

#### Introduction

The Left-Right Symmetric Mode Charged Sector

 $W_R$  Mass Limit at the LHC

Motivation

### Results

 $\begin{array}{l} \text{Scenario I:} \\ M_{\mathcal{V}_R} > M_{W_R} \\ \text{Scenario II:} \\ M_{\mathcal{V}_R} < M_{W_R} \\ \text{Correlating } W_R \text{ and} \\ \nu_R \text{ mass bounds} \end{array}$ 

Conclusion

Relaxing LHC constraints on the  $W_R$  mass based on Phys. Rev. D 99, 035001

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Scenario I:  $M_{\nu_R} > M_{W_R}$ Scenario II:  $M_{\nu_R} < M_{W_R}$ Correlating  $W_R$  and  $\nu_R$  mass bounds



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Scenario I:  $M_{\nu_R} > M_{W_R}$ Scenario II:  $M_{\nu_R} < M_{W_R}$ Correlating  $W_R$  and  $\nu_R$  mass bounds

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## The Left-Right Symmetric Model (LRSM)

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$$\begin{array}{|c|c|c|c|c|c|c|c|} \hline Fields & SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\ \hline & & Q_{L_i} & (\mathbf{2}, \mathbf{1}, +\frac{1}{3}) \\ \hline & & Q_{R_i} & (\mathbf{1}, \mathbf{2}, -\frac{1}{3}) \\ \hline & & L_{L_i} & (\mathbf{2}, \mathbf{1}, -1) \\ \hline & & L_{R_i} & (\mathbf{1}, \mathbf{2}, -1) \\ \hline & & & & \mathbf{1}, \mathbf{2}, -1 \\ \hline & & & & \mathbf{1}, \mathbf{2}, -1 \\ \hline & & & & \mathbf{1}, \mathbf{2}, -1 \\ \hline & & & & & \mathbf{1}, \mathbf{2}, \mathbf{2}, \mathbf{1}, \mathbf{2} \\ \hline & & & & & & \mathbf{1}, \mathbf{3}, \mathbf{2} \\ \hline & & & & & & \mathbf{1}, \mathbf{3}, \mathbf{2} \\ \hline & & & & & & \mathbf{2}, \mathbf{1}, \mathbf{3}, \mathbf{3}, \mathbf{2} \\ \hline & & & & & & \mathbf{2}, \mathbf{1}, \mathbf{3}, \mathbf{3}, \mathbf{3}, \mathbf{2} \\ \hline & & & & & & & \mathbf{2}, \mathbf{1}, \mathbf{3}, \mathbf{3},$$

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

 $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$   $\downarrow^{\Delta_R}$   $SU(3)_C \times SU(2)_L \times U(1)_Y$   $\downarrow^{\Phi}$ 

 $SU(3)_C imes$ 

 $U(1)_{EM}$ 

$$egin{aligned} \Phi &\equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (\mathbf{2},\mathbf{2},\mathbf{0}) \ \Delta_L &\equiv \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix} \sim (\mathbf{3},\mathbf{1},\mathbf{2}) \ \Delta_R &\equiv \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix} \sim (\mathbf{1},\mathbf{3},\mathbf{2}) \end{aligned}$$



## Symmetry Breaking

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$$SU(2)_R \otimes U(1)_{B-L} \longrightarrow U(1)_Y$$
  
 $\langle \Delta_L 
angle = egin{pmatrix} 0 & 0 \ v_L e^{i heta_L}/\sqrt{2} & 0 \end{pmatrix}, \quad \langle \Delta_R 
angle = egin{pmatrix} 0 & 0 \ v_R/\sqrt{2} & 0 \end{pmatrix}$ 



## Symmetry Breaking

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$$SU(2)_R \otimes U(1)_{B-L} \longrightarrow U(1)_Y$$
  
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angle = egin{pmatrix} 0 & 0 \ v_R/\sqrt{2} & 0 \end{pmatrix}$ 

$$SU(2)_L \otimes U(1)_Y \longrightarrow U(1)_{EM}$$
  
 $v_R \gg (\kappa_1, \kappa_2) \gg v_L, \qquad \sqrt{\kappa_1^2 + \kappa_2^2} = v = 246 \text{ GeV}$   
 $\langle \Phi \rangle = \begin{pmatrix} \kappa_1/\sqrt{2} & 0\\ 0 & \kappa_2 e^{i\alpha}/\sqrt{2} \end{pmatrix}$ 



