Direct bounds on Left-Right gauge boson masses

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for further details and references, see JHEP02(2024)027,
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EW Interactions and Unified Theories, Moriond - 26/03/2024

LRMs: gauge boson sector

- Enlarged gauge group; X = (B-L)/2
- A **discrete symmetry** (e.g. parity) can in principle be restored at energies >> κ_R
- LR-SSB: SM at low energies; hypercharge: $Y = T^3_R + (B\text{-}L)/2$
- New massive gauge bosons, W_R & Z_R; LR corrections to the SM: $\epsilon \sim \kappa_{EW}/\kappa_R << 1$
- Additional weak coupling constants; **perturbative region** g_R, g_X ~< 1

$$LRM = \underbrace{SU(3)_C}_{g_s} \times \underbrace{SU(2)_L}_{g_L} \times \underbrace{SU(2)_R}_{g_R} \times \underbrace{U(1)_X}_{g_X}$$

$$\text{LR-SSB @ scale } \kappa_R,\ \gamma\text{: mixing } W_R^3 \text{ and } W_X$$

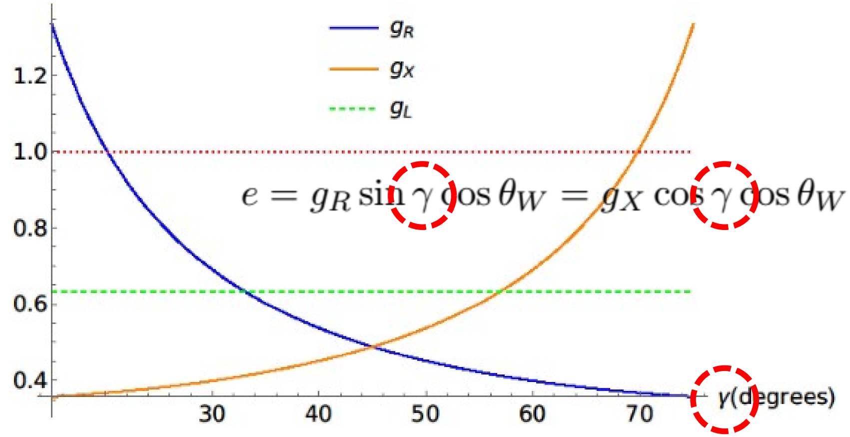
$$\downarrow$$

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

$$\text{EW-SSB @ scale } \kappa_{EW},\ \theta_W\text{: mixing } W_L^3 \text{ and } W_Y$$

$$\downarrow$$

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



[Pati, Salam, Mohapatra, Senjanovic '70s ...]

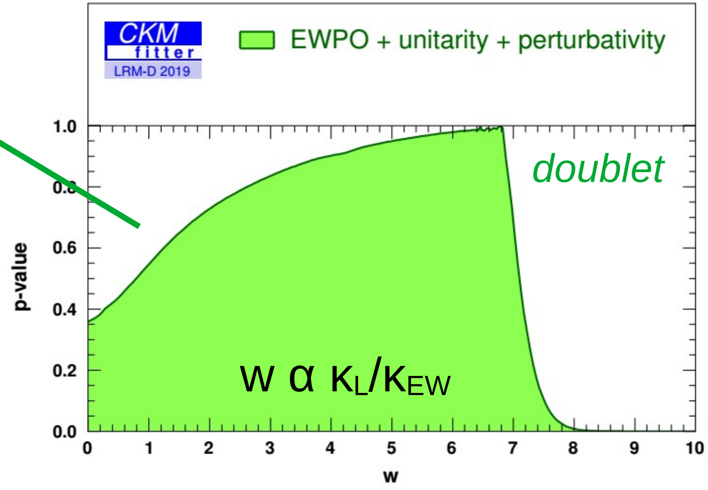
LRMs: scalar sector

- Multiple ways of implementing LR-SSB: (T) triplet, or (D) doublet under $SU(2)_R$ are the most studied cases

Triplets: $\Delta_R \sim (\mathbf{1},\mathbf{1},\mathbf{3})_1\,,\ \ \Delta_L \sim (\mathbf{1},\mathbf{3},\mathbf{1})_1$ Doublets: $\chi_R \sim (\mathbf{1},\mathbf{1},\mathbf{2})_{1/2}\,,\ \ \chi_L \sim (\mathbf{1},\mathbf{2},\mathbf{1})_{1/2}$

[In (T), doubly charged scalars are present]

- In (D), the EW-SSB can be triggered by the $SU(2)_L$ doublet VEV κ_L; in (T), EWPOs limit the size of the $SU(2)_L$ triplet VEV
- Additional scalar representations are considered for various reasons, e.g. EW-SSB in (T) scenario



[Bernard, Descotes-G., LVS '20]

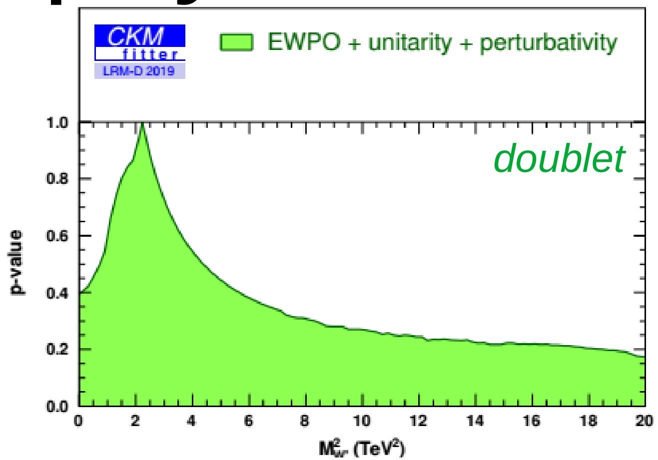
LRMs: fermionic sector

- A bi-doublet $\Phi \sim (\mathbf{1},\mathbf{2},\mathbf{2})_0$ also participates in the SSB, needed in the triplet case; Yukawa interactions: Dirac masses for $(Q_L, \Phi\, Q_R)$ and $(L_L, \Phi\, L_R)$
- (Eff) Non-ren. dim.-5 interactions with $SU(2)_L$ and $SU(2)_R$ doublets, e.g. $(Q_L, \chi_L\, \chi_R^\dagger\, Q_R)/\Lambda$ or $(L_R^c, \sigma_2\, \chi_R\, \chi_R^T\, \sigma_2\, L_R)/\Lambda$
- RH neutrinos are introduced (B-L is anomaly free); no additional fermion in the simplest version
- In (D), Dirac masses only; in (T), also Majorana masses $(L_R^c, \sigma_2\, \Delta_R\, L_R)$ and $(L_L^c, \sigma_2\, \Delta_L\, L_L)$: see-saw mechanism
- Extension of the PMNS matrix; RH unitary counterpart V^R of the CKM-like matrix V^L in the quark sector
- P: $V^R \sim V^L$ (manifest); C: $V^R \sim V^{L*}$ (pseudo-manifest)

