Loopholes in W' searches at the LHC

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Outline

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Review of GUTs

- All SM matter plus some Higgs multiplets and a singlet can be embedded into a **27**-plet of E_6.
- E_6 has the maximal subgroup, under which the **27** representation decomposes as

$$\mathbf{27} \rightarrow \mathbf{16}_1 + \mathbf{10}_{-2} + \mathbf{1}_4$$

- There is an alternative, and also quite interesting, embedding of the SM into E_6, which is through the subgroup $SU(3)_C \otimes SU(3)_L \otimes SU(3)_H$. **27** decomposes as

$$\mathbf{27} = (\mathbf{3}, \mathbf{3}, 1) \oplus (\bar{\mathbf{3}}, 1, \bar{\mathbf{3}}) \oplus (1, \bar{\mathbf{3}}, \mathbf{3}) \quad \equiv \quad q \quad + \quad \bar{q} \quad + \quad l$$

$$q = \begin{pmatrix} u_L \\ d_L \\ d'_L \end{pmatrix}, \qquad \bar{q} = \begin{pmatrix} u_R^c & d_R^c & d_R'^c \end{pmatrix}, \qquad l = \begin{pmatrix} E_R^c & N_L & \nu_L \\ N_R^c & E_L & e_L \\ e_R^c & \nu_R^c & n_R^c \end{pmatrix}$$

Review of GUTs

$$E_6 \longrightarrow SU(3)_C \otimes SU(3)_L \otimes SU(3)_H$$
$$\longrightarrow SU(3)_C \otimes SU(2)_L \otimes SU(2)_H \otimes U(1)_X$$

$$\mathbf{27} = (\mathbf{3},\mathbf{3},1) \oplus (\bar{\mathbf{3}},1,\bar{\mathbf{3}}) \oplus (1,\bar{\mathbf{3}},\mathbf{3}) \quad \equiv \quad q \quad + \quad \bar{q} \quad + \quad l$$

$$q = \begin{pmatrix} u_L \\ d_L \\ d'_L \end{pmatrix}, \quad \bar{q} = \begin{pmatrix} u^c_R & d^c_R & d'^c_R \end{pmatrix}, \quad l = \begin{pmatrix} E^c_R & N_L & \nu_L \\ N^c_R & E_L & e_L \\ e^c_R & \nu^c_R & n^c_R \end{pmatrix}$$

- There are three different ways to embed $SU(2)_H$ into $SU(3)_H$:

1) Generic Left Right SM (LRSM) $\longrightarrow SU(2)_H = SU(2)_R$
2) Alternative Left Right SM (ALRSM) $\longrightarrow SU(2)_H = SU(2)_{R'}$
3) Inert Doublet Model $\longrightarrow SU(2)_H = SU(2)_I$

The Left-Right Symmetric Model (LRSM)

	Fields	$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
Matter	Q_{L_i}	$(\mathbf{2}, \mathbf{1}, +\frac{1}{3})$
	Q_{R_i}	$(\mathbf{1}, \mathbf{2}, -\frac{1}{3})$
	L_{L_i}	$(\mathbf{2}, \mathbf{1}, -1)$
	L_{R_i}	$(\mathbf{1}, \mathbf{2}, -1)$
Higgs	Φ	$(\mathbf{2}, \mathbf{2}, 0)$
	Δ_L	$(\mathbf{3}, \mathbf{1}, 2)$
	Δ_R	$(\mathbf{1}, \mathbf{3}, 2)$

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\downarrow \Delta_R$$

$$SU(3)_C \times \quad SU(2)_L \times U(1)_Y$$

$$\downarrow \Phi$$

$$SU(3)_C \times \quad U(1)_{EM}$$

$$\Phi \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (\mathbf{2}, \mathbf{2}, \mathbf{0})$$

$$Q_{Li} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i \sim (\mathbf{2}, \mathbf{1}, \mathbf{1/3}) \,, \quad Q_{Ri} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i \sim (\mathbf{1}, \mathbf{2}, \mathbf{1/3}) \,,$$

$$\Delta_L \equiv \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix} \sim (\mathbf{3}, \mathbf{1}, \mathbf{2})$$

$$L_{Li} = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}_i \sim (\mathbf{2}, \mathbf{1}, -\mathbf{1}) \,, \quad L_{Ri} = \begin{pmatrix} \nu_R \\ \ell_R \end{pmatrix}_i \sim (\mathbf{1}, \mathbf{2}, -\mathbf{1}) \,,$$

$$\Delta_R \equiv \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, \mathbf{2})$$

LRSM Lagrangian & Symmetry Breaking

$$SU(2)_R \otimes U(1)_{B-L} \longrightarrow U(1)_Y$$

$$\langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L}/\sqrt{2} & 0 \end{pmatrix}, \quad \langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R/\sqrt{2} & 0 \end{pmatrix}$$

$$SU(2)_L \otimes U(1)_Y \longrightarrow U(1)_{EM}$$

$$v_R \gg (\kappa_1,\ \kappa_2) \gg v_L, \quad \sqrt{\kappa_1^2 + \kappa_2^2} = v = 246\ \text{GeV}$$

$$\langle \Phi \rangle = \begin{pmatrix} \kappa_1/\sqrt{2} & 0 \\ 0 & \kappa_2 e^{i\alpha}/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L}_{\text{LRSM}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_Y - V(\Phi, \Delta_L, \Delta_R)$$

$$\mathcal{L}_{\text{kin}} = i \sum \bar{\psi} \gamma^\mu D_\mu \psi$$

$$\begin{aligned} &= \bar{L}_L \gamma^\mu \left(i\partial_\mu + g_L \frac{\vec{\tau}}{2} \cdot \vec{W}_{L\mu} - \frac{g_{B-L}}{2} B_\mu \right) L_L \\ &+ \bar{L}_R \gamma^\mu \left(i\partial_\mu + g_R \frac{\vec{\tau}}{2} \cdot \vec{W}_{R\mu} - \frac{g_{B-L}}{2} B_\mu \right) L_R \\ &+ \bar{Q}_L \gamma^\mu \left(i\partial_\mu + g_L \frac{\vec{\tau}}{2} \cdot \vec{W}_{L\mu} + \frac{g_{B-L}}{6} B_\mu \right) Q_L \\ &+ \bar{Q}_R \gamma^\mu \left(i\partial_\mu + g_R \frac{\vec{\tau}}{2} \cdot \vec{W}_{R\mu} + \frac{g_{B-L}}{6} B_\mu \right) Q_R \end{aligned}$$