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# LRSM Lagrangian

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



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# **LRSM Lagrangian**

$$\mathcal{L}_{\mathrm{LRSM}} = \mathcal{L}_{\mathrm{kin}} + \mathcal{L}_{Y} - V(\Phi, \Delta_{L}, \Delta_{R})$$

$$\mathcal{L}_{\mathrm{kin}} = i \sum ar{\psi} \gamma^{\mu} \mathcal{D}_{\mu} \psi$$

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

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 $\begin{array}{l} \text{Scenario I:} \\ M_{\mathcal{V}_R} > M_{W_R} \\ \text{Scenario II:} \\ M_{\mathcal{V}_R} < M_{W_R} \\ \text{Correlating } W_R \text{ and } \\ \nu_R \text{ mass bounds} \end{array}$ 



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# **LRSM Lagrangian**

$$\mathcal{L}_{\mathrm{LRSM}} = \mathcal{L}_{\mathrm{kin}} + \mathcal{L}_{Y} - V(\Phi, \Delta_{L}, \Delta_{R})$$

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

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

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$$\begin{split} \mathcal{L}_{Y} &= - \left[ Y_{L_{L}} \bar{L}_{L} \Phi L_{R} + \tilde{Y}_{L_{R}} \bar{L}_{R} \Phi L_{L} + Y_{Q_{L}} \bar{Q}_{L} \tilde{\Phi} Q_{R} + \tilde{Y}_{Q_{R}} \bar{Q}_{R} \tilde{\Phi} Q_{L} \right. \\ &+ \left. h_{L}^{ij} \overline{L}_{L_{i}}^{c} i \tau_{2} \Delta_{L} L_{L_{j}} + h_{R}^{ij} \overline{L}_{R_{i}}^{c} i \tau_{2} \Delta_{R} L_{R_{j}} + \text{h.c.} \right], \end{split}$$



## LRSM Higgs Potential

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$$\begin{split} \mathcal{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 \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 \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_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 \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}_R^{\dagger} \right] \right) \end{split}$$



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 $\begin{array}{l} \text{Scenario I:} \\ M_{\mathcal{V}_R} > M_{W_R} \\ \text{Scenario II:} \\ M_{\mathcal{V}_R} < M_{W_R} \\ \text{Correlating } W_R \text{ and } \\ \nu_R \text{ mass bounds} \end{array}$ 

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



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

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

$$M_A = 0$$

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

$$\mp \sqrt{ \left[ g_L^2 v^2 + 2v_R^2 (g_R^2 + g_{B-L}^2) \right]^2 - 4g_L^2 (g_R^2 + 2g_{B-L}^2) v^2 v_R^2} \Big] .$$



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



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$$\left(\begin{array}{c}W_1\\W_2\end{array}\right) = \left(\begin{array}{c}\cos\xi & -\sin\xi\\\sin\xi & \cos\xi\end{array}\right) \left(\begin{array}{c}W_L\\W_R\end{array}\right)$$

In the limit of 
$$(\kappa_1, \kappa_2) \ll v_R$$
 and  $g_R \sim g_L$  we have  
 $\sin \xi \approx \frac{\kappa_1 \kappa_2}{v_R^2}$ ,  $\sin^2 \xi \approx 0$ ,  $\cos \xi \approx 1$ , leading to

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



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Results Scenario I:  $M_{\nu_R} > M_{W_R}$ Scenario II:  $M_{\nu_R} < M_{W_R}$ 

Correlating  $W_R$  and  $\nu_R$  mass bounds



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 $\begin{array}{l} \text{Scenario I:} \\ M_{\mathcal{V}_R} > M_{W_R} \\ \text{Scenario II:} \\ M_{\mathcal{V}_R} < M_{W_R} \\ \text{Correlating } W_R \text{ and} \\ \nu_R \text{ mass bounds} \end{array}$ 





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





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 $Scenario I: M_{\nu_R} > M_{W_R} \\ Scenario II: M_{\nu_R} < M_{W_R} \\ Correlating W_R and \nu_R mass bounds$ 