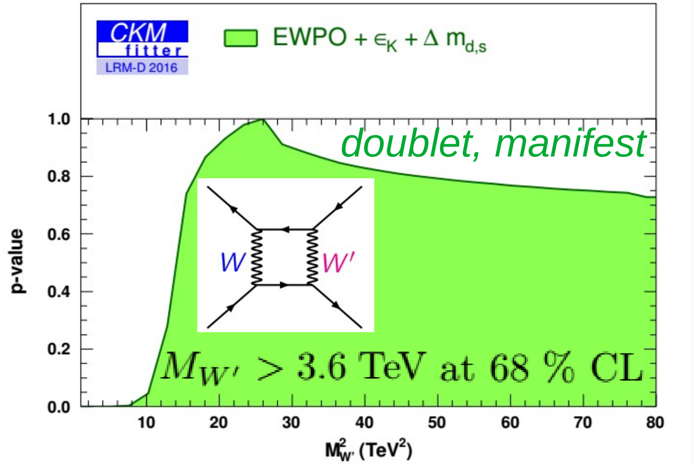
	Left	**Right**
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$
$SU(2)_R$	$\mathbf{1}$	$\mathbf{2}$
quarks : $B = 1/3$	$\begin{pmatrix} U_L \\ D_L \end{pmatrix}$	$\begin{pmatrix} U_R \\ D_R \end{pmatrix}$
leptons : $L = -1$	$\begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$	$\begin{pmatrix} \nu_R \\ \ell_R \end{pmatrix}$

EWPOs & quark flavor physics

- LRM parameters largely unconstrained
- Beyond tree level: many parameters from the scalar potential intervene



- Z' (typically) does not introduce FCNCs at tree level, part of the scalar sector typically does
- **RH charged weak currents**, possibly new sources of CP violation; observables: meson-mixing, etc.
- Bounds strongly depend on RH mixings, e.g. when $V^R \sim V^{L*}$: no constraint from ϵ_K (indirect CPV in kaons)



[Bernard, Descotes-G., LVS '16 '20]

Collider limits on LRMs

Various strategies used to look for W', Z'; for instance (LHC only):

- Z' to ℓℓ [1709.07242, 1903.06248, 2103.02708, etc.]
- Di-jet searches [1910.08447, 1911.03947, etc.]
- W': production and decay of massive RH neutrinos (includes LLPs)

  [1809.11105 ($M(N_R)<2*M(W_R)$), 1811.00806, 1904.12679, 2112.03949, 2304.09553, etc.]
- Leptonic decay of the W' with light (RH) neutrinos

  [1807.11421, 1906.05609, 2202.06075, 2402.16576, etc.]
- Search for W', Z' decaying to heavy quark flavors

  [tb unsuppressed for $V^R \sim V^{L(*)}$; 1801.07893, 1807.10473, 2104.04831, 2308.08521, 2310.19893, etc.]
- Decays to gauge bosons (W' to WZ, W' to Wh, Z' to WW, Z' to Zh)

  [1906.08589, 2004.14636, 2102.08198, 2109.06055, etc.]

SUMMARY PLOTS EXOTICS: CMS, ATLAS

Model-independent strategy

6

- Available bounds on W', Z' masses may correspond to different models (e.g. Sequential SM), or specific realizations of LRMs (e.g. having heavy RH neutrinos)
- **HERE**:
  - Consider **general g_R, g_X** (perturbative); move **beyond the (pseudo-)manifest** case $V^R \sim V^{L(*)}$ in the quark sector
  - Focus on **fermionic decay modes**: more restrictive bounds
  - Impact of the scalar sector: **total width, neutrino sector**

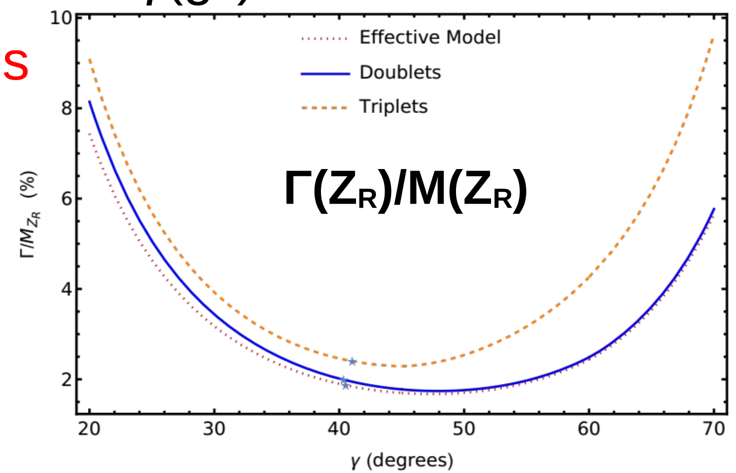
[see e.g. Langacker, Uma Sankar '89; Frank, Ozdal, Poulose '18]

Total widths of the W_R, Z_R

- Usually, only fermion sector considered when calculating Γ
- Non-fermionic width depends on specific scenario (scalar potential)
- To be conservative, maximize the total width ($g_{R,X}$ fixed) => minimize BR; consider limit where the full scalar sector is accessible in decays, and exploit equivalence theorem to simplify the expression of Γ
- $\Gamma(W_R)/M(W_R)$ [below ~10%] prop to g_R^2, decreases with $\gamma(g_R)$
- Collider searches available for different total widths

$$W_R^\pm \to f\bar{f}', W_L^\pm Z_L, W_L^\pm h^0, W_L^\pm H^0, H^\pm Z_L, H^\pm h^0, W_L^\mp H^{\pm\pm}, H_1 H_2$$

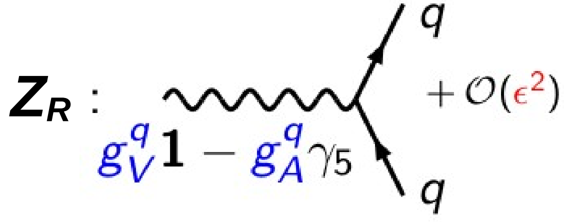
$$Z_R \to f\bar{f}, W_L^+ W_L^-, Z_L h^0, Z_L H^0, W_L^\pm H^\mp, h^0 H^0, W_L^\pm W_R^\mp, H_1 H_2, W_R^\pm H^\mp, W_R^+ W_R^-$$



RH sector parameters: γ(g_R)

