

Direct Bounds on Left-Right Gauge Boson Masses at LHC Run 2

Sergio Ferrando Solera

Antonio Pich

Luiz Vale Silva



Why LR Models?

- Mohapatra, Pati (1975)
- Senjanovic, Mohapatra (1975)
- Senjanovic (1979)

- New Physics: Dark Matter, Neutrino Masses,...
- The Laws of Physics are not invariant under **Parity**

$$\begin{array}{c} \text{SU(3)_{QCD}} \times \text{SU(2)_L} \times \text{U(1)_Y} \\ \downarrow \\ \text{SU(3)_{QCD}} \times \text{SU(2)_L} \times \text{SU(2)_R} \times \text{U(1)_X} \\ g_S \qquad \qquad \qquad g_L \qquad \qquad \qquad g_R \qquad \qquad \qquad g_X \\ X = (\text{B} - \text{L})/2 \end{array}$$

General Results of LR Models

$$\text{SU}(3)_{\text{QCD}} \times \text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_X$$

- Restoration of Parity: $g_L = g_R$
- New Gauge Bosons: $g \ A \ W_L^\pm \ Z_L^0 \ W_R^\pm \ Z_R^0$
- Right-Handed Neutrinos: ν_R
- Two Energy Scales: $\nu_R \gg \nu_{EW}$
- New mixing matrices for fermions: $V_L^{\text{CKM}} \ V_L^{\text{PMNS}} \ V_R^{\text{CKM}} \ V_R^{\text{PMNS}}$

Embedding of LR Models

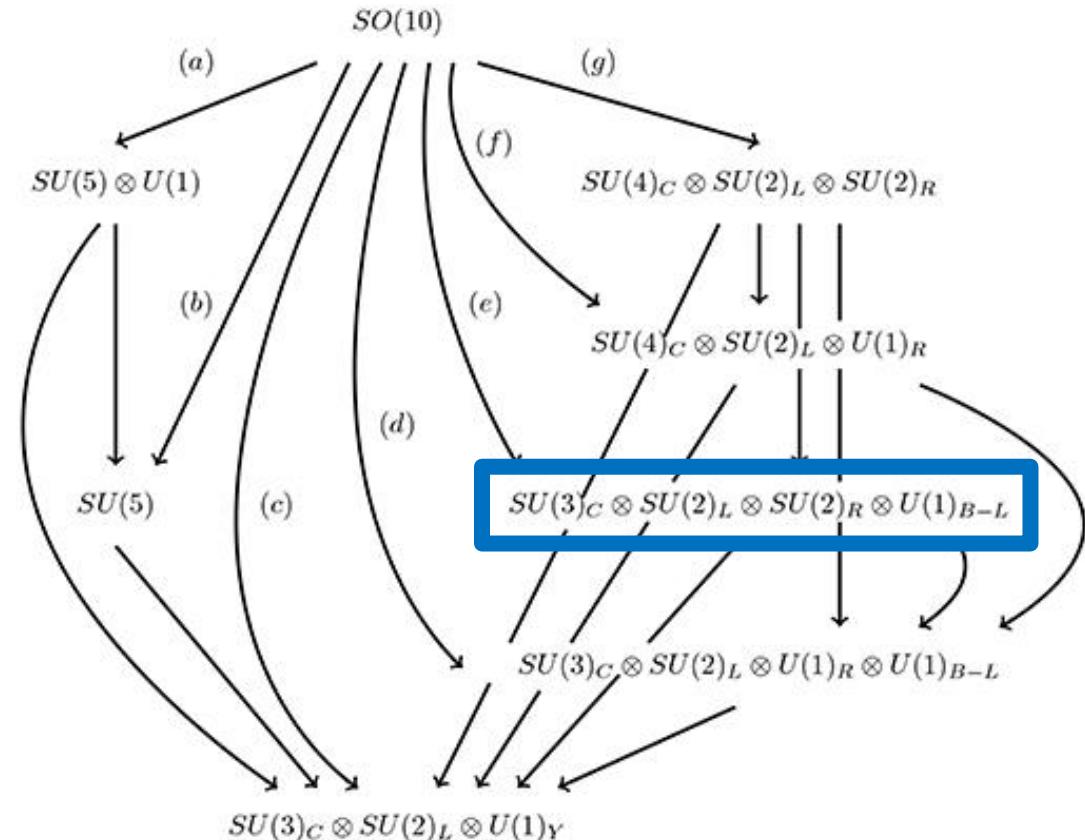
- Pati, Salam (1974)
- Fritzsch, Minkowski (1975)
- Chang, Mohapatra, Parida (1984)

- LR Models are Embedded in other BSM Theories
- Restoration of **Parity** can be pushed to higher energy scales

