Model Independent Bounds on Left-Right Gauge Boson Masses from LHC Run 2 and Flavour Observables

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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.

$$SU(3)_{QCD} \times SU(2)_L \times U(1)_Y$$

$$\downarrow$$

$$X = (B - L)/2$$

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

g_S g_L g_R g_X

General Results of LR Models

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

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

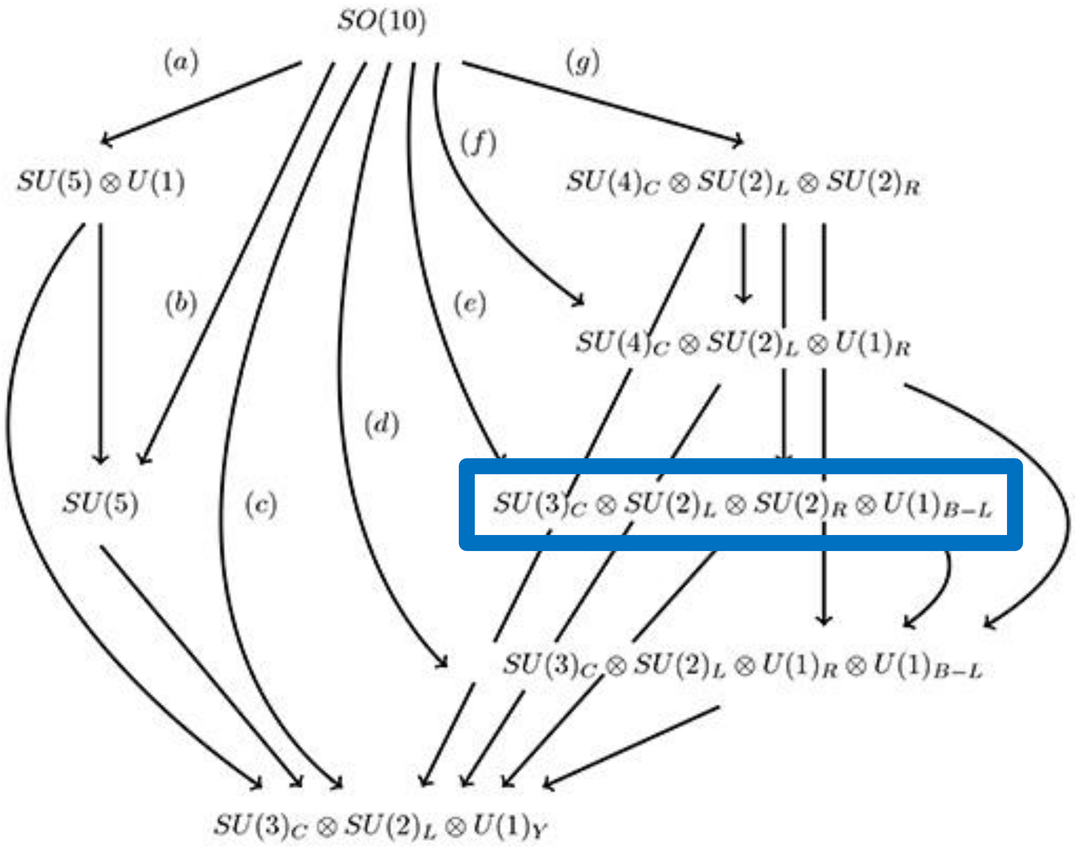
Embedding of LR Models

- 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.