- **"Effective couplings"** c^f_q: also functions of γ(g_R) only
- Z_R to ℓℓ: **M(Z_R)>4.2 TeV** (for the γ(g_R) that minimizes σ)

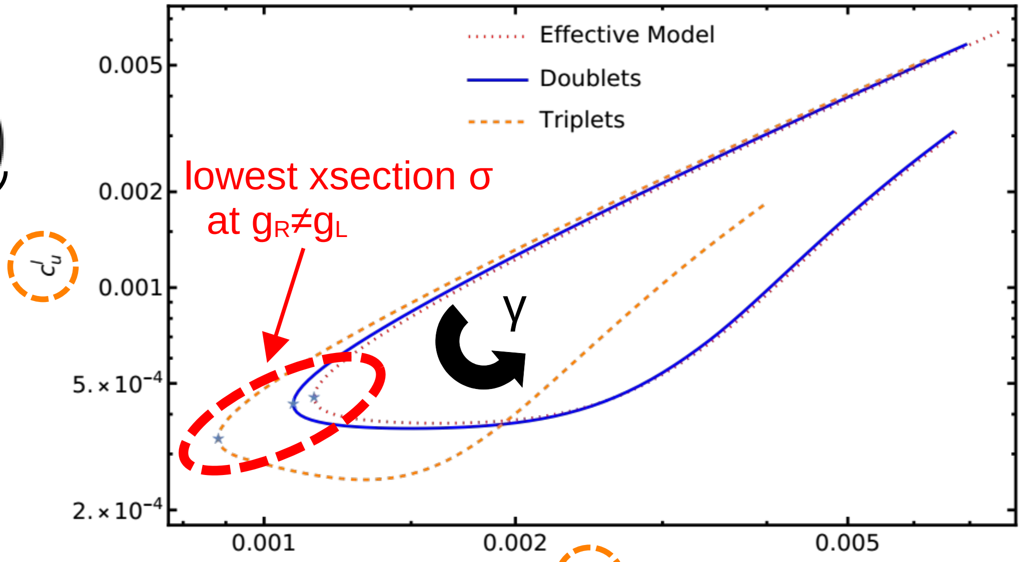
  >4.8 TeV for g_R=g_L & Γ(fermions)



[e, μ: ATLAS √s=13 TeV, 139/fb, CMS √s=13 TeV, ~140/fb;
tau: ATLAS √s=13 TeV, 36.1/fb]

$$\sigma\left(pp \to Z_R X \to f\bar{f}X\right) \approx \frac{\pi}{6s}\sum_q c_q^f\, \underbrace{\omega_q\left(s, M^2_{Z_R}\right)}_{\text{PDFs}}$$

$$c_q^f = \frac{1}{2}\underbrace{\left((g_V^q)^2 + (g_A^q)^2\right)}_{\text{production}}\underbrace{\mathrm{Br}\left(Z_R \to f\bar{f}\right)}_{\text{decay}}$$



c^l_d

LVS [see also Accomando, Belyaev, Fedeli, King, Shepherd-T. '10 (in the limit g_R=g_L)]

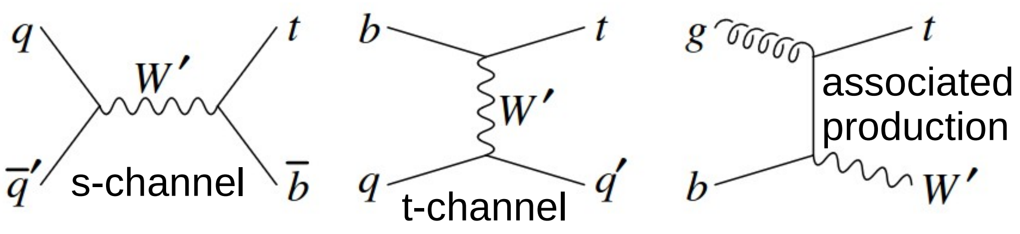
RH sector parameters: V^R

- **Production of W_R affected by V^R texture**: relax by **~1 TeV** bounds on $M(W_R)$

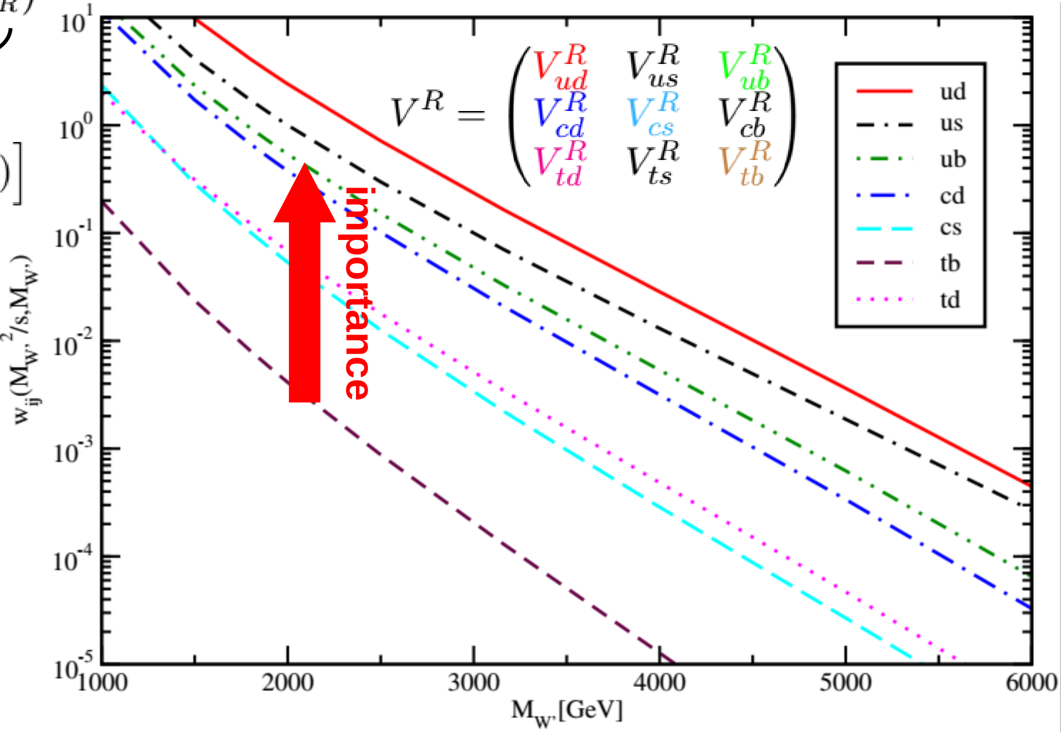
$$\sigma\left(pp \to W_R^{\pm} X\right) \approx \frac{2\pi^2}{3s}\frac{g_R^2}{4\pi}\sum_{ij}\left|\left(V^R\right)_{ij}\right|^2 \underbrace{\omega_{ij}\left(M_{W_R}^2/s,\, M_{W_R}\right)}_{\text{PDFs}}$$

$$\omega_{ij}\left(z,\,\mu\right) = \int_z^1 \frac{\mathrm{d}x}{x}\left[u_i\left(x,\,\mu\right)\bar{d}_j\left(z/x,\,\mu\right) + \bar{u}_i\left(x,\,\mu\right)d_j\left(z/x,\,\mu\right)\right]$$

[NLO: Sullivan '02; t-channel & assoc. prod.: small]



[W_Rt: Frank, Hayreter, Turan '10;
W'b: Abdullah, Calle, Dutta, Florez, Restrepo '18, etc.]