We will **not** assume that **Parity** or **Charge Conjugation** are Symmetries of the Theory

$$g_L \neq g_R$$

$$V_L \neq V_R$$



Gonzalo Velasco T. *Model Building and Phenomenology in Grand Unified Theories.*

SSB and Perturbativity

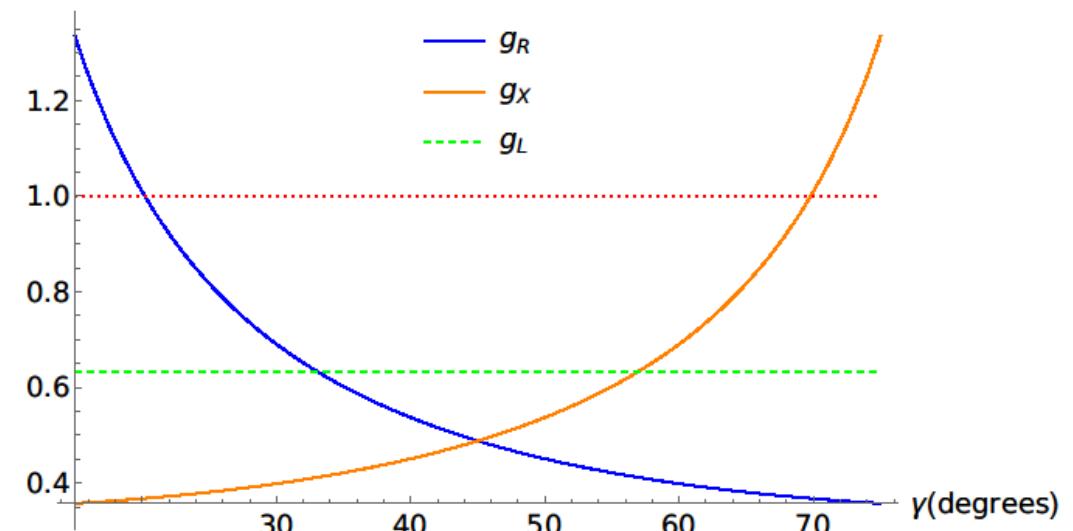
$$\begin{pmatrix} Z_L \\ Z_R \\ A \end{pmatrix} = \underbrace{\begin{pmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{Z_L - Z_R \text{ Mixing}} \begin{pmatrix} \cos \theta_W & 0 & -\sin \theta_W \\ 0 & 1 & 0 \\ \sin \theta_W & 0 & \cos \theta_W \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \gamma & -\sin \gamma \\ 0 & \sin \gamma & \cos \gamma \end{pmatrix} \begin{pmatrix} W_L^3 \\ W_R^3 \\ W_X \end{pmatrix}$$

$$Z_L - Z_R \text{ Mixing} \quad \alpha \sim \left(\frac{v_{EW}}{v_R} \right)^2$$

- Perturbativity: $g_R, g_X \leq 1$

$$e = g_R \cos \theta_W \sin \gamma = g_X \cos \theta_W \cos \gamma$$

70° > γ > 20°



Scalar Fields

- Bidoublet + Doublets (Dirac Neutrinos):

$$\Phi := \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \quad \chi_L := \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix}, \quad \chi_R := \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}. \quad \begin{aligned} \Phi &\sim (1, 2, \bar{2}, 0) \\ \chi_L &\sim (1, 2, 1, 1/2) \\ \chi_R &\sim (1, 1, 2, 1/2) \end{aligned}$$

- Bidoublet + Triplets (Majorana Neutrinos):

$$\Phi, \quad \Delta_L := \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix}, \quad \Delta_R := \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix}. \quad \begin{aligned} \Delta_L &\sim (1, 3, 1, 1) \\ \Delta_R &\sim (1, 1, 3, 1) \end{aligned}$$

- $\chi_L + \chi_R$ Effective LR Model.

- Babu, Dutta, Mohapatra (2019)
- Babu, He, Su, Thapa (2022)

The $\chi_L + \chi_R$ Effective LR Model

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

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

(Unitary Gauge)

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \chi_R^{0r} \\ \chi_L^{0r} \end{pmatrix}$$

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

- Only 5 free parameters in the scalar potential

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

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

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

The $\chi_L + \chi_R$ Effective LR Model

- No $W_L - W_R$ Mixing

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

- We need Effective Operators to produce Fermion Masses

$$\mathcal{L}_Y = -\frac{1}{\Lambda} \left\{ C_d^{ij} \bar{q}_L^i \chi_L \chi_R^\dagger q_R^j + C_u^{ij} \bar{q}_L^i \tilde{\chi}_L \tilde{\chi}_R^\dagger q_R^j + C_e^{ij} \bar{l}_L^i \chi_L \chi_R^\dagger l_R^j + C_{\nu_D}^{ij} \bar{l}_L^i \tilde{\chi}_L \tilde{\chi}_R^\dagger l_R^j \right. \\ \left. + C_{\nu_{L,M}}^{ij} \bar{l}_L^i \tilde{\chi}_L \tilde{\chi}_L^T l_L^{j,c} + C_{\nu_{R,M}}^{ij} \bar{l}_R^c i \tilde{\chi}_R^* \tilde{\chi}_R^\dagger l_R^j \right\} \quad (\text{Dirac Masses})$$