$g_L \neq g_R$ $\qquad$ $V_L \neq V_R$



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

SSB and Perturbativity

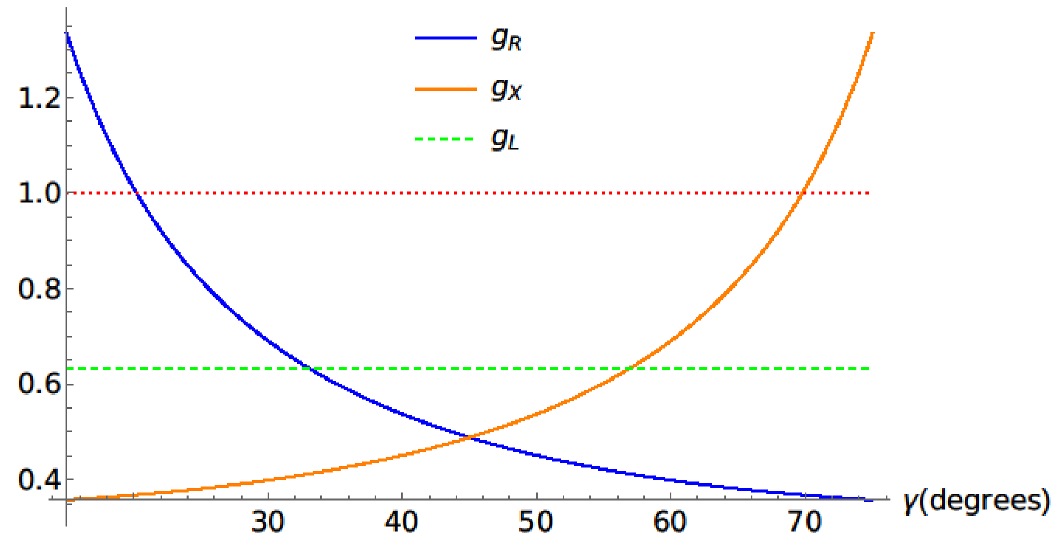
$$\begin{pmatrix} Z_L \\ Z_R \\ A \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{} \begin{pmatrix} \cos\theta_W & 0 & -\sin\theta_W \\ 0 & 1 & 0 \\ \sin\theta_W & 0 & \cos\theta_W \end{pmatrix} \begin{pmatrix} 1 & 0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

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

- Perturbativity: $g_R, g_X \leq 1$

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

$$70° > \gamma > 20°$$



Scalar Fields

- Bidoublet + Doublets (Dirac Neutrinos):

$$\Phi := \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \qquad \chi_L := \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix}, \qquad \chi_R := \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}.$$

$\Phi \sim (1, 2, \bar{2}, 0)$

$\chi_L \sim (1, 2, 1, 1/2)$

$\chi_R \sim (1, 1, 2, 1/2)$

- Bidoublet + Triplets (Majorana Neutrinos):

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

$\Delta_L \sim (1, 3, 1, 1)$

$\Delta_R \sim (1, 1, 3, 1)$

- $\chi_L + \chi_R$ 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:

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

(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)

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

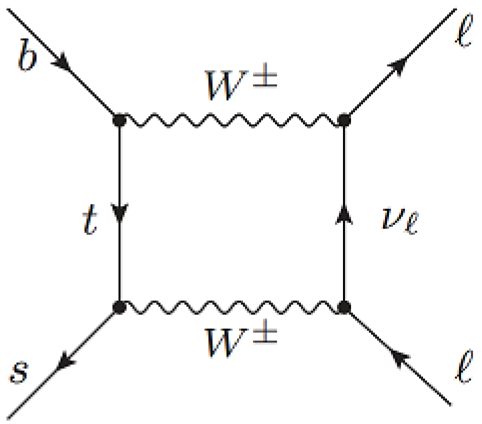
(Majorana Masses)

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

Bounds from Flavour Physics

- We want to put a Bound on the LR Scale that Does Not Depend on other Parameters of the Model.

- Doing this using Flavour Observables for the Effective Model is Highly Non-Trivial beacause the complete calculations will require the Addition of $D = 6$ Operators.



$$\sim m_{f_1} m_{f_2} \sim \frac{1}{\Lambda^2}$$

$b \to s\gamma$ and $b \to sll$ Preliminary Work

- For the Other Models we can calculate the contributions for these processes asuming that the Masses of the Scalars are much Bigger than the ones of the Gauge Bosons (FCNC) and Light RH Neutrinos.

$$C_7|_{\rm NP} = \frac{1}{\sqrt{2}} 4 e m_b G_F \sum_{i=u.c.t} \frac{g_R}{g_L}\frac{m_i}{m_b} \sin\xi_W e^{-i\lambda} \left(V_L^{\rm CKM}\right)^*_{is} \left(V_R^{\rm CKM}\right)_{ib} \tilde{F}(x^{f_i}_{W_L}) \qquad C_9^l|_{\rm NP} \sim \mathcal{O}\left(v_R^{-4}\right)$$