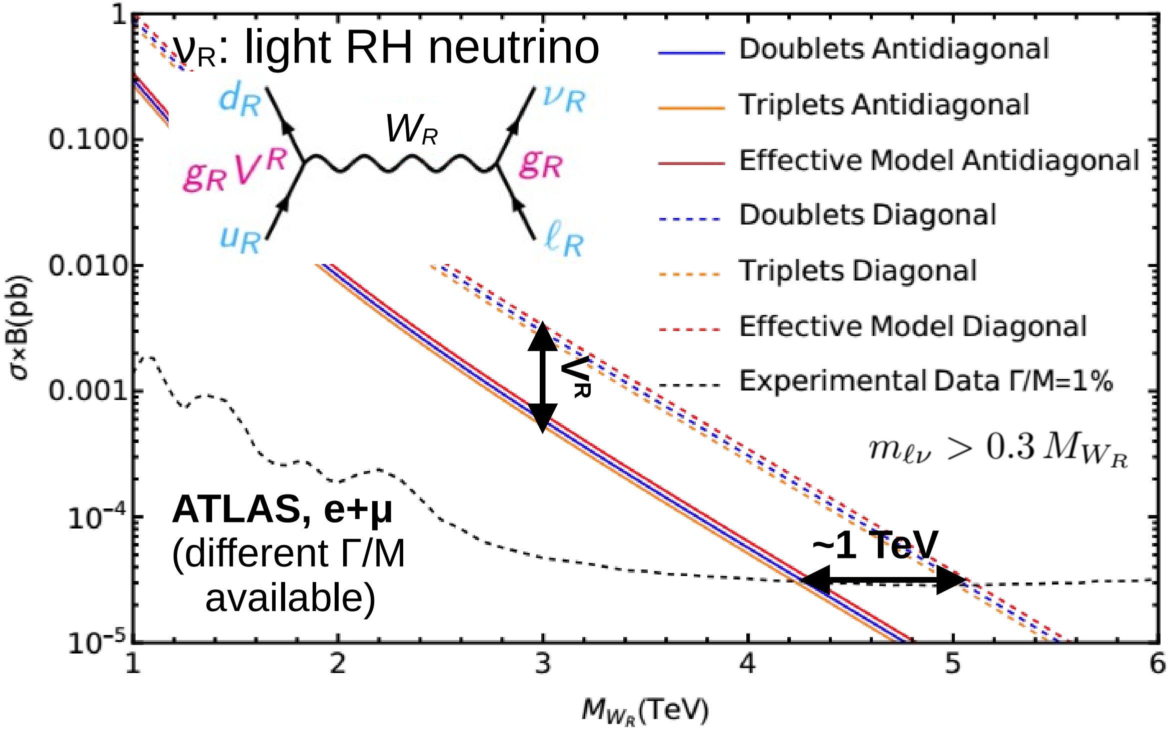
[NNPDF '12; Bernard, Descotes-G., LVS '20]

Neutrino sector

- Typical bounds for heavy RH neutrinos: **$M(W_R)$>O(5) TeV** [for $M(N_R)<M(W_R)$]
- Searches of W_R based on massive RH neutrinos depend on leptonic RH mixings

- Light RH neutrino case applies in the doublet LR scenario; it can also apply in the other cases
- Sum over neutrino species: $\Sigma_i |U^R_{i\ell}|^2 = 1$

[e, μ: ATLAS √s=13 TeV, 139/fb, CMS √s=13 TeV, 138/fb]
[tau: ATLAS √s=13 TeV, 139/fb, CMS √s=13 TeV, 36/fb]



Summary of bounds

- More conservative bounds: minimize w.r.t. γ(g_R) inside perturbative region
- Bounds can be relaxed by about **~1 TeV**

Channel		$\Phi + \chi_{L,R}$ (D)	$\Phi + \Delta_{L,R}$ (T)	$\chi_{L,R}$ (Eff)
$Z_R \to \ell_i \bar{\ell}_i$	M_{Z_R}	4.3	4.2	4.3
$W_R \to jj$, anti-diag.	M_{W_R}	2.1	2.0	2.1
$W_R \to \ell_i \bar{\nu}_R$, anti-diag.	M_{W_R}	4.3	4.2	4.3
$W_R \to jj$, diag.	M_{W_R}	2.9	2.7	3.0
$W_R \to \ell_i \bar{\nu}_R$, diag.	M_{W_R}	5.1	5.0	5.1