$$\begin{aligned} \mathcal{L}_Y = -\Big[& Y_{L_L} \bar{L}_L \Phi L_R + \tilde{Y}_{L_R} \bar{L}_R \Phi L_L \\ & + Y_{Q_L} \bar{Q}_L \tilde{\Phi} Q_R + \tilde{Y}_{Q_R} \bar{Q}_R \tilde{\Phi} Q_L \\ & + h_L^{ij} \bar{L}^c_{L_i} i\tau_2 \Delta_L L_{L_j} + h_R^{ij} \bar{L}^c_{R_i} i\tau_2 \Delta_R L_{R_j} + \text{h.c.} \Big] \end{aligned}$$

Gauge Sector

$$\begin{pmatrix} Z_L^\mu \\ B^\mu \\ Z_R^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \sin\phi & -\sin\theta_W \cos\phi \\ \sin\theta_W & \cos\theta_W \sin\phi & \cos\theta_W \cos\phi \\ 0 & \cos\phi & -\sin\phi \end{pmatrix} \begin{pmatrix} W_L^{3\mu} \\ W_R^{3\mu} \\ V^\mu \end{pmatrix}$$

Gauge Sector

$$\begin{pmatrix} Z_L^\mu \\ B^\mu \\ Z_R^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W\sin\phi & -\sin\theta_W\cos\phi \\ \sin\theta_W & \cos\theta_W\sin\phi & \cos\theta_W\cos\phi \\ 0 & \cos\phi & -\sin\phi \end{pmatrix} \begin{pmatrix} W_L^{3\mu} \\ W_R^{3\mu} \\ V^\mu \end{pmatrix}$$

$$\begin{pmatrix} Z_R^\mu \\ B^\mu \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} W_R^{3\mu} \\ V^\mu \end{pmatrix}$$

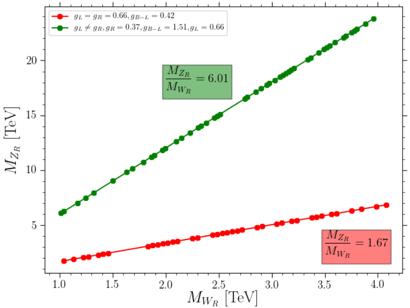
Gauge Sector

$$\begin{pmatrix} Z_L^\mu \\ B^\mu \\ Z_R^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \sin\phi & -\sin\theta_W\cos\phi \\ \sin\theta_W & \cos\theta_W\sin\phi & \cos\theta_W\cos\phi \\ 0 & \cos\phi & -\sin\phi \end{pmatrix} \begin{pmatrix} W_L^{3\mu} \\ W_R^{3\mu} \\ V^\mu \end{pmatrix}$$

$$\begin{pmatrix} Z_R^\mu \\ B^\mu \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} W_R^{3\mu} \\ V^\mu \end{pmatrix}$$

$$M_A = 0$$

$$M^2_{Z_{1,2}} = \frac{1}{4}\Big[\left[g_L^2 v^2 + 2v_R^2(g_R^2 + g_{B-L}^2)\right] \mp \sqrt{\left[g_L^2 v^2 + 2v_R^2(g_R^2+g_{B-L}^2)\right]^2 - 4g_L^2(g_R^2 + 2g_{B-L}^2)}$$

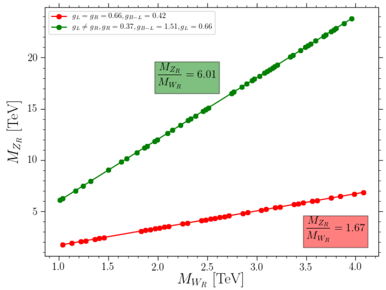


Charged Sector

$$\begin{pmatrix} W_1 \\ W_2 \end{pmatrix} = \begin{pmatrix} \cos\xi & -\sin\xi \\ \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} W_L \\ W_R \end{pmatrix}$$

Charged Sector

$$\begin{pmatrix} W_1 \\ W_2 \end{pmatrix} = \begin{pmatrix} \cos\xi & -\sin\xi \\ \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} W_L \\ W_R \end{pmatrix}$$



In the limit of $(\kappa_1, \kappa_2) \ll v_R$ and $g_R \sim g_L$ we have

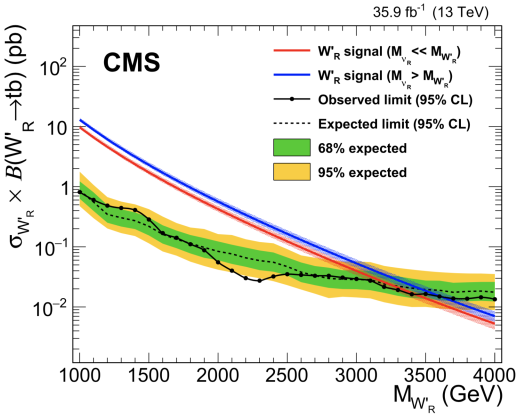
$$\sin\xi \approx \frac{\kappa_1\kappa_2}{v_R^2}, \quad \sin^2\xi \approx 0, \quad \cos\xi \approx 1, \text{ leading to}$$

$$M_{W_1}^2 = \frac{1}{4} g_L^2 v^2 , \qquad M_{W_2}^2 = \frac{1}{4}\left[2g_R^2 v_R^2 + g_R^2 v^2 + 2 g_R g_L \frac{\kappa_1^2\kappa_2^2}{v_R^2}\right]$$