(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

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

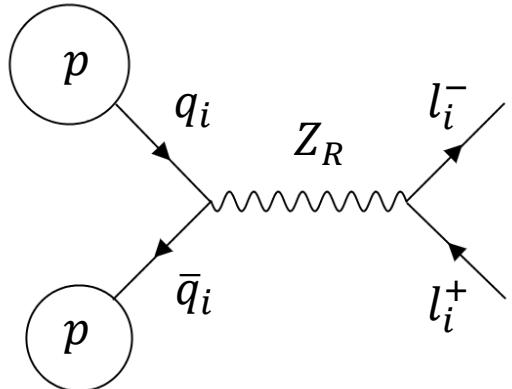
- No FCNCs in the Hadronic Sector

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

Z_R Physics in Colliders

- Narrow Resonance Approximation

$$\sqrt{s} = 13 \text{ TeV}$$



$$\sigma(pp \rightarrow Z_R X \rightarrow f\bar{f}X) \approx \frac{\pi}{6s} \sum_q c_q^f \cdot \omega_q(s, M_{Z_R}^2)$$

Ellis, Stirling, Webber (2011)

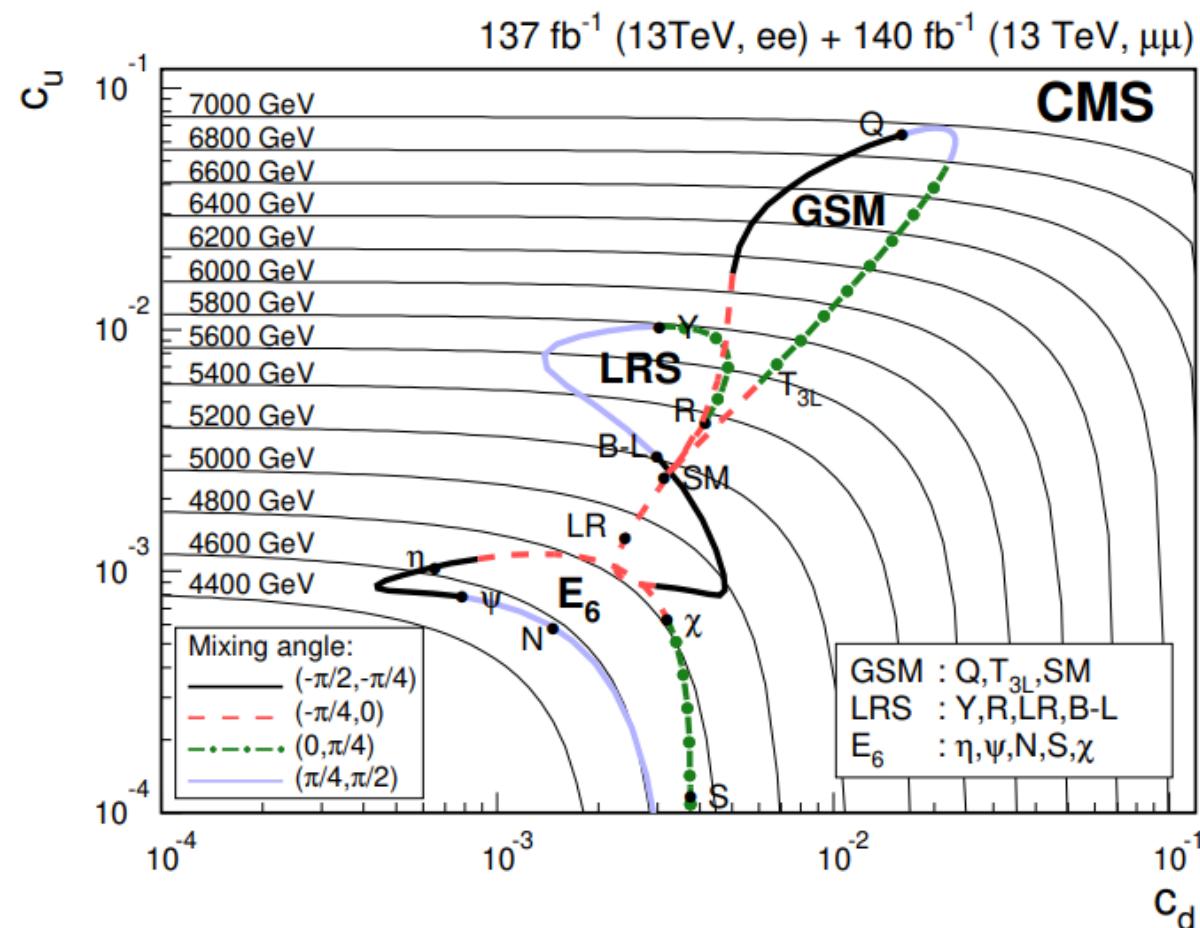
- The $\omega_q(s, M_{Z_R}^2)$ depend on the Parton Distribution Functions