$$C_7'|_{\rm NP} = \frac{1}{\sqrt{2}} 4 e m_b G_F \sum_{i=u,c,t} \frac{g_R}{g_L}\frac{m_i}{m_b} \sin\xi_W e^{i\lambda} \left(V_R^{\rm CKM}\right)^*_{is} \left(V_L^{\rm CKM}\right)_{ib} \underbrace{\tilde{F}(x^{f_i}_{W_L})}_{\text{Loop Function}} \qquad C_{10}^l|_{\rm NP} \sim \mathcal{O}\left(v_R^{-4}\right)$$

$$C_9'^l = \frac{4}{9}\left(\frac{e g_R}{M_{W_R}}\right)^2 \sum_{i=u,c,t} \left(V_R^{\rm CKM}\right)^*_{is} \left(V_R^{\rm CKM}\right)_{ib} \ln\left(\frac{m_i}{m_0}\right) \qquad C_{10}'^l \sim \mathcal{O}\left(v_R^{-4}\right)$$

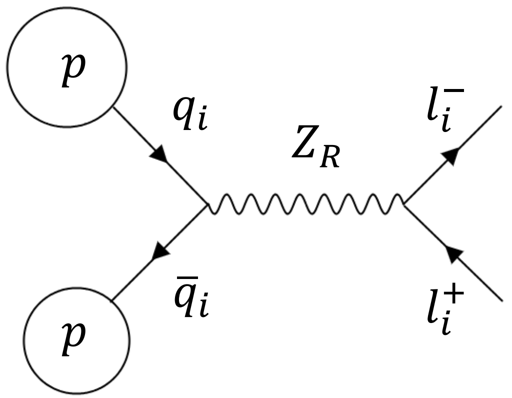
Bishara et al. (2104.10930)

- Assuming a Diagonal Structure of $V_R^{\rm CKM}$, $g_L = g_R$ and a Mixing Equal to $(v_{EW}/v_R)^2$ between the W_L and the W_R we get from $C_7|_{\rm NP}$:

$$\boxed{v_R \sim 7\ \text{TeV}}$$

LHCb Collaboartion (2111.10194)

Z_R Physics in Colliders



- Narrow Resonance Approximation $\sqrt{s} = 13\ \text{TeV}$

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

Ellis, Stirling, Webber (2011)

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

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

No Dependence on the Mixing Matrices

Z_R Decay to Charged Leptons

- We only need to compute

(Assuming $M_{Z_R} \gg m_f$)

$$\text{Br}(Z_R \to l^+ l^-) \coloneqq \Gamma(Z_R \to l^+ l^-)/\Gamma_{Z_R} \qquad \Gamma\left(Z_R \to f\bar{f}\right) \approx N_C^f \frac{M_{Z_R}}{48\pi}\left[g_V^{f\,2}(\gamma) + g_A^{f\,2}(\gamma)\right]$$

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

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

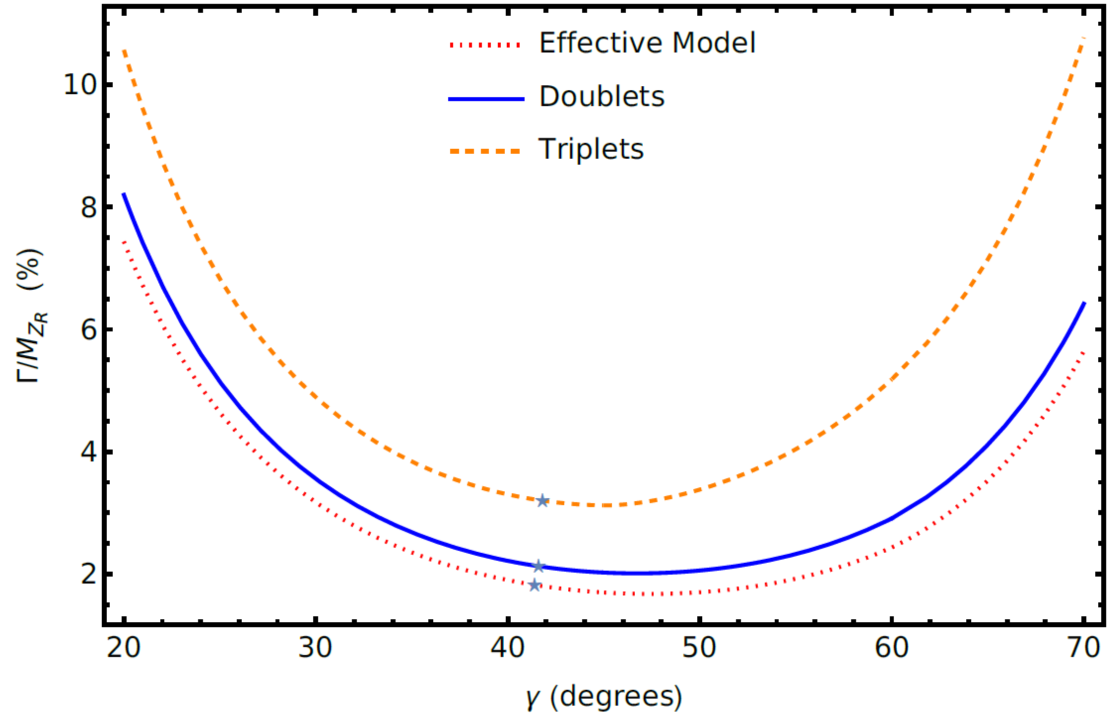
- Since the Diagonalization of the Scalar Potentials is highly non-trivial we will only put an Upper Bound on Γ_{Z_R}. Consequently, we will get the Less Constraining Lower Bound on M_{Z_R}.