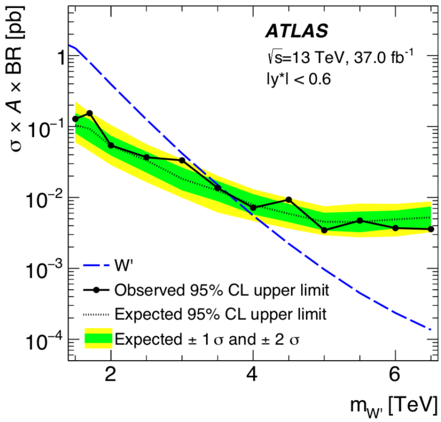
Outline

Searches for W' bosons at the LHC

$W_R \to t\bar{b}$ channel

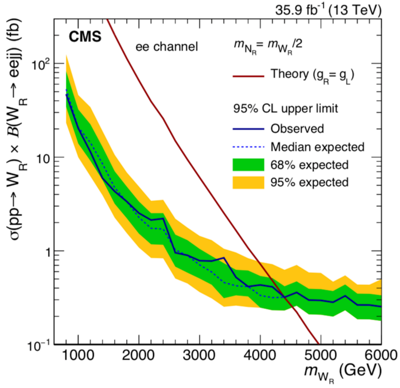


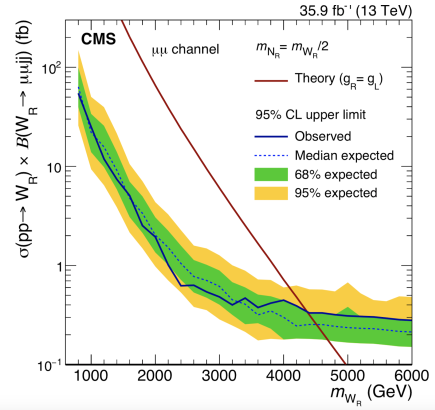
$W_R \to jj$ channel



Searches for W' bosons at the LHC

$$W_R \to \ell \nu_R \to \ell \ell W_R^{\star} \to \ell \ell q q', \quad \ell = e \text{ or } \mu \,.$$





Outline

Motivation for $g_L \neq g_R$

Breaking the symmetry to $U(1)_{EM}$ impose,

$$\frac{1}{e^2} = \frac{1}{g_L^2} + \frac{1}{g_R^2} + \frac{1}{g_{B-L}^2}$$

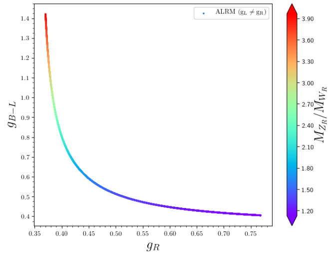
$SU(2)_R \otimes U(1)_{B-L} \longrightarrow U(1)_Y$ requires,

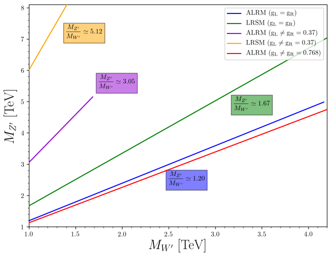
$$\frac{1}{g_Y^2} = \frac{1}{g_R^2} + \frac{1}{g_{B-L}^2}$$

$$\tan\theta_W = \frac{g_R \sin\phi}{g_L} \leq \frac{g_R}{g_L},$$

Theoretical constraint on g_R gauge coupling

$$g_L \tan\theta_W \leq g_R$$





Outline

Analysis

Observable	Constraints	Observable	Constraints
ΔB_s	[10.2-26.4]	ΔB_d	[0.294-0.762]
ΔM_K	$< 5.00 \times 10^{-15}$	$\frac{\Delta M_K}{\Delta M_K^{SM}}$	[0.7-1.3]
ϵ_K	$< 3.00 \times 10^{-3}$	$\frac{\epsilon_K}{\epsilon_K^{SM}}$	[0.7-1.3]
$\text{BR}(B^0 \to X_s\gamma)$	$[2.99, 3.87] \times 10^{-4}$	$\frac{BR(B^0\to X_s\gamma)}{BR(B^0\to X_s\gamma)_{SM}}$	[0.7-1.3]
M_h	[124, 126] GeV	$M_{H^{\pm\pm}_{1,2}}$	> 535 GeV
$M_{H_4, A_2, H_2^\pm}$	$> 4.75 \times M_{W_R}$		

Table: Current experimental bounds imposed for consistent solutions.

Parameter	Scanned range
v_R	[2.2, 20] TeV
$V^R_{\rm CKM}$: c^R_{12}, c^R_{13}, c^R_{23}	$[-1, 1]$
$\text{diag}(h^{ij}_R)$	[0.001, 1]

Table: Scanned parameter space.

$$M^{ij}_{\nu_R} = h^{ij}_R v_R$$

$$V^R_{\rm CKM} = \begin{bmatrix} c^R_{12}c^R_{13} & s^R_{12}c^R_{13} & s^R_{13}e^{i\delta_R} \\ -s^R_{12}c^R_{23} - c^R_{12}s^R_{23}s_{13}e^{i\delta_R} & c^R_{12}c^R_{23} - s^R_{12}s^R_{23}s^R_{13}e^{i\delta_R} & s^R_{23}c^R_{13} \\ s^R_{12}s^R_{23} - c^R_{12}c^R_{23}s^R_{13}e^{i\delta_R} & -c^R_{12}c^R_{23} - s^R_{12}c^R_{23}s^R_{13}e^{i\delta_R} & c^R_{23}c^R_{13} \end{bmatrix}$$

Scenario I: $M_{\nu_R} > M_{W_R}$

$g_L \neq g_R = 0.37$, $\tan\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$

$$\left.\begin{array}{l} BR(W_R \to W_L h) \\ BR(W_R \to W_L Z_L) \end{array}\right\} \text{invisible}$$