significant impact of the V^R texture, decay mode, and neutrino sector

masses in TeV, about 95%CL

ν_R: light RH neutrino

not significant impact of the scalar realization

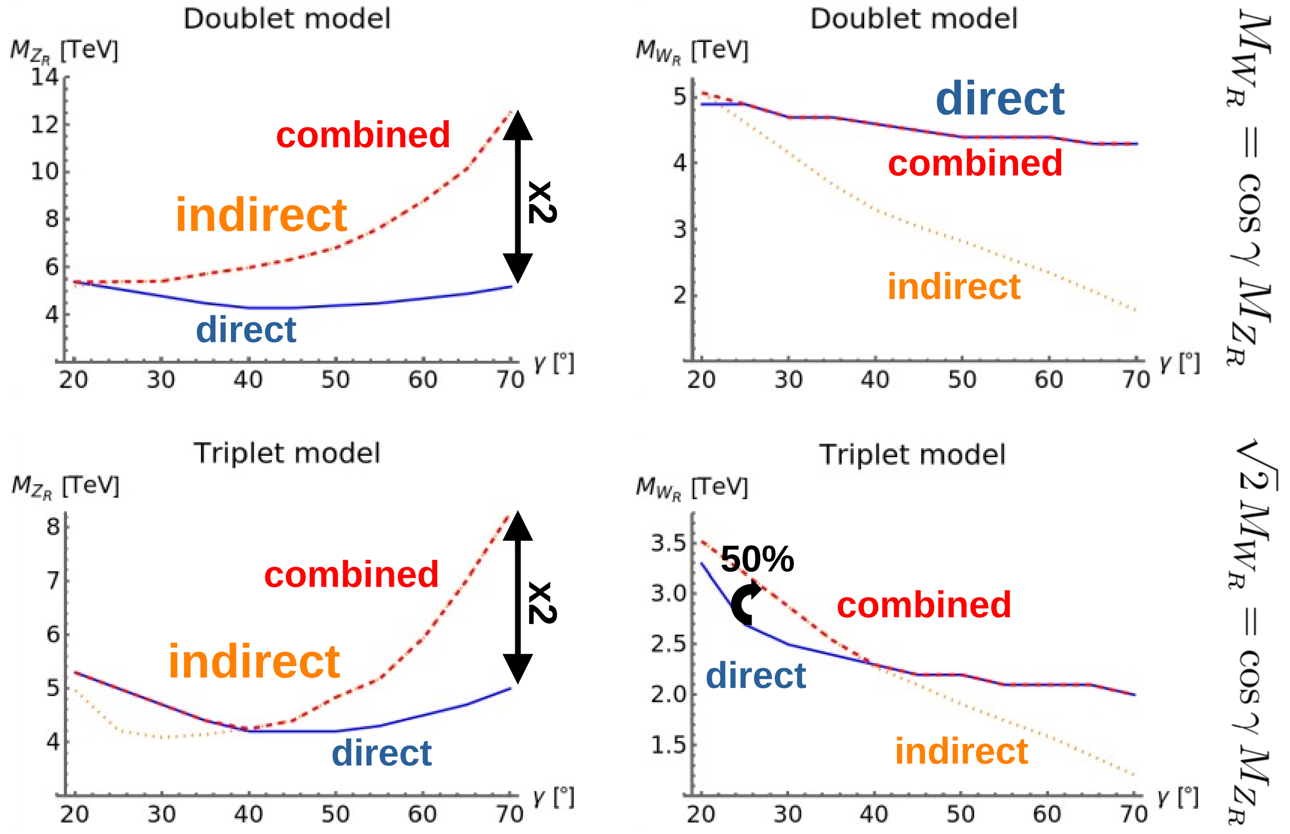
LVS

Synergy of W_R, Z_R searches

- In typical LRMs, $M(W_R)$ and $M(Z_R)$ are deeply connected
- From doublet to triplet, $\sqrt{2}$ due to LR-SSM
- For higher γ [$\cos(\gamma) \rightarrow 0$], bound on $M(W_R)$ tends to dominate; for lower γ, the inverse happens

[see also Araz, Frank, Fuks, Moretti, Ozdal '21 (in the limit $g_R = g_L$, etc.)]

Doublet: Z_R to $\ell\ell$, W_R to $\ell\nu_R$



Triplet: Z_R to $\ell\ell$, W_R to jj (avoid $U^R(\nu_R)$)

Conclusions

- LRMs: different realizations, e.g. a LR discrete symmetry can be pushed to higher energies
- Mostly impacted by $g_R \neq g_L$, $V^R \neq V^{L(*)}$ parametric LR asymmetries
- After relaxing bounds, still **sensitive to multi-TeV** gauge bosons
- Complementarity of W_R and Z_R searches
- Collider constraints provide a powerful way to constrain LRMs; very competitive w.r.t. flavor physics

Thanks!

BACK UP

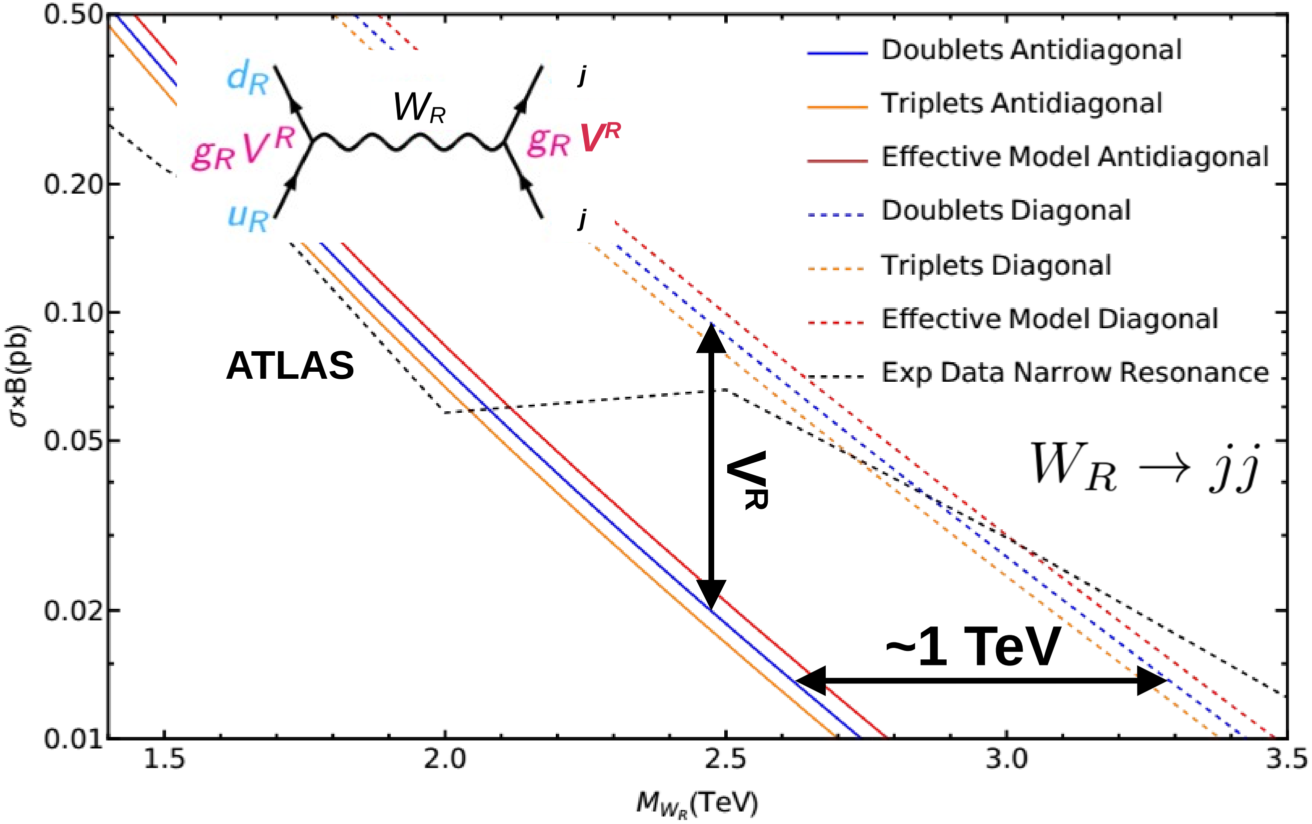
Di-jet searches

App 1

- W_R to jj: independent of the neutrino sector
- jj: top-quark considered as a possible final state flavor (i.e. inclusive in the flavor)
- Similar bounds achieved with W_R to tb