$$c_q^f := \frac{1}{2} (g_V^{q^2}(\gamma) + g_A^{q^2}(\gamma)) \text{Br}(Z_R \rightarrow f\bar{f}) \quad \mathcal{L}_{Z_R}^{ff} = \frac{1}{2} Z_R^\mu \bar{f} \gamma_\mu \left(g_V^f - g_A^f \gamma_5 \right) f$$

- Due to Flavour Universality only c_u^f and c_d^f are relevant

Z_R Decay to Charged Leptons

- We will put the bounds using the processes: $Z_R \rightarrow e^+e^-, \mu^+\mu^-$



CMS (2103.02708)

Z_R Decay to Charged Leptons

- We only need to compute

$$\text{Br}(Z_R \rightarrow l^+l^-) := \Gamma(Z_R \rightarrow l^+l^-)/\Gamma_{Z_R}$$

- The Partial Width of the decay to two fermions only depends on the mixing angle γ and it is proportional to M_{Z_R}

$$\Gamma(Z_R \rightarrow f\bar{f}) \approx N_C^f \frac{M_{Z_R}}{48\pi} \left[g_V^{f2}(\gamma) + g_A^{f2}(\gamma) \right] \quad (\text{Assuming } M_{Z_R} \gg m_f)$$

The Total Width of the Z_R

- The processes that contribute to the total width of the Z_R at leading order in e are

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

- Since the **Diagonalization of the Scalar Potentials** is highly non-trivial we will only put an **Upper Bound** on Γ_{Z_R} .
- Consequently, we will get the **Less Constraining Lower Bound** on M_{Z_R}

$$\Gamma(Z_R \rightarrow \nu_R \bar{\nu}_R) \leq \Gamma(Z_R \rightarrow \nu_R \bar{\nu}_R)|_{m_{\nu_R}=0}$$

The Total Width of the Z_R

- The Partial Width of $Z_R \rightarrow W_R^\pm W_L^\mp$ is negligible

$$\bullet \quad \Gamma(Z_R \rightarrow W_R^\pm W_R^\mp) = \frac{M_{Z_R}}{192\pi} \frac{e^2}{\cos^2 \theta_W} \frac{(1 - 4 \cos^2 \gamma)^{3/2}}{\sin^2 \gamma \cos^2 \gamma} \{1 + 20 \cos^2 \gamma + 12 \cos^4 \gamma\} \quad (\text{Bidoublet + 2 Doublets})$$

$$\bullet \quad \Gamma(Z_R \rightarrow H^\pm W_R^\mp) \leq \Gamma(Z_R \rightarrow H^\pm W_R^\mp)|_{M_{H^\pm}=0} \quad (\text{Bidoublet + 2 Doublets})$$

$$\Gamma(Z_R \rightarrow H^\pm W_R^\mp) \leq \frac{M_{Z_R}}{12\pi} \frac{e^2}{\cos^2 \theta_W} \sin^4 \gamma \left\{ 1 + \frac{(1 + \cos^2 \gamma)^2}{8 \cos^2 \gamma} \right\}$$

The Total Width of the Z_R

- In the processes that we consider, if an **Emitted Gauge Boson** carries a **Large Momentum** the **Amplitude is Dominated** by its **Longitudinal Degree of Freedom**. We use the **Equivalence Theorem**.

$$M_{Z_R} \gg M_{W_L}, M_{Z_L}, M_{h^0}$$

- $\Gamma(Z_R \rightarrow W_L^+ W_L^-) \approx \Gamma(Z_R \rightarrow G_L^+ G_L^-)$ • $\Gamma(Z_R \rightarrow Z_L h^0) \approx \Gamma(Z_R \rightarrow G_L^0 h^0)$
- $\Gamma(Z_R \rightarrow H^\pm W_L^\mp) \leq \Gamma(Z_R \rightarrow H^\pm W_L^\mp)|_{M_{H^\pm}=0} \approx \Gamma(Z_R \rightarrow H^\pm G_L^\mp)|_{M_{H^\pm}=0}$
- $\Gamma(Z_R \rightarrow H^0 Z_L) \leq \Gamma(Z_R \rightarrow H^0 Z_L)|_{M_{H^0}=0} \approx \Gamma(Z_R \rightarrow H^0 G_L^0)|_{M_{H^0}=0}$