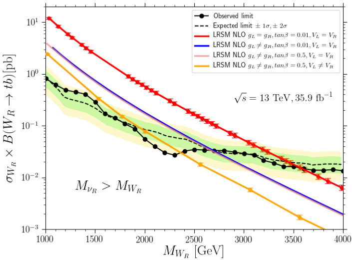
$$BR(W_R \to t\bar{b}) \sim 32\% \text{ - } 33\%$$

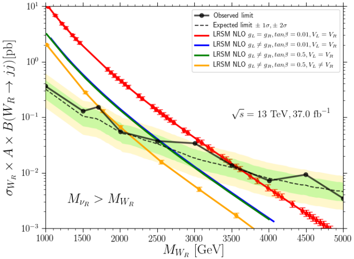
$g_L \neq g_R = 0.37$, $\tan\beta = 0.5$, $V^L_{\rm CKM} = V^R_{\rm CKM}$

$$BR(W_R \to W_L h) \sim 1.95\%$$
$$BR(W_R \to W_L Z_L) \sim 2.0\%$$
$$BR(W_R \to t\bar{b}) \sim 31.0\% \text{ - } 31.8\%$$

$g_L \neq g_R = 0.37$, $\tan\beta = 0.5$, $V^L_{\rm CKM} \neq V^R_{\rm CKM}$

$$BR(W_R \to t\bar{b}) \sim 20\% \text{ for high } M_{W_R} \text{ (4 TeV)}$$
$$\sim 29\% \text{ for low } M_{W_R} \text{ (1.5 TeV)}$$





Scenario I: $M_{\nu_R} > M_{W_R}$

Scenario I: $M_{\nu_R} > M_{W_R}$	Lower limits for M_{W_R} (GeV)		Exclusion channel
	Expected	Observed	
$g_L = g_R$, $\tan\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	3450	3600	$W_R \to tb$
$g_L \neq g_R$, $\tan\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	2700	2700	$W_R \to tb$
$g_L \neq g_R$, $\tan\beta = 0.5$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	2675	2675	$W_R \to tb$
$g_L \neq g_R$, $\tan\beta = 0.5$, $V^L_{\rm CKM} \neq V^R_{\rm CKM}$	1940	2360	$W_R \to tb$
$g_L = g_R$, $\tan\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	3625	3620	$W_R \to jj$
$g_L \neq g_R$, $\tan\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	2700	2555	$W_R \to jj$
$g_L \neq g_R$, $\tan\beta = 0.5$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	2650	2500	$W_R \to jj$
$g_L \neq g_R$, $\tan\beta = 0.5$, $V^L_{\rm CKM} \neq V^R_{\rm CKM}$	2010	2000	$W_R \to jj$

Table: Lower limits for M_{W_R} in GeV, when $M_{\nu_R} > M_{W_R}$.

Scenario II: $M_{\nu_R} < M_{W_R}$

$g_L = g_R$,tan $\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$

$$\text{BR}(W_R \to \nu_R \ell) \sim 5.8\% \text{ (each family)}$$
$$\text{BR}(W_R \to t\bar{b}) \sim 26.5\% \text{ - } 27.3\%$$

$g_L \neq g_R = 0.37$, tan $\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$

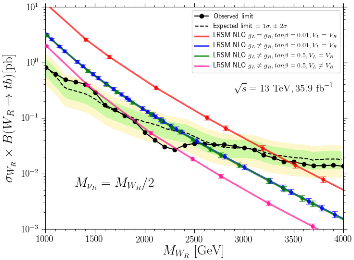
$$\text{BR}(W_R \to \nu_R \ell) \sim 6.7\% \text{ (each family)}$$
$$\text{BR}(W_R \to t\bar{b}) \sim 25.7\% \text{ - } 26.5\%$$

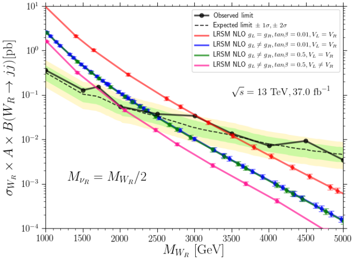
$g_L \neq g_R = 0.37$, tan $\beta = 0.5$, $V^L_{\rm CKM} = V^R_{\rm CKM}$

$$\text{BR}(W_R \to \nu_R \ell) \sim 6.7\% \text{ (each family)}$$
$$\text{BR}(W_R \to W_L h) \sim 1.95\%$$
$$\text{BR}(W_R \to W_L Z_L) \sim 2.0\%$$
$$\text{BR}(W_R \to t\bar{b}) \sim 24.8\% \text{ - } 25.6\%$$

$g_L \neq g_R = 0.37$, tan $\beta = 0.5$, $V^L_{\rm CKM} \neq V^R_{\rm CKM}$

$$\text{BR}(W_R \to t\bar{b}) \sim 15.7\% \text{ for high } M_{W_R} \text{ (4 TeV)}$$
$$\sim 24.7\% \text{ for low } M_{W_R} \text{ (1.5 TeV)}$$





Scenario II: $M_{\nu_R} < M_{W_R}$

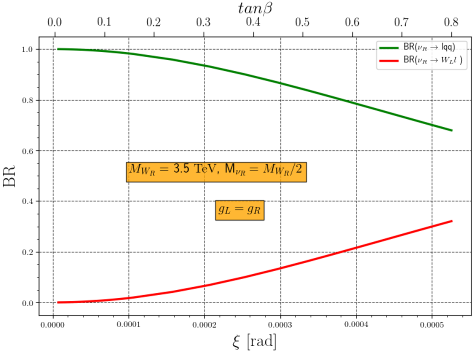
Scenario II: $M_{\nu_R} < M_{W_R}$	Lower limits for M_{W_R} (GeV)		Exclusion channel
	Expected	Observed	
$g_L = g_R$, $\tan\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	3320	3450	$W_R \to tb$
$g_L \neq g_R$, $\tan\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	2375	2575	$W_R \to tb$
$g_L \neq g_R$, $\tan\beta = 0.5$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	2350	2565	$W_R \to tb$
$g_L \neq g_R$, $\tan\beta = 0.5$, $V^L_{\rm CKM} \neq V^R_{\rm CKM}$	1850	2320	$W_R \to tb$
$g_L = g_R$, $\tan\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	3500	3500	$W_R \to jj$
$g_L \neq g_R$, $\tan\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	2500	2430	$W_R \to jj$
$g_L \neq g_R$, $\tan\beta = 0.5$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	2460	2400	$W_R \to jj$
$g_L \neq g_R$, $\tan\beta = 0.5$, $V^L_{\rm CKM} \neq V^R_{\rm CKM}$	2000	2000	$W_R \to jj$