[WR: ATLAS √s=13 TeV, 139/fb; CMS √s=13 TeV, 139/fb, with different Γ/M available, also ZR; ZR: ATLAS √s=13 TeV, 139/fb; CMS √s=13 TeV, 35.9/fb]

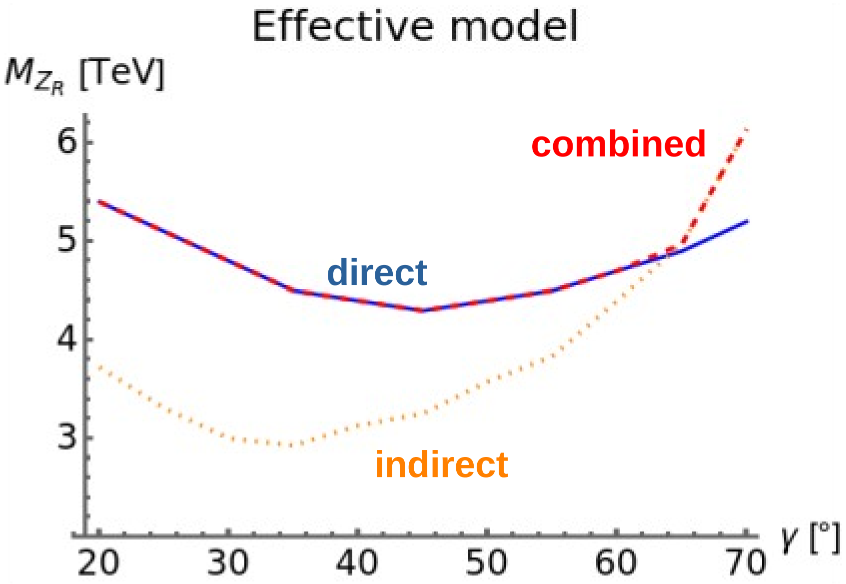
[tb, had: ATLAS √s=13 TeV, 139/fb; CMS √s=13 TeV, 137/fb][tb, lept: ATLAS √s=13 TeV, 139/fb; CMS √s=13 TeV, 138/fb, with different Γ/M available]

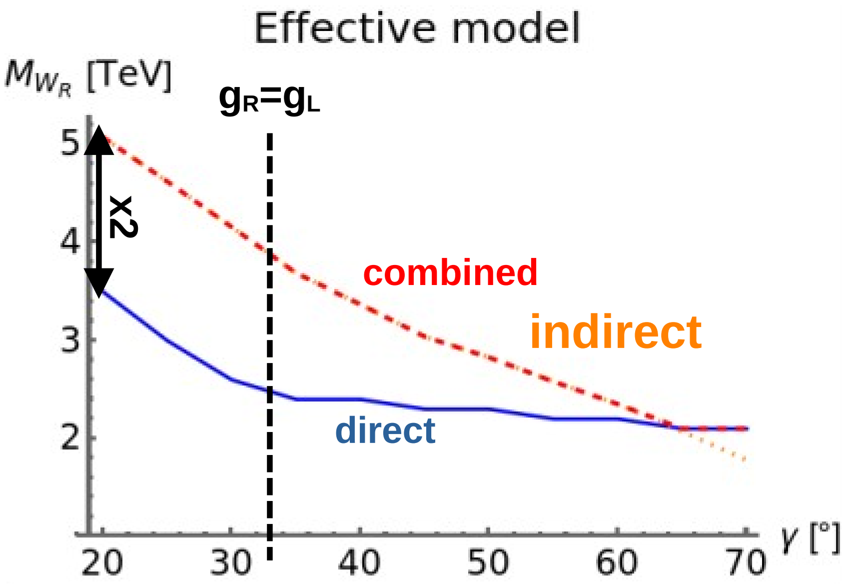


Synergy of W_R, Z_R searches

App 2

Effective: Z_R to ℓℓ, W_R to jj (avoid $U^R(\nu_R)$)

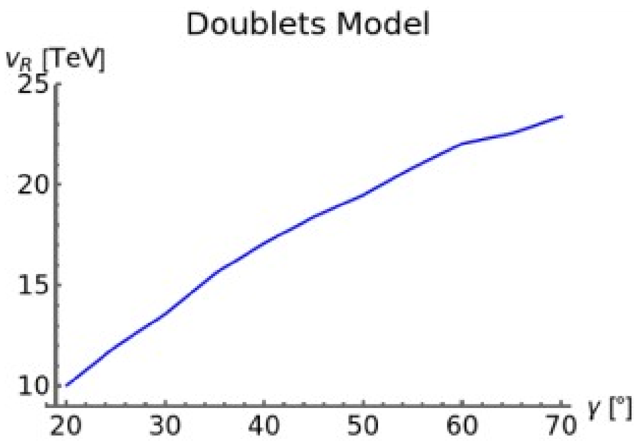


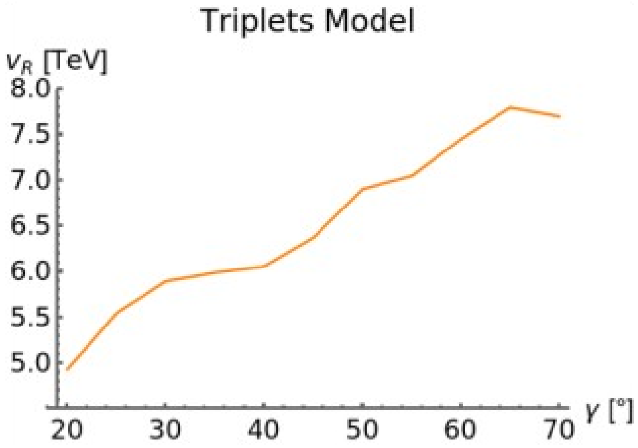


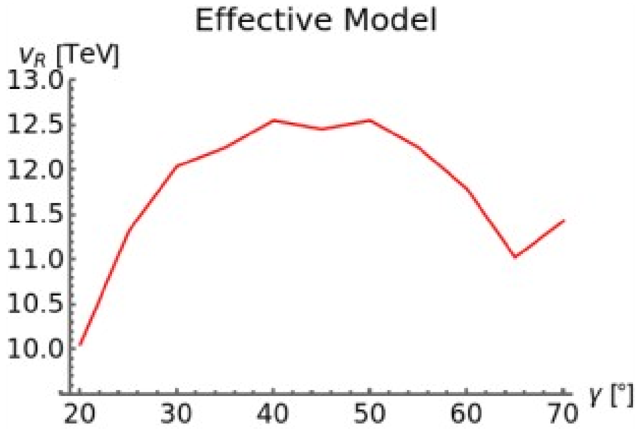
$$M_{W_R} = \cos\gamma \, M_{Z_R}$$

LR-SSB scale

App 3







$$|v_R|_D \gtrsim 10\,\mathrm{TeV}, \qquad |v_R|_T \gtrsim 4.9\,\mathrm{TeV}, \qquad |v_R|_{\mathrm{Eff}} \gtrsim 10\,\mathrm{TeV}.$$