# Motivation for $\mathbf{g}_L \neq \mathbf{g}_R$

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### Conclusion

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

Setting 
$$\sin \phi = \frac{g_{B-L}}{\sqrt{g_R^2 + g_{B-L}^2}}$$
 and  $\sin \theta_W = \frac{g_Y}{\sqrt{g_L^2 + g_Y^2}}$ , we get

$$an heta_W = rac{g_R \sin \phi}{g_L} \leq rac{g_R}{g_L} \,,$$

Theoretical constraint on g<sub>R</sub> gauge coupling

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





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Scenario I:  $M_{\nu_R} > M_{W_R}$ Scenario II:  $M_{\nu_R} < M_{W_R}$ Correlating  $W_R$  and  $\nu_R$  mass bounds



Analysis

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### Conclusion

Observable	Constraints	Observable	Constraints
$\Delta B_s$	[10.2-26.4]	$\Delta B_d$	[0.294-0.762]
$\Delta M_K$	$< 5.00 \times 10^{-15}$	$\frac{\Delta M_K}{\Delta M_K^{SM}}$	[0.7-1.3]
$\epsilon_K$	$< 3.00 \times 10^{-3}$	$\frac{\epsilon_K}{\epsilon_K}$	[0.7-1.3]
${\sf BR}(B^0 \to X_s \gamma)$	$[2.99, 3.87]  imes 10^{-4}$	$\frac{BR(B^0 \to X_s \gamma)}{BR(B^0 \to X_s \gamma)_{SM}}$	[0.7-1.3]
M <sub>h</sub>	[124, 126] GeV	$M_{H_{1,2}^{\pm\pm}}$	$> 535~{ m GeV}$
$M_{H_4,A_2,H_2^{\pm}}$	$>$ 4.75 $ imes$ $M_{W_R}$	-,-	

### Table: Current experimental bounds imposed for consistent solutions.

Parameter	Scanned range	
VR	[2.2, 20] TeV	
$V^R_{ m CKM}$ : $c^R_{12}$ , $c^R_{13}$ , $c^R_{23}$	$[-1, \ 1]$	
$diag(h_R^{ij})$	[0.001, 1]	

$$\begin{split} M^{ij}_{\nu_R} &= h^{ij}_R v_R \\ V^R_{\rm CKM} &= \begin{bmatrix} c^R_{12}c^R_{13} & s^R_{12}c^R_{13} & s^R_{13}e^{i\delta_R} \\ -s^R_{12}c^R_{23} - c^R_{12}s^R_{23}s_{13}e^{i\delta_R} & c^R_{12}c^R_{23} - s^R_{12}s^R_{23}s^R_{13}e^{i\delta_R} & s^R_{23}c^R_{13} \\ s^R_{12}s^R_{23} - c^R_{12}c^R_{23}s^R_{13}e^{i\delta_R} & -c^R_{12}c^R_{23} - s^R_{12}c^R_{23}s^R_{13}e^{i\delta_R} & c^R_{23}c^R_{13} \end{bmatrix} \end{split}$$

### Table: Scanned parameter space.



 $g_L 
eq$ 

ł

The Left-Right Symmetric Model

Scenario I:  $M_{\nu_e} > M_{W_e}$ Scenario II:  $M_{\nu_p} < M_{W_p}$ Correlating  $W_R$  and  $\nu_B$  mass bounds

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

$$g_R = 0.37, ext{ tan } eta = 0.01, V_{ ext{CKM}}^L = V_{ ext{CKM}}^R$$
  
 $egin{array}{c} \mathsf{BR}(W_R o W_L h) \ \mathsf{BR}(W_R o W_L Z_L) \ \mathsf{BR}(W_R o t ar{b}) \sim 32\% - 33\% \end{array}$ 

.

$$g_L 
eq g_R = 0.37$$
, tan  $\beta = 0.5$ ,  $V_{CKM}^L = V_{CKM}^R$   
 $BR(W_R \rightarrow W_L h) \sim 1.95\%$   
 $BR(W_R \rightarrow W_L Z_L) \sim 2.0\%$   
 $BR(W_R \rightarrow t\bar{b}) \sim 31.0\%$  - 31.8%

$$\frac{g_L \neq g_R = 0.37, \text{ tan } \beta = 0.5, V_{\text{CKM}}^L \neq V_{\text{CKM}}^R}{\text{BR}(W_R \rightarrow t\bar{b}) \sim 20\% \text{ for high } M_{W_R} \text{ (4 TeV)}} \sim 29\% \text{ for low } M_{W_R} \text{ (1.5 TeV)}}$$