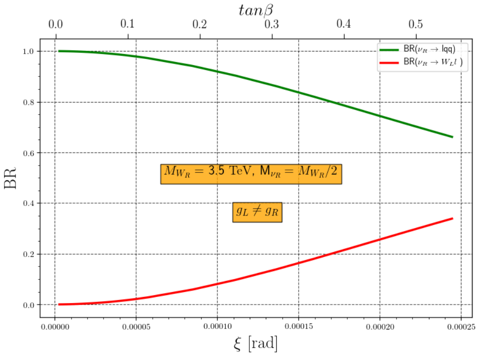
Table: Lower limits for M_{W_R} in GeV when $M_{\nu_R} < M_{W_R}$.

Scenario II: $M_{\nu_R} < M_{W_R}$

$$W_R \to \ell\nu_R \to \ell\ell W_R^\star \to \ell\ell qq', \quad \ell = e \text{ or } \mu .$$

$$W_R \to \ell\nu_R \to \ell\ell W_L \to \ell\ell qq', \quad \ell = e \text{ or } \mu .$$





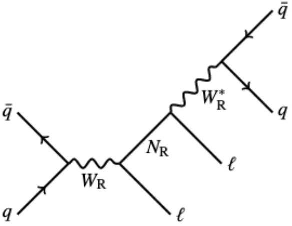
$$\overline{\nu} W_L^{+\mu} \ell \longrightarrow \frac{i}{\sqrt{2}} \gamma^\mu \left(g_L P_L K_L \cos\xi - g_R P_R K_R \sin\xi \right)$$

$$\overline{\nu} W_R^{+\mu} \ell \longrightarrow \frac{i}{\sqrt{2}} \gamma^\mu \left(g_R P_R K_R \cos\xi - g_L P_L K_L \sin\xi \right)$$

K_L and K_R are PMNS mixing matrices in the left and right leptonic sectors, defined as

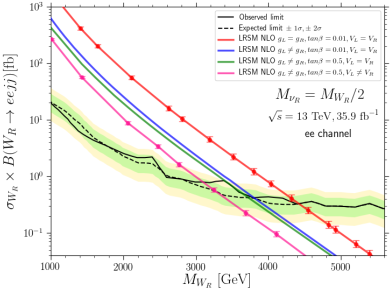
$$K_L = V_L^{\nu\dagger} V_L^{\ell},$$

$$K_R = V_R^{\nu\dagger} V_R^{\ell}.$$

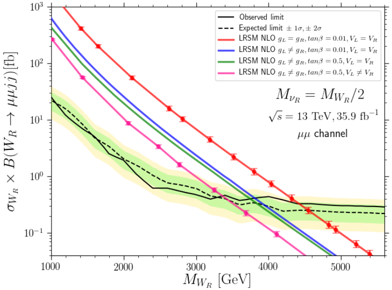


Scenario II: $M_{\nu_R} < M_{W_R}$

eejj final state

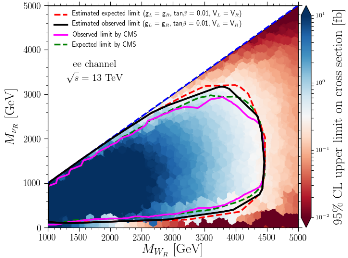


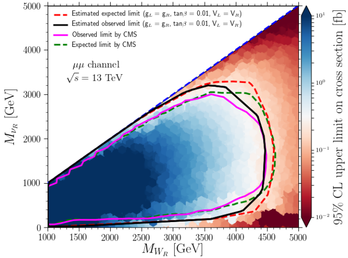
$\mu\mu$jj final state



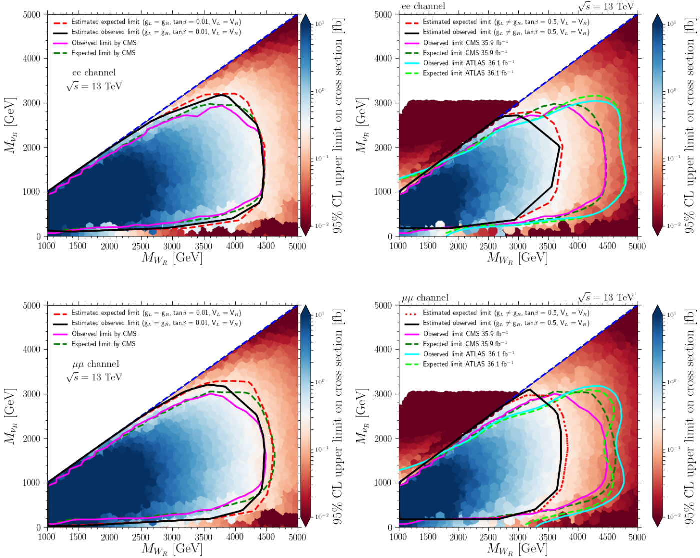
Scenario II: $M_{\nu_R} < M_{W_R}$	Lower limits for M_{W_R} (GeV)		Exclusion channel
	Expected	Observed	
$g_L = g_R$, $\tan\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	4420 (4500)	4420 (4420)	$W_R \to qqee$ $(\mu\mu jj)$
$g_L \neq g_R$, $\tan\beta = 0.01$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	3800 (3950)	3800 (3800)	$W_R \to qqee$ $(\mu\mu jj)$
$g_L \neq g_R$, $\tan\beta = 0.5$, $V^L_{\rm CKM} = V^R_{\rm CKM}$	3720 (3900)	3725 (3750)	$W_R \to qqee$ $(\mu\mu jj)$
$g_L \neq g_R$, $\tan\beta = 0.5$, $V^L_{\rm CKM} \neq V^R_{\rm CKM}$	3300 (3400)	3100 (3350)	$W_R \to qqee$ $(\mu\mu jj)$