The $\chi_L + \chi_R$ Effective LR Model

- The scalar sector is very simple. We only have two physical degrees of freedom:

$$\chi_{L,R} := \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_{L,R} + \chi^{0r}_{L,R} \end{pmatrix}$$

(Unitary Gauge)

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \chi^{0r}_R \\ \chi^{0r}_L \end{pmatrix}$$

$$v_R \gg v_L = v_{EW}$$

- Only 5 free parameters in the scalar potential

$$M_H^2 \approx 2\lambda_R v_R^2, \qquad M_h^2 \approx \frac{4\lambda_L\lambda_R - \lambda_{LR}^2}{2\lambda_R} v_L^2$$

$$V = -\mu_L^2 \chi_L^\dagger \chi_L - \mu_R^2 \chi_R^\dagger \chi_R + \lambda_L \left(\chi_L^\dagger \chi_L\right)^2 + \lambda_R \left(\chi_R^\dagger \chi_R\right)^2 + \lambda_{LR}\left(\chi_L^\dagger \chi_L\right)\left(\chi_R^\dagger \chi_R\right).$$

$$\tan\theta = \frac{\lambda_{LR} v_L v_R}{\lambda_L v_L^2 - \lambda_R v_R^2}$$

The $\chi_L + \chi_R$ Effective LR Model

- No $W_L - W_R$ Mixing

$$M_{W_L} = \frac{1}{2} g_L v_L, \qquad M_{W_R} = \frac{1}{2} g_R v_R, \qquad M_{Z_L} \approx \frac{M_{W_L}}{\cos\theta_W}, \qquad M_{Z_R} \approx \frac{M_{W_R}}{\cos\gamma}$$

- We need Effective Operators to produce Fermion Masses

$$\mathcal{L}_Y = -\frac{1}{\Lambda}\Big\{C_d^{ij}\bar{q}_L^i \chi_L \chi_R^\dagger q_R^j + C_u^{ij}\bar{q}_L^i \tilde{\chi}_L \tilde{\chi}_R^\dagger q_R^j + C_e^{ij}\bar{l}_L^i \chi_L \chi_R^\dagger l_R^j + C_{\nu_D}^{ij}\bar{l}_L^i \tilde{\chi}_L \tilde{\chi}_R^\dagger l_R^j$$

(Dirac Masses)

$$+C_{\nu_{L,M}}^{ij}\bar{l}_L^i \tilde{\chi}_L \tilde{\chi}_L^{\mathrm{T}} l_L^{j\,c} + C_{\nu_{R,M}}^{ij}\bar{l}_R^{c\,i} \tilde{\chi}_R^* \tilde{\chi}_R^\dagger l_R^j\Big\}$$

(Majorana Masses)

$$\tilde{\chi}_{L,R} := i\sigma^2 \chi_{L,R}^*$$

The $\chi_L + \chi_R$ Effective LR Model

- Dirac Masses for Quarks and Charged Leptons and Majorana Masses for Neutrinos

$$m_{q,l^\pm} \propto \frac{v_L v_R}{\Lambda}, \qquad m_{\nu_h} \propto \frac{v_R^2}{\Lambda}, \qquad m_{\nu_l} \propto \frac{v_L^2}{\Lambda}$$

- No FCNCs in the Hadronic Sector

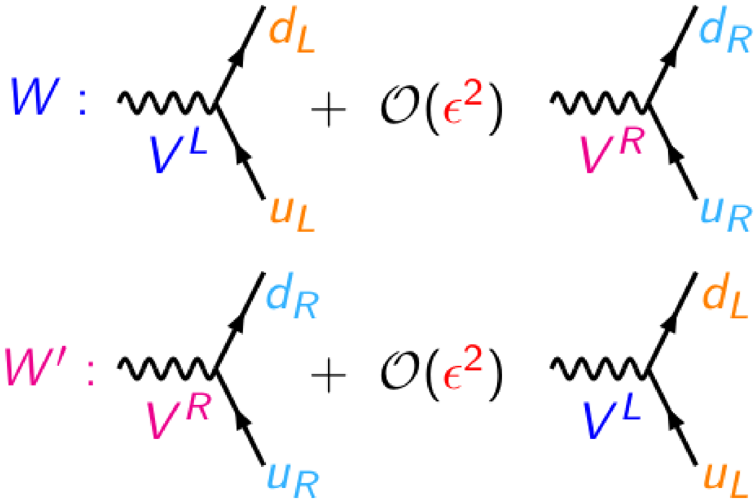
$$\mathcal{L}^Y_{u,d,e} = -\left(1 + \frac{\chi_L^{0r}}{v_L}\right)\left(1 + \frac{\chi_R^{0r}}{v_R}\right) \sum_{f=u,d,e} \bar{f} \mathcal{M}_f f.$$

Sources of **CP** violation in the quark sector

→ Φ is included for a mass generation mechanism for fermions:

$$\overline{Q}_L Y \Phi Q_R + \overline{Q}_L \tilde{Y} \tilde{\Phi} Q_R + h.c.$$
$$\Rightarrow M_u = \kappa_1 Y + \kappa_2 \tilde{Y} \text{ and } M_d = \kappa_1 \tilde{Y} + \kappa_2 Y$$

→ Bi-diagonalization: mixing matrices V^L and V^R



→ Mixing of gauge bosons:
V^{CKM} interpreted as $V^L + \mathcal{O}(\epsilon^2) V^R$
→ V^R: new currents violating **CP**

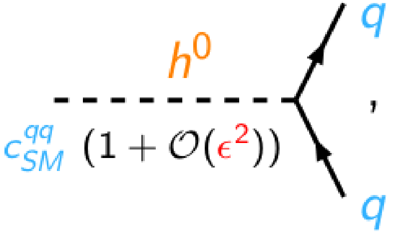
→ **P** relates V^R to V^L [Senjanovic, Tello '15]
→ If the unification of *couplings* happens above κ_R, the structure of V^R is left unknown

