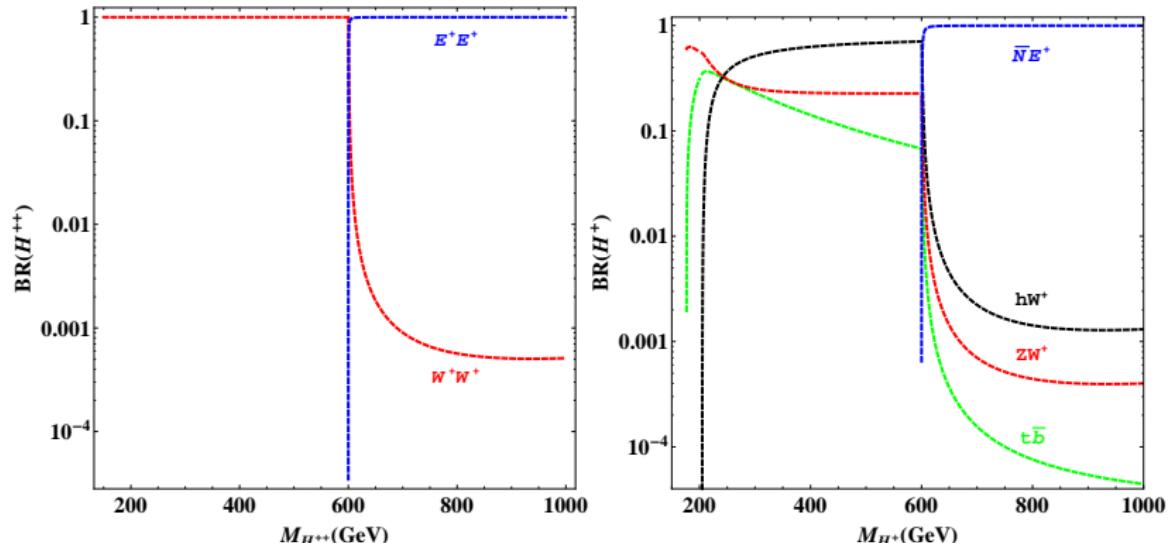
**Figure:** Velocity-averaged cross sections times velocity  $\langle \sigma v \rangle$  for the annihilation into  $b\bar{b}$  (a),  $\gamma\gamma$  (b),  $W^+ W^-$  (c), and  $hh$  (d) with bounds from Fermi-LAT , H. E. E. S. , and CTA .

# Higgs Invisible Decay



**Figure:** Distribution of  $\text{BR}_{\text{inv}}$ (a) and  $\lambda_{11}^{s\phi}$ (b) as a function of  $M_{S1}$  in the low mass region.

# Decay Properties



**Figure:** Branching ratios of scalar triplet  $\xi$  versus  $M_\xi$ . Here, we have set  $u = 0.5$  GeV,  $M_\chi = 300$  GeV, and  $z^{L,R} = 1$ .

# Four-Lepton Signature

- ◊ The four-lepton signature:

$$pp \rightarrow H^{++}H^{--} \rightarrow E^+E^+E^-E^- \rightarrow \ell^+\ell^+\ell^-\ell^- + \cancel{E}_T \quad (11)$$

- ◊ SM backgrounds: di-bosons ( $WZ, ZZ, WW$ ), tri-bosons ( $VVV$  with  $V = W, Z$ ), top-pair ( $t\bar{t}$ ), and top+boson (mainly from  $t\bar{t}V$ ) with leptonic decays of  $W, Z$ . (CMS 1404.5801)

- ◊ Basic cuts:

$$p_T^\ell > 10 \text{ GeV}, p_T^{\ell_1} > 20 \text{ GeV}, |\eta(\ell)| < 2.4. \quad (12)$$

- ◊ We choose OSSF0 four-lepton events:

$$N(\ell) = 4, \quad N(b) = 0, \quad (13)$$

$$N(e^+, e^-) = 0, \quad N(\mu^+, \mu^-) = 0. \quad (14)$$

# Four-Lepton Signature

Channels	No Cuts	$p_T^\ell > 10 \text{ GeV}$ , $p_T^{\ell_1} > 20 \text{ GeV}$ , $ \eta(\ell)  < 2.4$	$N(\ell) = 4$	$N(b) = 0$	$N(e^+e^-) = 0$ , $N(\mu^+\mu^-) = 0$
BP-A	173(205)	169.66(200.61)	53.52(61.60)	51.16(58.90)	6.30(7.60)
BP-B	155(184)	146.29(173.51)	39.85(43.69)	38.22(41.40)	4.79(5.05)
BP-C	62(75)	60.14(73.32)	18.23(22.06)	17.29(21.00)	2.11(2.63)
$WZ$	35980(39760)	31581(34547)	0.00(0.00)	0.00(0.00)	0.00(0.00)
$ZZ$	4220(4666)	3884.1(4254.1)	781.8(837.9)	771.7(826.4)	0.00(0.00)
$WW$	305900(336200)	226498(245794)	0.00(0.00)	0.00(0.00)	0.00(0.00)
$VVV$	145(163)	132.92(148.77)	5.61(5.95)	5.5(5.81)	0.00(0.00)
$t\bar{t}$	2273000(2685000)	1795961(2112294)	0.00(0.00)	0.00(0.00)	0.00(0.00)
$t\bar{t}V$	520(604)	473.27(548.70)	27.83(32.87)	5.06(6.17)	0.00(0.00)

**Table:** Cut-flow of four-lepton signature for the three benchmark points and dominant backgrounds at 13(14) TeV LHC with  $100 \text{ fb}^{-1}$ .