The Total Width of the Z_R

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

2 Scalars

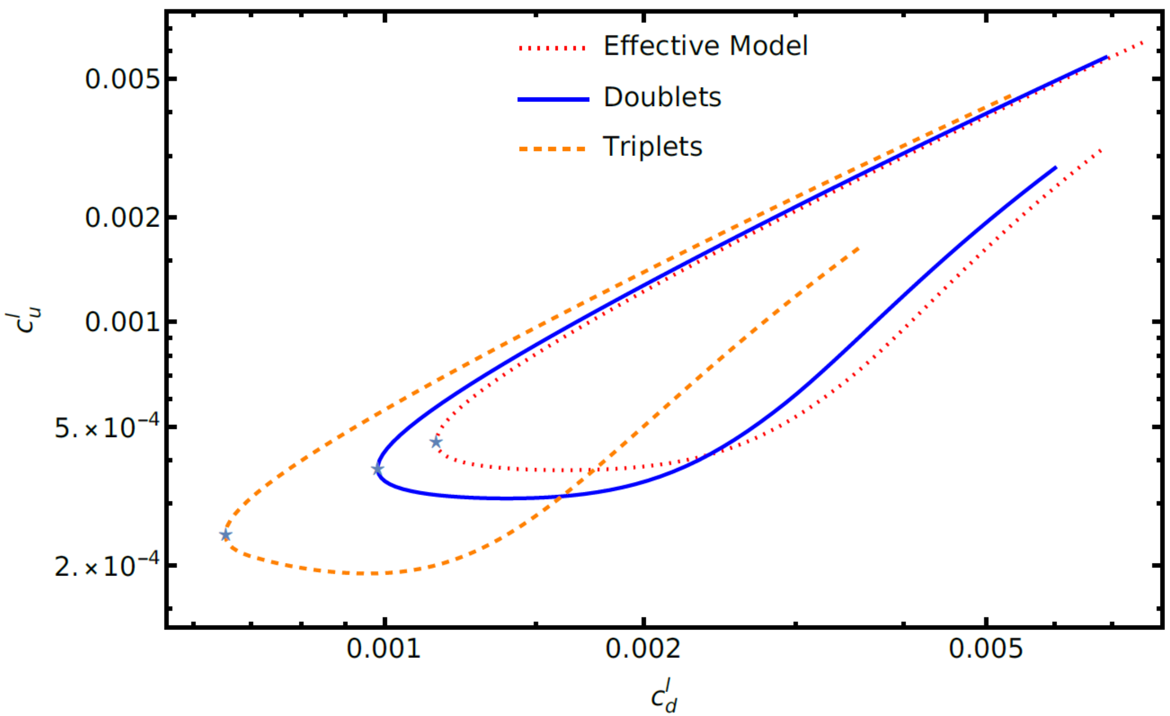
(Using the Equivalence Theorem)