Correlating W_R and ν_R mass bounds

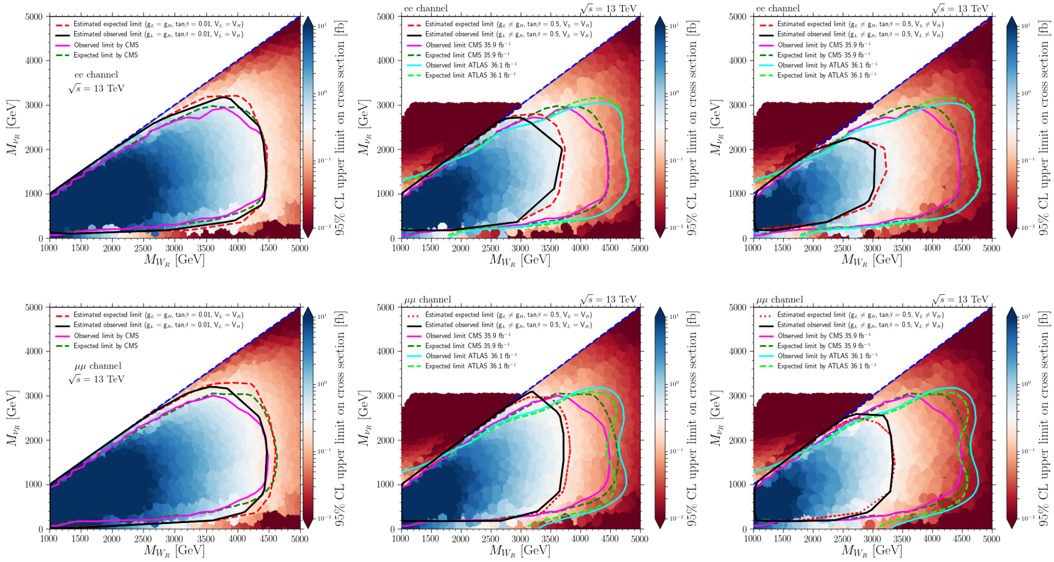




Correlating W_R and ν_R mass bounds



Correlating W_R and ν_R mass bounds



Benchmarks (LRSM)

	BM I : $M_{\nu_R} > M_{W_R}$	**BM II** : $M_{\nu_R} < M_{W_R}$
m_{W_R} [GeV]	2557	3689
m_{ν_R} [GeV]	16797	1838
$\sigma(pp \to W_R)$ [fb] @13 TeV	48.7	3.98
$\sigma(pp \to W_R)$ [fb] @27 TeV	478.0	77.3
$BR(W_R \to t\bar{b})$ [%]	26.3	19.9
$BR(W_R \to jj)$ [%]	58.6	45.8
$BR(W_R \to \nu_R \ell)$ [%]	-	6.5 (each family)
$BR(W_R \to h_1 W_L)$ [%]	1.8	1.5
$BR(W_R \to W_L Z)$ [%]	2.0	1.6
$BR(\nu_R \to \ell q q')$ [%]	-	65.3
$BR(\nu_R \to W_L \ell)$ [%]	1.1×10^{-4}	33.1
$BR(\nu_R \to W_R \ell)$ [%]	99.9	-

Table: Related Branching Ratios and Cross Sections for **BM I** and **BM II**.

Outline

Alternative Left-Right Symmetric Model (ALRSM)

Fields	Repr.	$U(1)_S$
$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$(\mathbf{3}, \mathbf{2}, \mathbf{1}, \frac{1}{6})$	0
$Q_R = \begin{pmatrix} u_R \\ d'_R \end{pmatrix}$	$(\mathbf{3}, \mathbf{1}, \mathbf{2}, \frac{1}{6})$	$-\frac{1}{2}$
d'_L	$(\mathbf{3}, \mathbf{1}, \mathbf{1}, -\frac{1}{3})$	-1
d_R	$(\mathbf{3}, \mathbf{1}, \mathbf{1}, -\frac{1}{3})$	0
$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, \mathbf{1}, -\frac{1}{2})$	1
$L_R = \begin{pmatrix} n_R \\ e_R \end{pmatrix}$	$(\mathbf{1}, \mathbf{1}, \mathbf{2}, -\frac{1}{2})$	$\frac{3}{2}$
n_L	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, 0)$	2
ν_R	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, 0)$	1
$\phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, \mathbf{2}^*, 0)$	$-\frac{1}{2}$
$\chi_L = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, \mathbf{1}, \frac{1}{2})$	0
$\chi_R = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{1}, \mathbf{2}, \frac{1}{2})$	$\frac{1}{2}$

$$\mathcal{L}_{\rm Y} = \bar{Q}_L \hat{\mathbf{Y}}^u \hat{\phi}^\dagger Q_R - \bar{Q}_L \hat{\mathbf{Y}}^d \chi_L d_R - \bar{Q}_R \hat{\mathbf{Y}}^{d'} \chi_R d'_L - \bar{L}_L \hat{\mathbf{Y}}^e \phi L_R + \bar{L}_L \hat{\mathbf{Y}}^\nu \hat{\chi}_L^\dagger \nu_R + \bar{L}_R \hat{\mathbf{Y}}^n \hat{\chi}_R^\dagger n_L + \text{h.c.}$$

$$\langle\phi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ 0 & k \end{pmatrix}, \quad \langle\chi_L\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_L \end{pmatrix}, \quad \langle\chi_R\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_R \end{pmatrix}$$