The Total Width of the Z_R

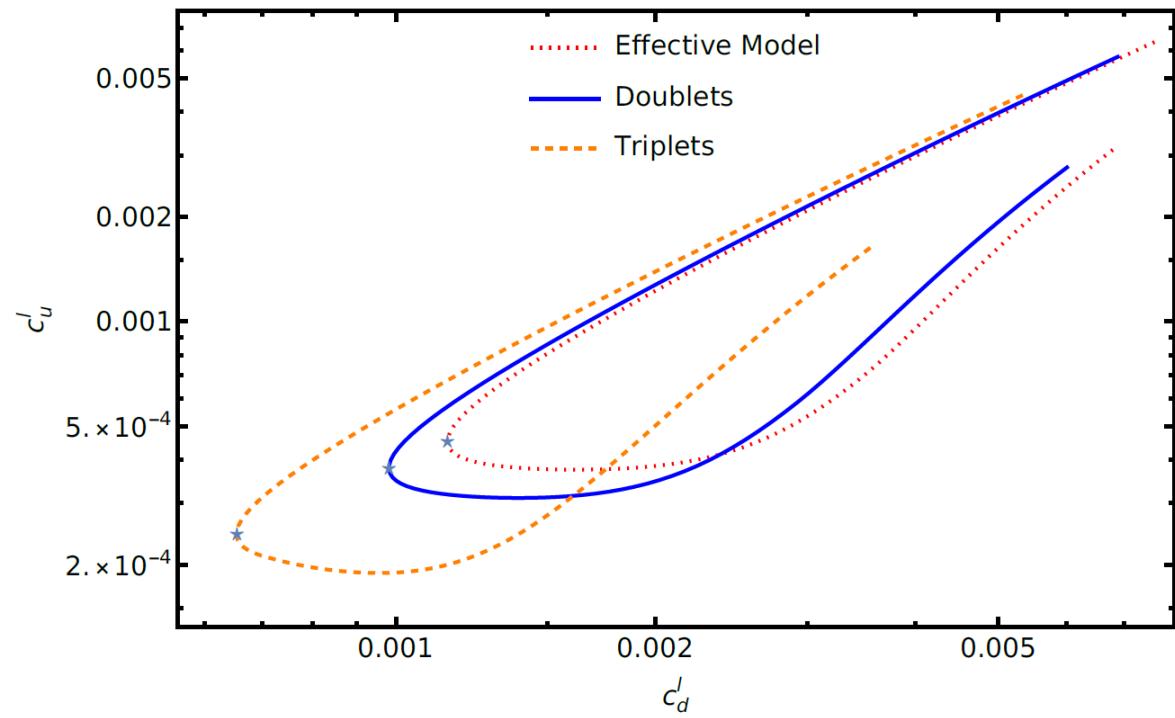
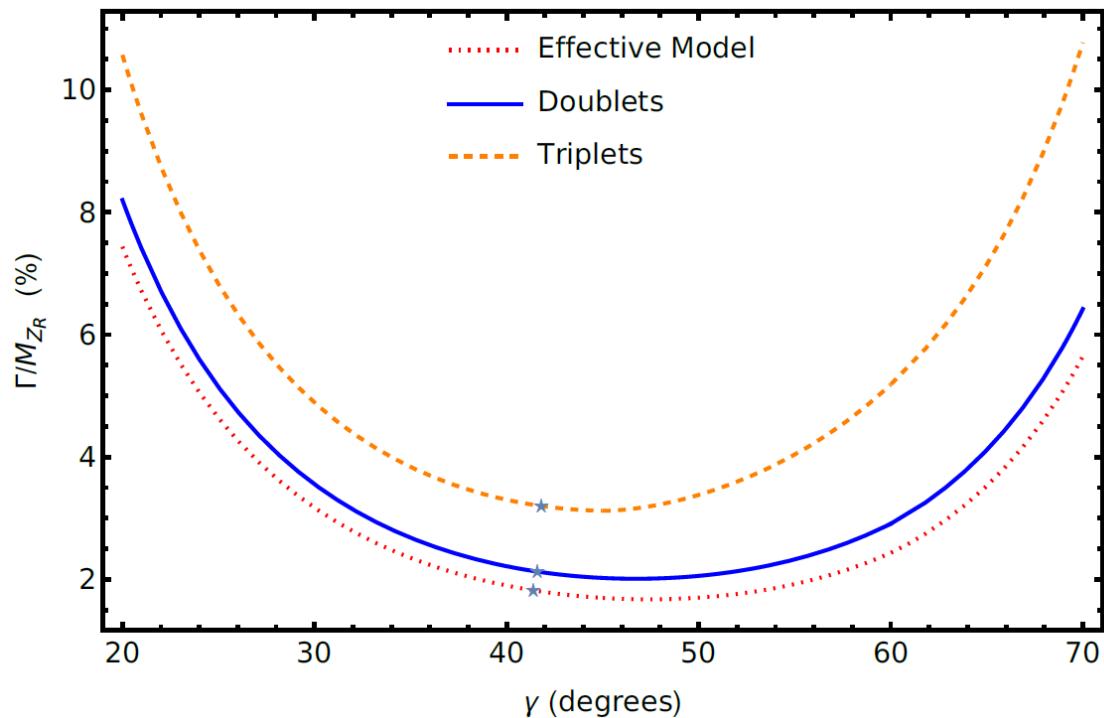
$$Z_R \rightarrow W_L^+ W_L^-, Z_L h^0, Z_L H^0, W_L^\pm H^\mp, h^0 H^0, H_1 H_2$$