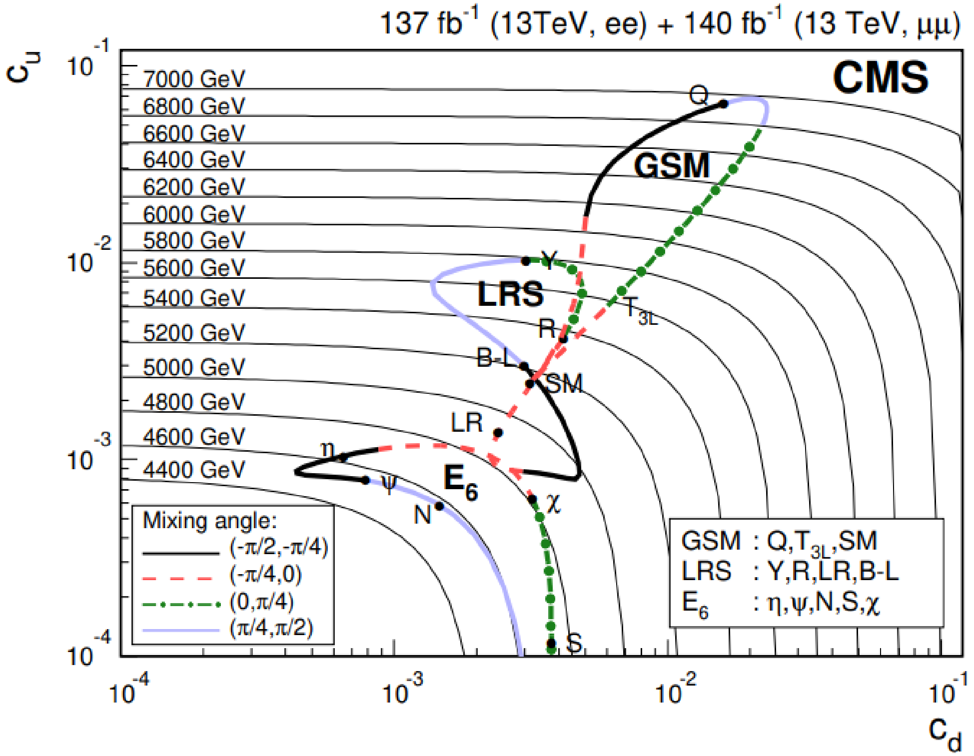


$$\Gamma(Z_R \to 2\ \text{Scalars}) \leq \Gamma(Z_R \to 2\ \text{Scalars})\Big|_{m_S=0} = \frac{M_{Z_R}}{96\pi} \frac{e^2}{\cos^2\theta_W}\{2\tan^2\gamma + 3\cot^2\gamma\}$$

Bound on the Mass of the Z_R

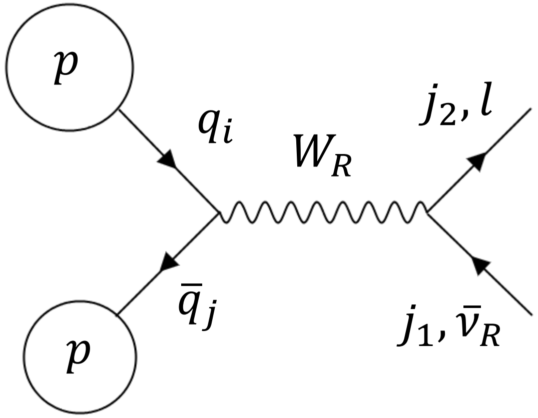
CMS (2103.02708)





$Z_R \to e^+e^-, \mu^+\mu^-$	$\Phi + \chi_{L,R}$	$\Phi + \Delta_{L,R}$	$\chi_L + \chi_R$
$M_{Z_R}(\mathrm{TeV})$	4.3	4.2	4.3

W_R Physics in Colliders



- We will study the Decay of the W_R into Two Jets and $l\nu_R$ (model dependent for Majorana neutrinos).
- Narrow Resonance Approximation. $\sqrt{s} = 13\ \mathrm{TeV}$

$$\sigma(pp \to W_R X \to jjX) \approx \sigma(pp \to W_R X)\mathrm{Br}(W_R \to qq)$$