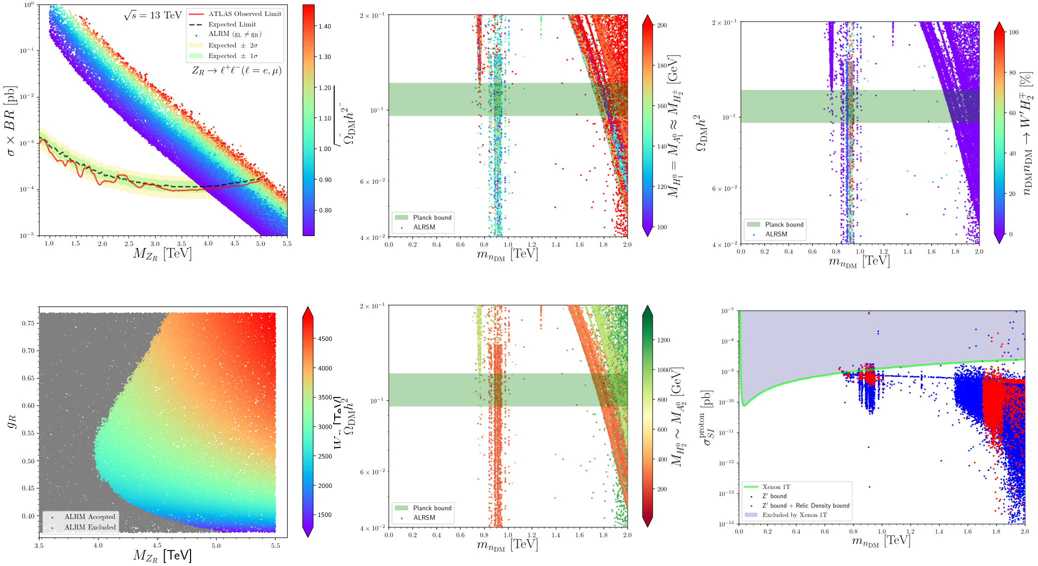
$$\mathcal{L}_{\rm H} = D_\mu \phi^\dagger D^\mu \phi + D_\mu \chi_L^\dagger D^\mu \chi_L + D_\mu \chi_R^\dagger D^\mu \chi_R - V_{\rm H}(\phi, \chi_L, \chi_R)$$

$$M_W = \frac{1}{2} g_L \sqrt{k^2 + v_L^2} \equiv \frac{1}{2} g_L v \quad \text{and} \quad M_{W'} = \frac{1}{2} g_R \sqrt{k^2 + v_R^2} \equiv \frac{1}{2} g_R v'$$

$$M_Z = \frac{g_L}{2 c_{\theta_W}} v \quad \text{and} \quad M_{Z'} = \frac{1}{2} \sqrt{g_{B-L}^2 s_{\varphi_W}^2 v_L^2 + \frac{g_R^2 (c_{\varphi_W}^4 k^2 + v_R^2)}{c_{\varphi_W}^2}}$$

$$s_{\varphi_W} = \frac{g_{B-L}}{\sqrt{g_{B-L}^2 + g_R^2}} = \frac{g_Y}{g_R} \quad \text{and} \quad s_{\theta_W} = \frac{g_Y}{\sqrt{g_L^2 + g_Y^2}} = \frac{e}{g_L},$$

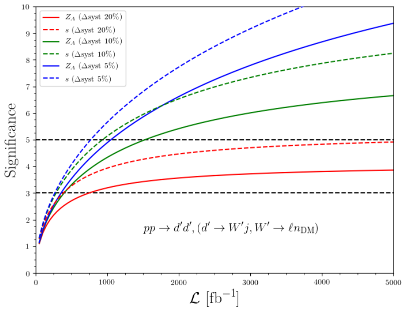
W' & Z' mass limits in ALRSM and Scotino Dark Matter



Benchmarks (ALRSM)

	$M_{H_1^0}$ [GeV]	$M_{H_2^0}$ [GeV]	$M_{H_3^0}$ [GeV]	$M_{A_1^0}$ [GeV]	$M_{A_2^0}$ [GeV]	$M_{H_1^\pm}$ [GeV]	$M_{H_2^\pm}$ [GeV]
BM I	193	907	1546	193	907	907	194
BM II	82	213	1578	82	167	167	82
BM III	192	894	1546	192	894	894	192

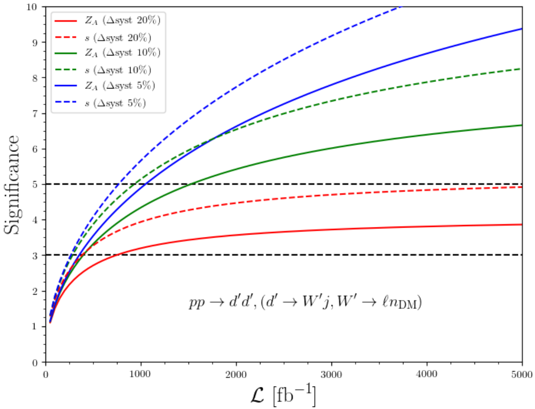
	$M_{Z'}$ [GeV]	$M_{W'}$ [GeV]	M_{n_1} [GeV]	M_{n_2} [GeV]	M_{n_3} [GeV]	$M_{d'}$ [GeV]	$M_{s'}$ [GeV]	$M_{b'}$ [GeV]
BM I	4992	1460	756	971	1202	1500	1800	2000
BM II	5113	1288	909	1134	1223	1400	1822	2200
BM III	4992	1460	902	1023	1312	1500	1936	2821



	$\Omega_{\rm DM} h^2$	$\sigma_{\rm SI}^{\rm proton}$ [pb]	$\sigma_{\rm SI}^{\rm neutron}$ [pb]	$\langle \sigma v \rangle$ [cm^{3}s^{-1}]
BM I	0.118	8.08×10^{-10}	2.88×10^{-11}	7.81×10^{-28}
BM II	0.120	8.09×10^{-10}	8.37×10^{-10}	3.29×10^{-27}
BM III	0.119	7.72×10^{-10}	3.67×10^{-11}	1.17×10^{-27}

	BM II
$\sigma(pp \to d_1' d_1')$ [pb] @13 TeV	2.72×10^{-3}
BR($d_1' \to W' j$) [%]	96.8
BR($W' \to \ell n_{\rm DM}$) [%]	21.4
s @$\mathscr{L}$ =3 ab^{-1}	4.7
Z_A @$\mathscr{L}$ =3 ab^{-1}	3.72

Thank you!