2 Scalars

(Bidoublet + 2 Doublets)

$$\Gamma(Z_R \rightarrow \text{2 Scalars}) \leq \Gamma(Z_R \rightarrow \text{2 Scalars}) \Big|_{m_S=0} = \frac{M_{Z_R}}{96\pi} \frac{e^2}{\cos^2 \theta_W} \{2 \tan^2 \gamma + 3 \cot^2 \gamma\}$$

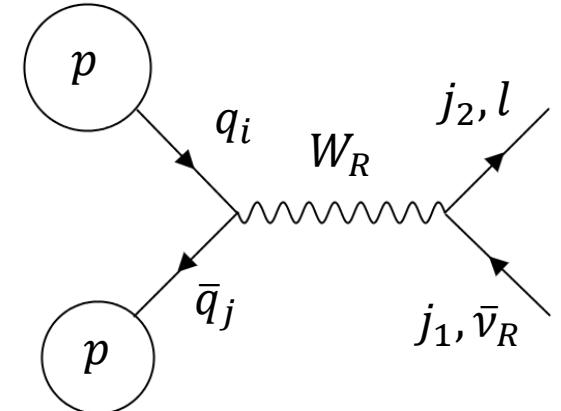
Bound on the Mass of the Z_R



$Z_R \rightarrow e^+e^-, \mu^+\mu^-$	$\Phi + \chi_{L,R}$	$\Phi + \Delta_{L,R}$	$\chi_L + \chi_R$
M_{Z_R} (TeV)	4.4	4.2	4.4

W_R Physics in Colliders

- We will study the Decay of the W_R into two Jets and $l\nu_R$ (model dependent)
- Narrow Resonance Approximation $\sqrt{s} = 13 \text{ TeV}$



$$\sigma(pp \rightarrow W_R X \rightarrow jjX) \approx \sigma(pp \rightarrow W_R X) \text{Br}(W_R \rightarrow qq)$$

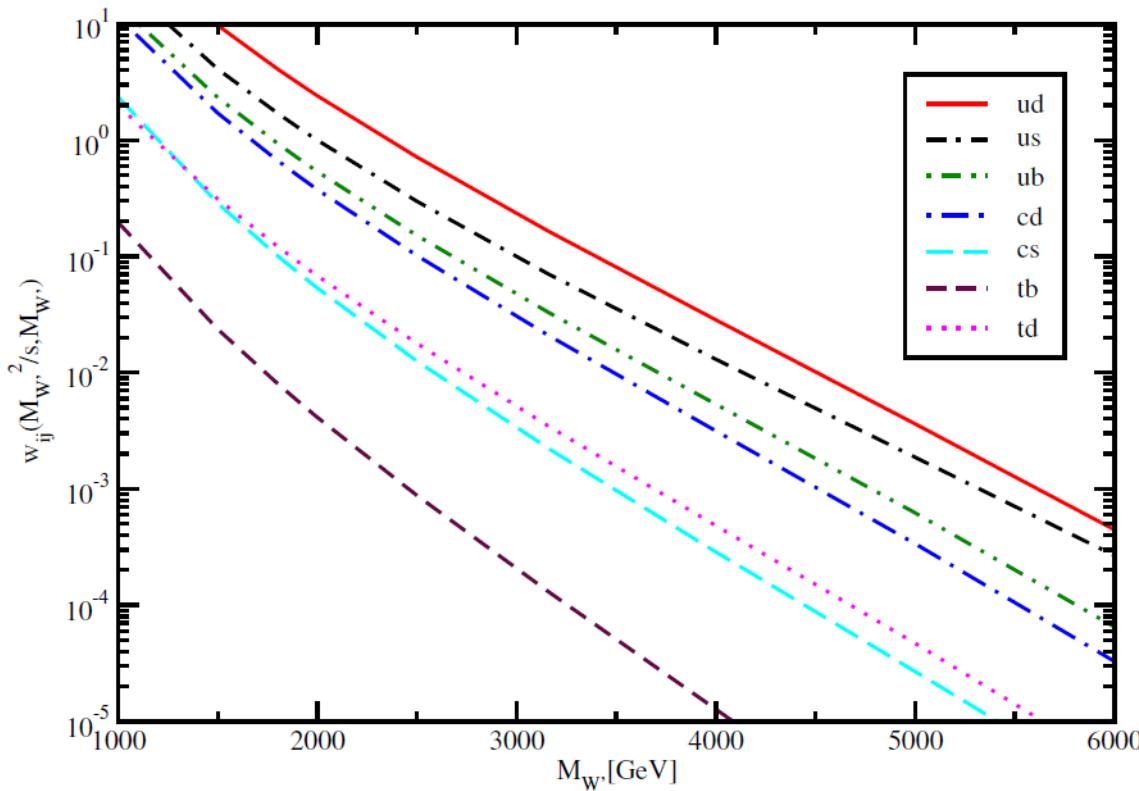
Ellis, Stirling, Webber (2011)