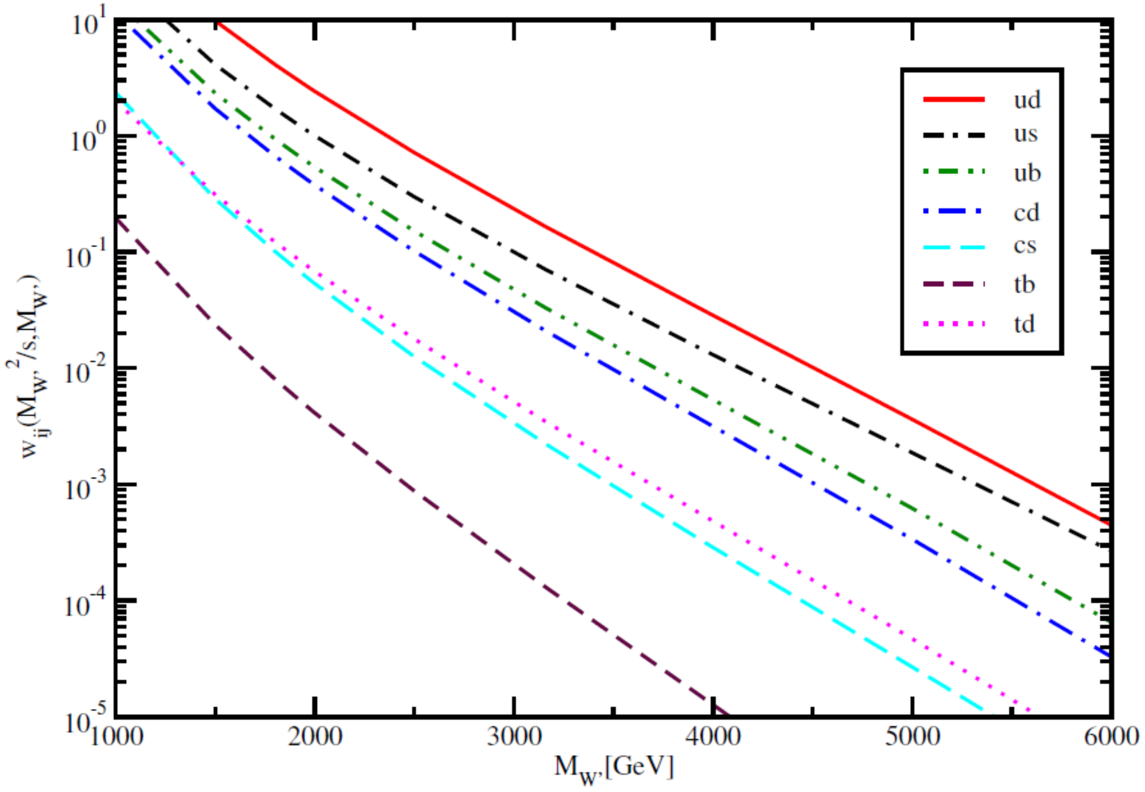
Ellis, Stirling, Webber (2011)

$$\sigma(pp \to W_R X \to l\nu_R X) \approx \sigma(pp \to W_R X)\mathrm{Br}(W_R \to l\nu_R)$$

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

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).



(Unitarity)

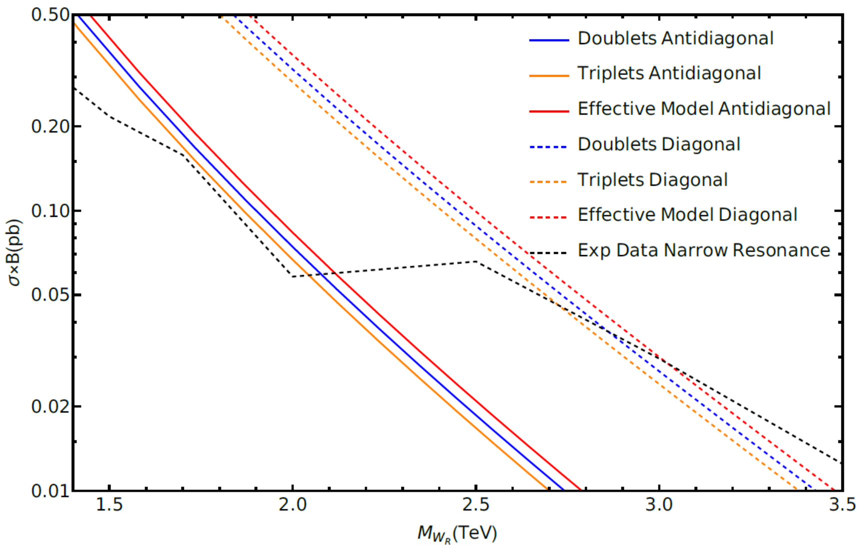
$$V_R^{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

- We can also compare with the diagonal structure.