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Scenario I:  $M_{\nu_{R}} > M_{w_{R}}$ Scenario II:  $M_{\nu_{R}} < M_{w_{R}}$ Correlating  $W_{R}$  and  $\nu_{R}$  mass bounds

Conclusion

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

$$g_L=g_R$$
 ,tan  $eta=0.01$ ,  $V^L_{
m CKM}=V^R_{
m CKN}$ 

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

$$g_L 
eq g_R = 0.37$$
, tan  $eta = 0.01$ ,  $V_{
m CKM}^L = V_{
m CKM}^R$ 

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

$$g_L 
eq g_R = 0.37$$
, tan  $eta = 0.5$ ,  $V^L_{
m CKM} = V^R_{
m CKM}$ 

 $\begin{array}{l} \mathsf{BR}(W_R \rightarrow \nu_R \ell) \sim 6.7\% \text{ (each family)} \\ \mathsf{BR}(W_R \rightarrow W_L h) \sim 1.95\% \\ \mathsf{BR}(W_R \rightarrow W_L Z_L) \sim 2.0\% \\ \mathsf{BR}(W_R \rightarrow t \bar{b}) \sim 24.8\% - 25.6\% \end{array}$ 

$$g_L 
eq g_R =$$
 0.37, tan  $eta =$  0.5,  $V^L_{
m CKM} 
eq V^R_{
m CKM}$ 

$${f BR}(W_R o tar{b}) \sim 15.7\%$$
 for high  $M_{W_R}$  (4 TeV)  $\sim 24.7\%$  for low  $M_{W_R}$  (1.5 TeV)





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

$$\begin{split} &W_R \to \ell \nu_R \to \ell \ell W_R^{\star} \to \ell \ell q q', \ \ell = e \ \mathrm{or} \ \mu \, . \\ &W_R \to \ell \nu_R \to \ell \ell W_L \to \ell \ell q q', \ \ell = e \ \mathrm{or} \ \mu \, . \end{split}$$

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 $\begin{array}{l} \text{Scenario I:} \\ M_{\mathcal{V}_{R}} > M_{W_{R}} \\ \text{Scenario II:} \\ M_{\mathcal{V}_{R}} < M_{W_{R}} \\ \text{Correlating } W_{R} \text{ and} \\ \nu_{R} \text{ mass bounds} \end{array}$ 







Scenario II:  $M_{\nu_{P}} < M_{W_{P}}$ 

The Left-Right Charged Sector

103

103

101

1000

2000

3000

 $M_{W_R}$  [GeV]

 $B(W_R \to eejj)[\mathrm{fb}]$ 

×  $10^{0}$ 

 $\sigma_{W_R}$  $10^{-1}$ 

 $M_{\nu} > M_{W}$ Scenario II:  $M_{\nu_a} < M_{W_a}$ Correlating W. and

### eejj final state

- Observed limit

--- Expected limit  $\pm 1\sigma, \pm 2\sigma$ 

4000

 $M_{\nu_{P}} = M_{W_{P}}/2$ 

ee channel

5000

### $\mu\mu$ jj final state





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 $\begin{array}{l} \text{Scenario I:} \\ M_{\mathcal{V}_R} > M_{\mathcal{W}_R} \\ \text{Scenario II:} \\ M_{\mathcal{V}_R} < M_{\mathcal{W}_R} \\ \text{Correlating } \mathcal{W}_R \text{ and} \\ \mathcal{V}_R \text{ mass bounds} \end{array}$ 







 $M_{\nu} > M_{W}$ 

 $M_{\nu_{-}} < M_{W_{-}}$ 

## Correlating $W_R$ and $\nu_R$ mass bounds





# Correlating $W_R$ and $\nu_R$ mass bounds





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 $\begin{array}{l} \text{Scenario I:} \\ M_{\mathcal{V}_R} > M_{W_R} \\ \text{Scenario II:} \\ M_{\mathcal{V}_R} < M_{W_R} \\ \text{Correlating } W_R \text{ and} \\ \nu_R \text{ mass bounds} \end{array}$ 

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u_R} > M_{W_R}$ Scenario II:  $M_{
u_R} < M_{W_R}$ 