# Tri-Lepton Signature

- ◊ The tri-lepton signature

$$pp \rightarrow H^{\pm\pm} H^\mp \rightarrow E^\pm E^\pm E^\mp N \rightarrow \ell^\pm \ell^\pm \ell^\mp + \cancel{E}_T, \quad (15)$$

- ◊ Similar SM backgrounds as the four-lepton signature.
- ◊ Basic cuts:

$$p_T^\ell > 10 \text{ GeV}, p_T^{\ell_1} > 20 \text{ GeV}, |\eta(\ell)| < 2.4. \quad (16)$$

- ◊ Selection cuts:

$$N(\ell) = 3, \quad N(b) = 0, \quad (17)$$

$$85 \text{ GeV} < M_{\ell^+\ell^-} < 95 \text{ GeV}, (\text{Zveto}) \quad (18)$$

$$\cancel{E}_T > 150 \text{ GeV}, \quad \Delta R_{\ell^\pm \ell^\pm} < 2 \quad (19)$$

# Tri-Lepton Signature

Channels	No Cuts	$p_T^\ell > 10 \text{ GeV}$ , $p_T^{\ell_1} > 20 \text{ GeV}$ , $ \eta(\ell)  < 2.4$	$N(\ell) = 3$ $N(b) = 0$	$Z$ Veto	$\cancel{E}_T > 150 \text{ GeV}$	$\Delta R_{\ell^\pm \ell^\pm} < 2$
BP-A	562(665)	543.35(639.85)	215.04(252.59)	143.76(169.03)	57.02(65.20)	48.10(55.19)
BP-B	501(597)	471.93(560.78)	172.29(201.86)	114.09(133.42)	31.13(38.00)	28.64(34.65)
BP-C	202(245)	194.26(235.12)	76.87(91.25)	52.39(63.83)	21.74(25.88)	18.99(22.86)
$WZ$	35980(39760)	31578.2(34543.5)	8492.0(9012.4)	835.8(932.4)	16.19(20.68)	1.08(0.79)
$ZZ$	4220(4666)	3884.1(4254.1)	1218.2(1311.1)	119.2(129.2)	0.00(0.23)	0.00(0.05)
$WW$	305900(336200)	226474(245754)	0.31(0.67)	0.31(0.67)	0.00(0.00)	0.00(0.00)
$VVV$	145(163)	132.91(148.76)	40.53(44.7)	19.66(21.60)	1.17(1.20)	0.35(0.32)
$t\bar{t}$	2273000(2685000)	1795961(2112120)	36.37(25.39)	14.09(9.76)	0.91(0.00)	0.45(0.00)
$t\bar{t}V$	520(604)	473.27(548.68)	25.68(30.03)	11.08(12.94)	1.29(1.40)	0.51(0.62)

**Table:** Cut-flow of tri-lepton signature for the three benchmark points and dominant backgrounds at 13(14) TeV LHC with an integrated luminosity of  $100 \text{ fb}^{-1}$ .

# Significance

Benchmark Points	Four-Lepton		
	$S$	$B$	$S/\sqrt{S+B}$
BP-A	6.30(7.60)	0.00(0.00)	2.50(2.76)
BP-B	4.79(5.05)		2.19(2.25)
BP-C	2.11(2.63)		1.45(1.62)
Benchmark Points	Tri-Lepton		
	$S$	$B$	$S/\sqrt{S+B}$
BP-A	48.2(55.2)	2.39(1.78)	6.77(7.31)
BP-B	28.6(34.7)		5.14(5.74)
BP-C	19.0(22.9)		4.11(4.61)

**Table:** Testability of four-lepton and tri-lepton signatures at 13(14) TeV LHC.  
Here, the four-lepton signature contains only the OSSF0 final states.

# Conclusion

- ◊ Type II radiative seesaw with DM is realised by **soft broken** of **lepton parity**, in which neutrino mass and DM are related at **one-loop level**.
- ◊ The existence of  $s_2$  enlarged parameter space of  $s_1$  DM under constraints from **relic density**, its **direct and indirect detection**, and **invisible Higgs decays**:
  - $M_{s_1} \sim M_h/2$
  - $M_{s_1} \sim M_h$
  - $M_{s_1} \sim M_{s_2}$
- ◊ New decay channel  $H^{++} \rightarrow E^+ E^+$  and  $H^+ \rightarrow N E^+$ 
  - Four-lepton Signature: Clean BG, some signal events
  - Tri-lepton Signature: Some BG, many signal events
  - Tri-lepton is the "**golden channel**".