Z_A (Δsyst 20%)
s (Δsyst 20%)
Z_A (Δsyst 10%)
s (Δsyst 10%)
Z_A (Δsyst 5%)
s (Δsyst 5%)
Significance
$pp \to d'd', (d' \to W'j, W' \to \ell n_{DM})$
$\mathcal{L}$ [fb^{-1}]
0
1
2
3
4
5
6
7
8
9
10
0
1000
2000
3000
4000
5000

LRSM Higgs Potential

$$
\begin{aligned}
V(\phi, \Delta_L, \Delta_R) = & -\mu_1^2 \left(\mathrm{Tr}\left[\Phi^\dagger \Phi\right]\right) - \mu_2^2 \left(\mathrm{Tr}\left[\tilde{\Phi}\Phi^\dagger\right] + \left(\mathrm{Tr}\left[\tilde{\Phi}^\dagger \Phi\right]\right)\right) - \mu_3^2 \left(\mathrm{Tr}\left[\Delta_L \Delta_L^\dagger\right] + \mathrm{Tr}\left[\Delta_R \Delta_R^\dagger\right]\right) \\
& + \lambda_1 \left(\left(\mathrm{Tr}\left[\Phi\Phi^\dagger\right]\right)^2\right) + \lambda_2 \left(\left(\mathrm{Tr}\left[\tilde{\Phi}\Phi^\dagger\right]\right)^2 + \left(\mathrm{Tr}\left[\tilde{\Phi}^\dagger\Phi\right]\right)^2\right) + \lambda_3 \left(\mathrm{Tr}\left[\tilde{\Phi}\Phi^\dagger\right] \mathrm{Tr}\left[\tilde{\Phi}^\dagger\Phi\right]\right) \\
& + \lambda_4 \left(\mathrm{Tr}\left[\Phi\Phi^\dagger\right] \left(\mathrm{Tr}\left[\tilde{\Phi}\Phi^\dagger\right] + \mathrm{Tr}\left[\tilde{\Phi}^\dagger\Phi\right]\right)\right) + \rho_1 \left(\left(\mathrm{Tr}\left[\Delta_L\Delta_L^\dagger\right]\right)^2 + \left(\mathrm{Tr}\left[\Delta_R\Delta_R^\dagger\right]\right)^2\right) \\
& + \rho_2 \left(\mathrm{Tr}\left[\Delta_L\Delta_L\right] \mathrm{Tr}\left[\Delta_L^\dagger\Delta_L^\dagger\right] + \mathrm{Tr}\left[\Delta_R\Delta_R\right] \mathrm{Tr}\left[\Delta_R^\dagger\Delta_R^\dagger\right]\right) + \rho_3 \left(\mathrm{Tr}\left[\Delta_L\Delta_L^\dagger\right] \mathrm{Tr}\left[\Delta_R\Delta_R^\dagger\right]\right) \\
& + \rho_4 \left(\mathrm{Tr}\left[\Delta_L\Delta_L\right] \mathrm{Tr}\left[\Delta_R^\dagger\Delta_R^\dagger\right] + \mathrm{Tr}\left[\Delta_L^\dagger\Delta_L^\dagger\right] \mathrm{Tr}\left[\Delta_R\Delta_R\right]\right) + \alpha_1 \mathrm{Tr}\left[\Phi\Phi^\dagger\right] \left(\mathrm{Tr}\left[\Delta_L\Delta_L^\dagger\right] + \mathrm{Tr}\left[\Delta_R\Delta_R^\dagger\right]\right) \\
& + \alpha_2 \left(\mathrm{Tr}\left[\Phi\tilde{\Phi}^\dagger\right] \mathrm{Tr}\left[\Delta_R\Delta_R^\dagger\right] + \mathrm{Tr}\left[\Phi^\dagger\tilde{\Phi}\right] \mathrm{Tr}\left[\Delta_L\Delta_L^\dagger\right]\right) + \alpha_2^* \left(\mathrm{Tr}\left[\Phi^\dagger\tilde{\Phi}\right] \mathrm{Tr}\left[\Delta_R\Delta_R^\dagger\right] + \mathrm{Tr}\left[\tilde{\Phi}^\dagger\Phi\right] \mathrm{Tr}\left[\Delta_L\Delta_L^\dagger\right]\right) \\
& + \alpha_3 \left(\mathrm{Tr}\left[\Phi\Phi^\dagger\Delta_L\Delta_L^\dagger\right] + \mathrm{Tr}\left[\Phi^\dagger\Phi\Delta_R\Delta_R^\dagger\right]\right) + \beta_1 \left(\mathrm{Tr}\left[\Phi\Delta_R\Phi^\dagger\Delta_L^\dagger\right] + \mathrm{Tr}\left[\Phi^\dagger\Delta_L\Phi\Delta_R^\dagger\right]\right) \\
& + \beta_2 \left(\mathrm{Tr}\left[\tilde{\Phi}\Delta_R\Phi^\dagger\Delta_L^\dagger\right] + \mathrm{Tr}\left[\tilde{\Phi}^\dagger\Delta_L\Phi\Delta_R^\dagger\right]\right) + \beta_3 \left(\mathrm{Tr}\left[\Phi\Delta_R\tilde{\Phi}^\dagger\Delta_L^\dagger\right] + \mathrm{Tr}\left[\Phi^\dagger\Delta_L\tilde{\Phi}\Delta_R^\dagger\right]\right)
\end{aligned}
$$