Light SM-like Higgs

$$h^0 = \frac{1}{\sqrt{\kappa_1^2+\kappa_2^2+\kappa_L^2}}\Big(\underbrace{\kappa_1\,\varphi_1^{0r} + \kappa_2\,\varphi_2^{0r}}_{bi-doublet} \underbrace{+\ \kappa_L\,\chi_L^{0r}}_{SU(2)_L-doublet} \Big) + \underbrace{\mathcal{O}(\epsilon)\,\chi_R^{0r}}_{SU(2)_R-doublet}$$

Couplings to fermions similar to the SM:

$$-\left(\frac{m_d^i}{\sqrt{\kappa_1^2+\kappa_2^2+\kappa_L^2}}\overline{d_L^i}\,d_R^i + \frac{m_u^j}{\sqrt{\kappa_1^2+\kappa_2^2+\kappa_L^2}}\overline{u_L^j}\,u_R^j\right) h^0 + \mathcal{O}(\epsilon^2) + h.c.$$



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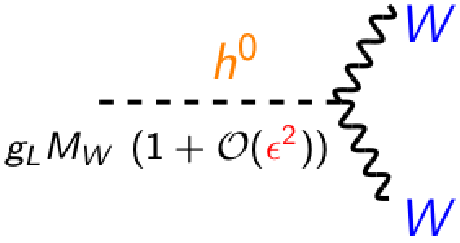
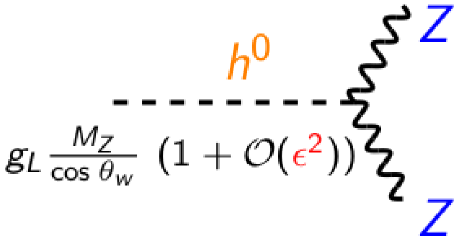
and in particular h^0 is flavour diagonal up to $\mathcal{O}(\epsilon^2)$

Couplings to gauge bosons corrected at $\mathcal{O}(\epsilon^2)$



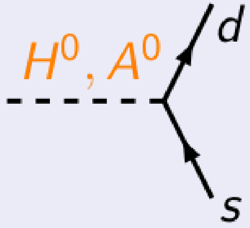


Physical scalars and FCNC

Scalar content: $1\times$ light SM-like Higgs h^0
$3\times$ $\mathcal{CP}-$even $H^0_{1,2,3}$, $2\times$ $\mathcal{CP}-$odd $A^0_{1,2}$, of mass $\sim \kappa_R$
$2\times$ singly charged $H^{\pm}_{1,2}$, of mass $\sim \kappa_R$
$2\times$ doubly charged $H^{\pm\pm}_{1,2}$, of mass $\sim \kappa_R$ (*triplet only*)

Flavour Changing Neutral Currents (FCNC) at tree level

$\overline{Q}_L Y \Phi Q_R + \overline{Q}_L \tilde{Y} \tilde{\Phi} Q_R + h.c. \Rightarrow M_u = \kappa_1 Y + \kappa_2 \tilde{Y}$ and $M_d = \kappa_1 \tilde{Y} + \kappa_2 Y$,
since couplings are not diagonalized simultaneously: FCN couplings



Higgses	d.o.f.	FCNC for sd
H^0_1, A^0_1	$f_1\,\Phi + g_1\,\chi_L$	$f_C \sum_a m_u^a V_L^{as*} V_R^{ad}$
H^0_2, A^0_2	$f_2\,\chi_L + g_2\,\Phi$	$g_C \sum_a m_u^a V_L^{as*} V_R^{ad}$

$f_{1,2,C} \to 1$, $g_{1,2,C} \to 0$, when $\kappa_L \to 0$

FCNC: ***triplets*** $\{H^0_1, A^0_1\}$, and ***doublets*** $\{H^0_1, A^0_1, H^0_2, A^0_2\}$

Higgs potential, differences triplet and doublet

P symmetric case (parameters in total: 15 + 1 complex phase):

$$
\begin{aligned}
V = & -\mu_1^2 \,\mathrm{tr}(\Phi^\dagger\Phi) - \mu_2^2 \,\mathrm{tr}(\tilde{\Phi}^\dagger\Phi + \tilde{\Phi}\Phi^\dagger) - \mu_3^2(\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R) \\
& + {\mu'}_1(\chi_L^\dagger\Phi\chi_R + \chi_R^\dagger\Phi^\dagger\chi_L) + {\mu'}_2(\chi_L^\dagger\tilde{\Phi}\chi_R + \chi_R^\dagger\tilde{\Phi}^\dagger\chi_L) + \lambda_1[\mathrm{tr}(\Phi^\dagger\Phi)]^2 \\
& + \lambda_2\left([\mathrm{tr}(\tilde{\Phi}^\dagger\Phi)]^2 + [\mathrm{tr}(\tilde{\Phi}\Phi^\dagger)]^2\right) + \lambda_3 \,\mathrm{tr}(\tilde{\Phi}^\dagger\Phi)\,\mathrm{tr}(\tilde{\Phi}\Phi^\dagger) \\
& + \lambda_4 \,\mathrm{tr}(\Phi^\dagger\Phi)\,\mathrm{tr}(\tilde{\Phi}^\dagger\Phi + \tilde{\Phi}\Phi^\dagger) + \rho_1[(\chi_L^\dagger\chi_L)^2 + (\chi_R^\dagger\chi_R)^2] \\
& + \rho_3(\chi_L^\dagger\chi_L)(\chi_R^\dagger\chi_R) + \alpha_1(\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R)\,\mathrm{tr}(\Phi^\dagger\Phi) \\
& + \frac{\alpha_2}{2}\{e^{i\delta_2}[\chi_L^\dagger\chi_L \,\mathrm{tr}(\tilde{\Phi}\Phi^\dagger) + \chi_R^\dagger\chi_R \,\mathrm{tr}(\tilde{\Phi}^\dagger\Phi)] \\
& \qquad + e^{-i\delta_2}[\chi_L^\dagger\chi_L \,\mathrm{tr}(\tilde{\Phi}^\dagger\Phi) + \chi_R^\dagger\chi_R \,\mathrm{tr}(\tilde{\Phi}\Phi^\dagger)]\} \\
& + \alpha_3(\chi_L^\dagger\Phi\Phi^\dagger\chi_L + \chi_R^\dagger\Phi^\dagger\Phi\chi_R) + \alpha_4(\chi_L^\dagger\tilde{\Phi}\tilde{\Phi}^\dagger\chi_L + \chi_R^\dagger\tilde{\Phi}^\dagger\tilde{\Phi}\chi_R),
\end{aligned}
\tag{1}
$$

Triplet case: no ${\mu'}_1, {\mu'}_2$, but other terms are present (parameters in total: 17 + 1 complex phase)

C symmetric case: further phases are present beyond δ_2