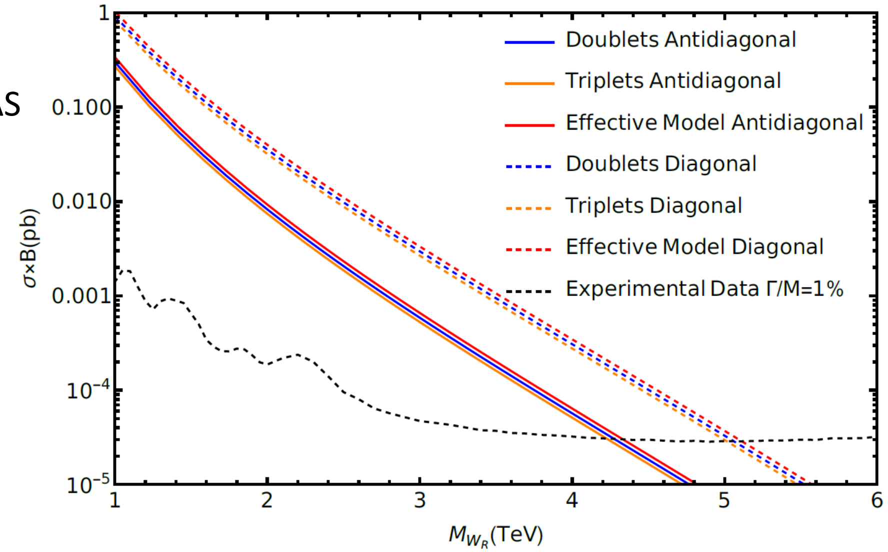
- Bernard, Descotes-Genon, Vale Silva (2001.00886)
- Ball et Al. (1207.1303)

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)

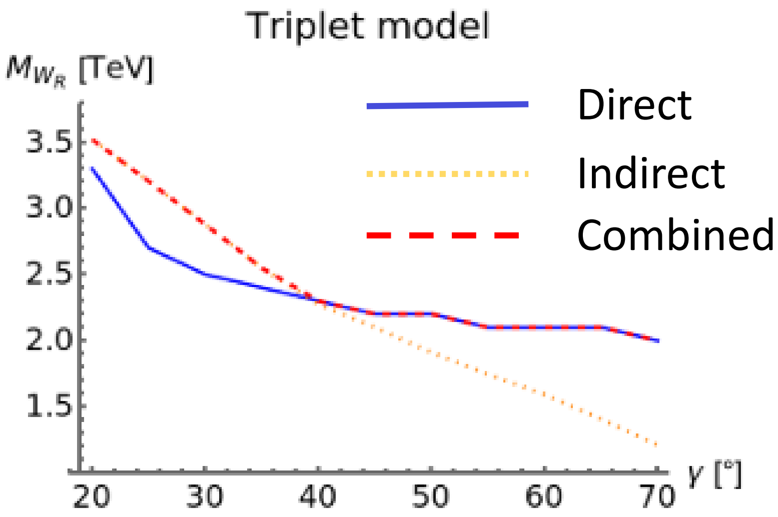
$W_R \to j_1 j_2$	$\Phi + \chi_{L,R}$	$\Phi + \Delta_{L,R}$	$\chi_L + \chi_R$
$M_{W_R}(\mathrm{TeV})_{\mathrm{AD}}$	2.1	2.0	2.1
$M_{W_R}(\mathrm{TeV})_{\mathrm{D}}$	2.9	2.7	3.0