$$\sigma(pp \rightarrow W_R X \rightarrow l\nu_R X) \approx \sigma(pp \rightarrow W_R X) \text{Br}(W_R \rightarrow l\nu_R)$$

$$\boxed{\sigma(pp \rightarrow W_R X) \approx \frac{2\pi^2}{3s} \alpha_R \sum_{ij} \left| \left(V_R^{\text{CKM}} \right)_{ij} \right|^2 \omega_{ij} \left(\frac{M_{W_R}^2}{s}, M_{W_R} \right)}$$

V_R^{CKM} Structures

- We can use a structure of the V_R^{CKM} matrix for which we get the less stringent bound on M_{W_R} (minimum Cross Section)

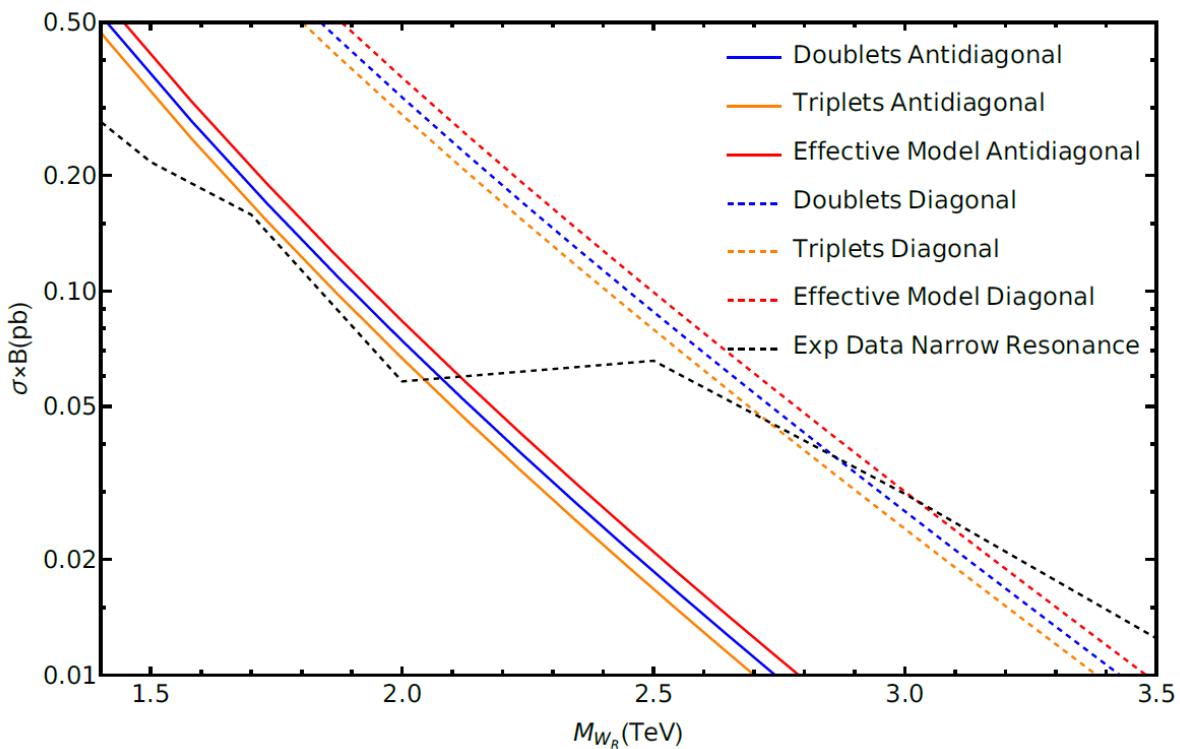


$$V_R^{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad (\text{Unitarity})$$