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### Results

 $\begin{array}{l} \text{Scenario I:} \\ M_{\mathcal{V}_R} > M_{W_R} \\ \text{Scenario II:} \\ M_{\mathcal{V}_R} < M_{W_R} \\ \text{Correlating } W_R \text{ and } \\ \nu_R \text{ mass bounds} \end{array}$ 

### Conclusion

Scenario I: $M_{\nu_R} > M_{W_R}$	Lower limits for $M_{W_R}$ (GeV)		Exclusion
	<b>–</b>		channel
	Expected	Observed	
$g_L=g_R$ , tan $eta=0.01,\;V_{ m CKM}^L=V_{ m CKM}^R$	3450	3600	$W_R \rightarrow tb$
$g_L  eq g_R$ , tan $eta = 0.01, \; V_{ m CKM}^L = V_{ m CKM}^R$	2700	2700	$W_R  ightarrow tb$
$g_L  eq g_R$ , tan $eta = 0.5, \; V_{ m CKM}^L = V_{ m CKM}^R$	2675	2675	$W_R  ightarrow tb$
$g_L  eq g_R$ , tan $eta = 0.5, \; V^L_{ m CKM}  eq V^R_{ m CKM}$	1940	2360	$W_R \rightarrow tb$
$g_L=g_R$ , tan $eta=0.01,\;V_{ m CKM}^L=V_{ m CKM}^R$	3625	3620	$W_R \rightarrow jj$
$g_L  eq g_R$ , tan $eta = 0.01, \; V^L_{ m CKM} = V^R_{ m CKM}$	2700	2555	$W_R  ightarrow jj$
$g_L  eq g_R$ , tan $eta = 0.5, \; V_{ m CKM}^L = V_{ m CKM}^R$	2650	2500	$W_R \rightarrow jj$
$g_L  eq g_R$ , tan $eta = 0.5, \; V_{ m CKM}^L  eq V_{ m CKM}^R$	2010	2000	$W_R \rightarrow jj$

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



## Conclusion

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The Left-Right Symmetric Model

 $M_{\nu_o} > M_{W_o}$ Scenario II:  $M_{\mathcal{V}_{p}} < M_{W_{p}}$ Correlating  $W_R$  and  $\nu_R$  mass bounds

Conclusion

Scenario II: $M_{ u_R} < M_{W_R}$	Lower limits for $M_{W_R}$ (GeV) Expected Observed		Exclusion channel
$g_L=g_R$ , tan $eta=0.01$ , $V^L_{ m CKM}=V^R_{ m CKM}$	4420	4420	$W_R  ightarrow qqee$
$g_L  eq g_R$ , tan $eta = 0.01$ , $V^L_{ m CKM} = V^R_{ m CKM}$	3800	3800	$W_R  o qqee$
$g_L  eq g_R$ , tan $eta = 0.5, \; V_{ m CKM}^L = V_{ m CKM}^R$	3720	3725	$W_R  ightarrow qqee$
$g_L  eq g_R$ , tan $eta = 0.5, \; V^L_{ m CKM}  eq V^R_{ m CKM}$	3300	3100	$W_R  ightarrow qqee$
$g_L=g_R$ , tan $eta=0.01,\;V^L_{ m CKM}=V^R_{ m CKM}$	4500	4420	$W_R  o q q \mu \mu$
$g_L  eq g_R$ , tan $eta = 0.01$ , $V^L_{ m CKM} = V^R_{ m CKM}$	3950	3800	$W_R  ightarrow qq\mu\mu$
$g_L  eq g_R$ , tan $eta = 0.5, \; V_{ m CKM}^L = V_{ m CKM}^R$	3900	3750	$W_R  ightarrow qq\mu\mu$
$g_L  eq g_R$ , tan $eta = 0.5$ , $V^L_{ m CKM}  eq V^R_{ m CKM}$	3400	3350	$W_R  ightarrow qq\mu\mu$

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



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 $M_{\nu_R} > M_{w_R}$ Scenario II:  $M_{\nu_R} < M_{w_R}$ Correlating  $W_R$  and  $\nu_R$  mass bounds

## Conclusion

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

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



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 $\begin{array}{l} \text{Scenario I:} \\ M_{\mathcal{V}_R} > M_{W_R} \\ \text{Scenario II:} \\ M_{\mathcal{V}_R} < M_{W_R} \\ \text{Correlating } W_R \text{ and} \\ \nu_R \text{ mass bounds} \end{array}$ 

Conclusion

# Thank you!