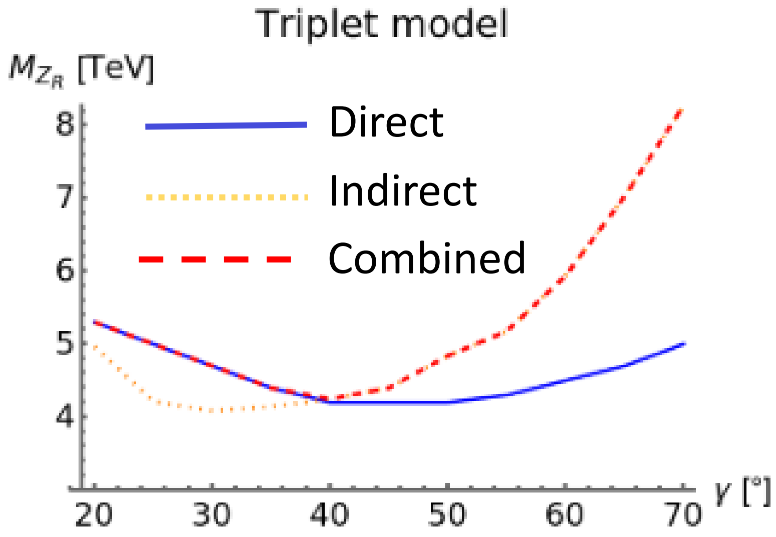
$W_R \to e\nu_R, \mu\nu_R$	$\Phi + \chi_{L,R}$	$\Phi + \Delta_{L,R}$	$\chi_L + \chi_R$
$M_{W_R}(\mathrm{TeV})_{\mathrm{AD}}$	4.3	4.2	4.3
$M_{W_R}(\mathrm{TeV})_{\mathrm{D}}$	5.1	5.0	5.1

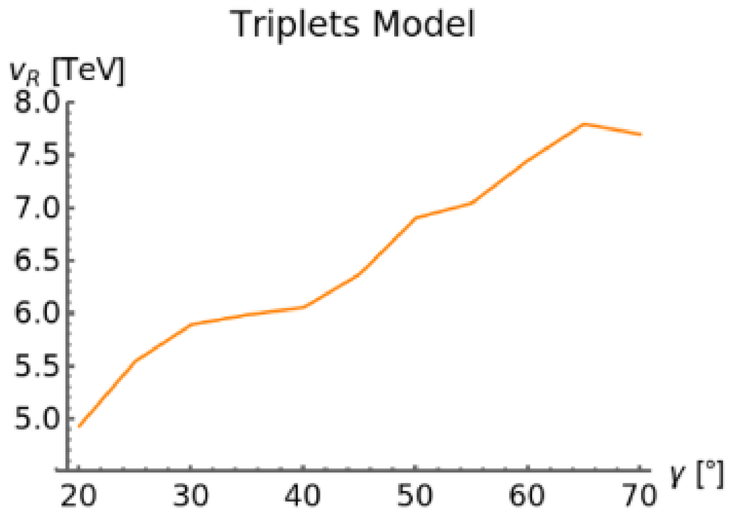
Combination of Direct and Indirect Bounds

If we put a Direct Bound on the mass of One Gauge Boson for a certain value of γ, we can put an Indirect Bound on the mass of the Other Gauge Boson and v_R using:

$$M_{W_R} \approx M_{Z_R} \cos\gamma \approx \frac{e v_R}{2\cos\theta_W \sin\gamma} \quad \text{(Doublets)} \qquad M_{W_R} \approx \frac{1}{\sqrt{2}} M_{Z_R} \cos\gamma \approx \frac{e v_R}{\sqrt{2}\cos\theta_W \sin\gamma} \quad \text{(Triplets)}$$







Summary of Bounds

	$\Phi + \chi_{L,R}$	$\Phi + \Delta_{L,R}$	$\chi_L + \chi_R$
M_{W_R}(TeV)	4.3	2.0	2.1
M_{Z_R}(TeV)	5.4	4.2	4.3
v_R(TeV)	10	4.9	10

	Origin of the Bound
M_{W_R} Doublets	Direct $W_R \to l\nu_R$
M_{Z_R} Doublets	Indirect $W_R \to l\nu_R$
M_{W_R} Triplets	Direct $W_R \to qq$
M_{Z_R} Triplets	Combination $Z_R \to ll$ $W_R \to qq$
M_{W_R} Effective	Direct $W_R \to qq$
M_{Z_R} Effective	Direct $Z_R \to ll$

Results

- We have proposed a new way to study LR Models using Effective Field Theory.

- We have seen that achieving Model Independent Bounds with Flavour Observables requires a Global Fit allowing for Any Possible Structure of the RH Quark Mixing Matrix.

- 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 Model Independent Bounds on M_{W_R}, M_{Z_R} and v_R for the different SSB Mechanisms.

Backup Slide: Summary of Plots