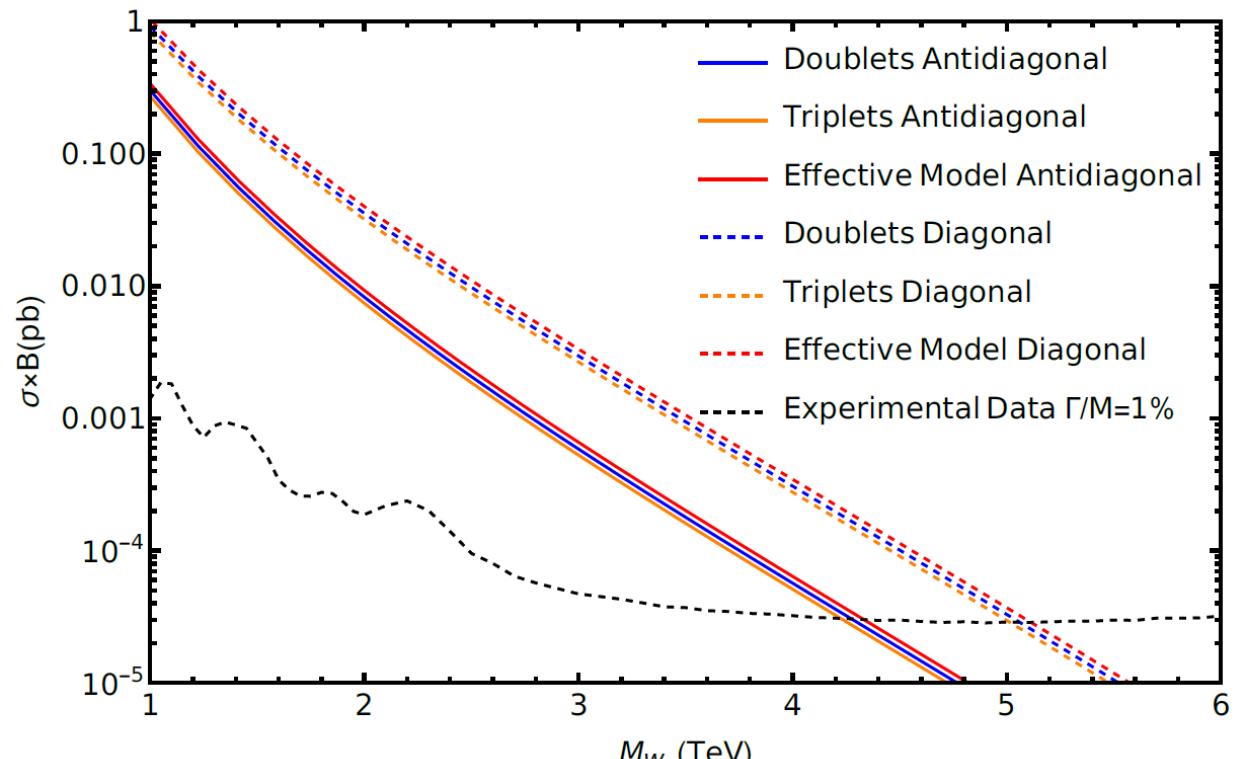
- We can also compare with the diagonal structure
- Bernard, Descotes-Genon, Vale Silva (2001.00886)
- Ball et Al. (1207.1303)

Bound on the Mass of the W_R

- We take the minimum possible value of the cross section. It corresponds to the less constraining bound on M_{W_R} and $\Gamma_{W_R} \approx 1\%$



Hadronic: ATLAS (1910.08447)



Leptonic: ATLAS (1906.05609)

Summary of Bounds

$Z_R \rightarrow e^+e^-,\mu^+\mu^-$	$\Phi + \chi_{L,R}$	$\Phi + \Delta_{L,R}$	$\chi_L + \chi_R$
M_{Z_R} (TeV)	4.4	4.2	4.4

$W_R \rightarrow j_1j_2$	$\Phi + \chi_{L,R}$	$\Phi + \Delta_{L,R}$	$\chi_L + \chi_R$
M_{W_R} (TeV) _{AD}	2.1	2.0	2.1
M_{W_R} (TeV) _D	2.9	2.7	3.0

$W_R \rightarrow e\nu_R, \mu\nu_R$	$\Phi + \chi_{L,R}$	$\Phi + \Delta_{L,R}$	$\chi_L + \chi_R$
M_{W_R} (TeV) _{AD}	4.3	4.2	4.3
M_{W_R} (TeV) _D	5.1	5.0	5.1

Results

- We have proposed a new way to study LR Models using **Effective Field Theory**
- We have been able to put a **General Bound** on the **Width** of the W_R and Z_R using the **Equivalence Theorem**
- Assuming **perturbativity**, we obtain from the LHC Run 2 data that $M_{W_R} > 2 \text{ TeV}$ and $M_{Z_R} > 4 \text{ TeV}$