A minimal non-universal EW extension of the Standard Model: a chiral family of models

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Outline

- Introduction and motivations
- Building the model
- Phenomenological analysis
- Conclusions and perspectives

Introduction and motivations

- From a phenomenological viewpoint, owing to the absence of exotic fermions at low energies, minimal models are useful to explain isolated anomalies in low-energy experimental data.
- Although many minimal models have been proposed, a general analysis and a parameterization of these are not present in the current literature.
- An additional U(1)' gauge symmetry and its associated Z' gauge boson is among the best motivated extensions of the SM. These are generic predictions of grand unification models and string theories.
- A massive Z' would imply the breaking of the associated U(1)' symmetry, which would require an extended Higgs sector.

Introduction and motivations

- By imposing universality the possible EW extensions of the SM are basically E_6 subgroups, but realistic scenarios for symmetry breaking in E_6 require large Higgs representations to explain the flavor phenomenology. By relaxing the universality condition it is possible to have small Higgs and fermion representations.
- If universal U(1)' charges are assumed, non-trivial solutions are not possible from anomaly cancellation if only SM fermions are considered. Thus, almost all U(1)' constructions involve exotics, which are usually assumed to be quasi-chiral.
- Under some suitable assumptions, many non-universal models are able to evade FCNC constraints and explain some of the current flavor anomalies.
- Non-universal models can be used to answer questions related to the number of families and the hierarchies in the fermion spectrum.

Building the model:

EW gauge sector

$$SU(2)_L \otimes U(1)$$

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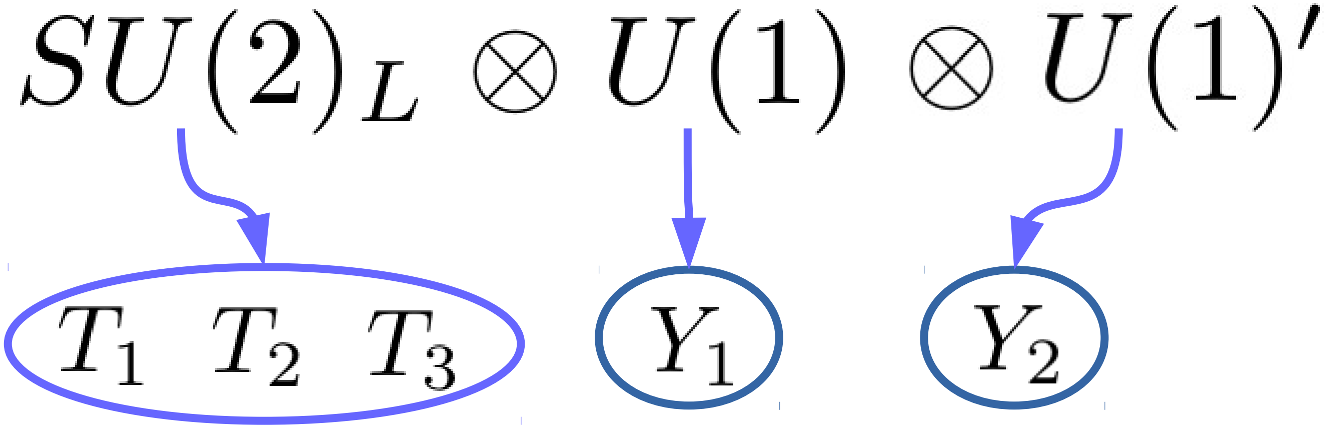
$$SU(2)_L \otimes U(1) \otimes U(1)'$$

Building the model:

EW gauge sector

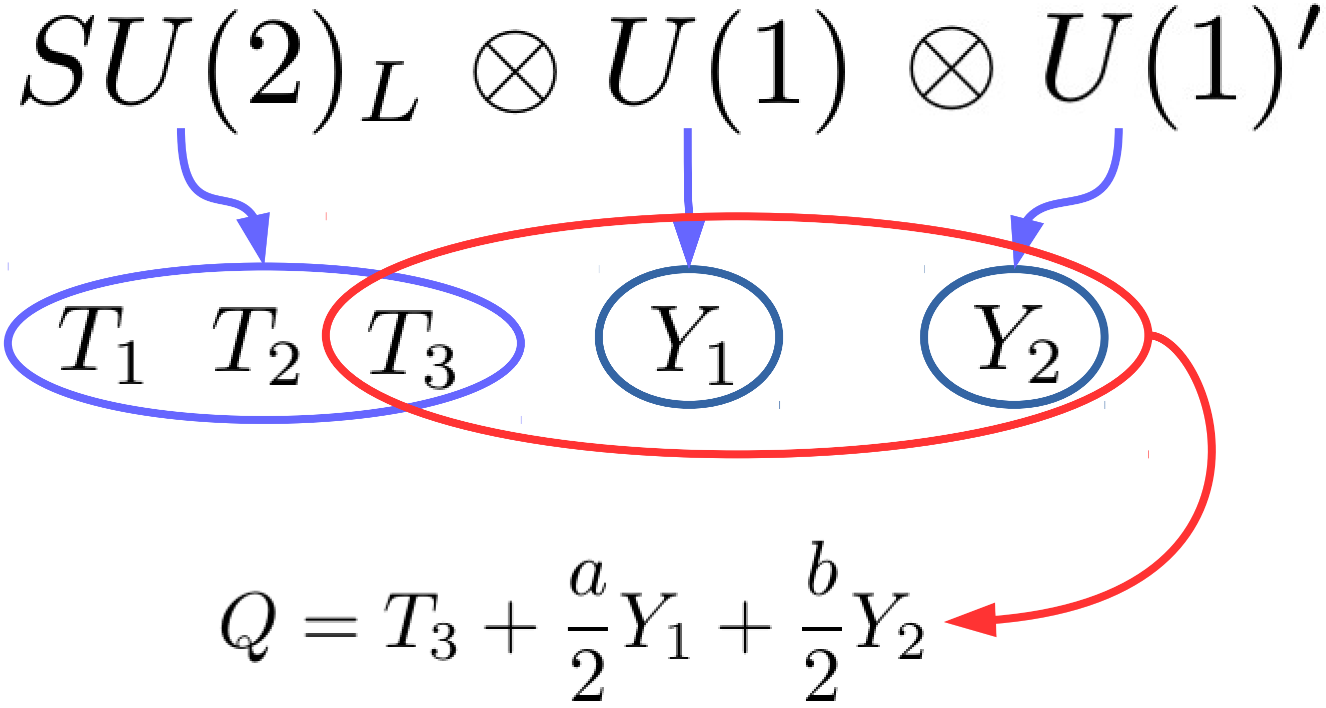


$$SU(2)_L \otimes U(1) \otimes U(1)'$$

$$T_1 \quad T_2 \quad T_3 \qquad Y_1 \qquad Y_2$$

Building the model:

EW gauge sector



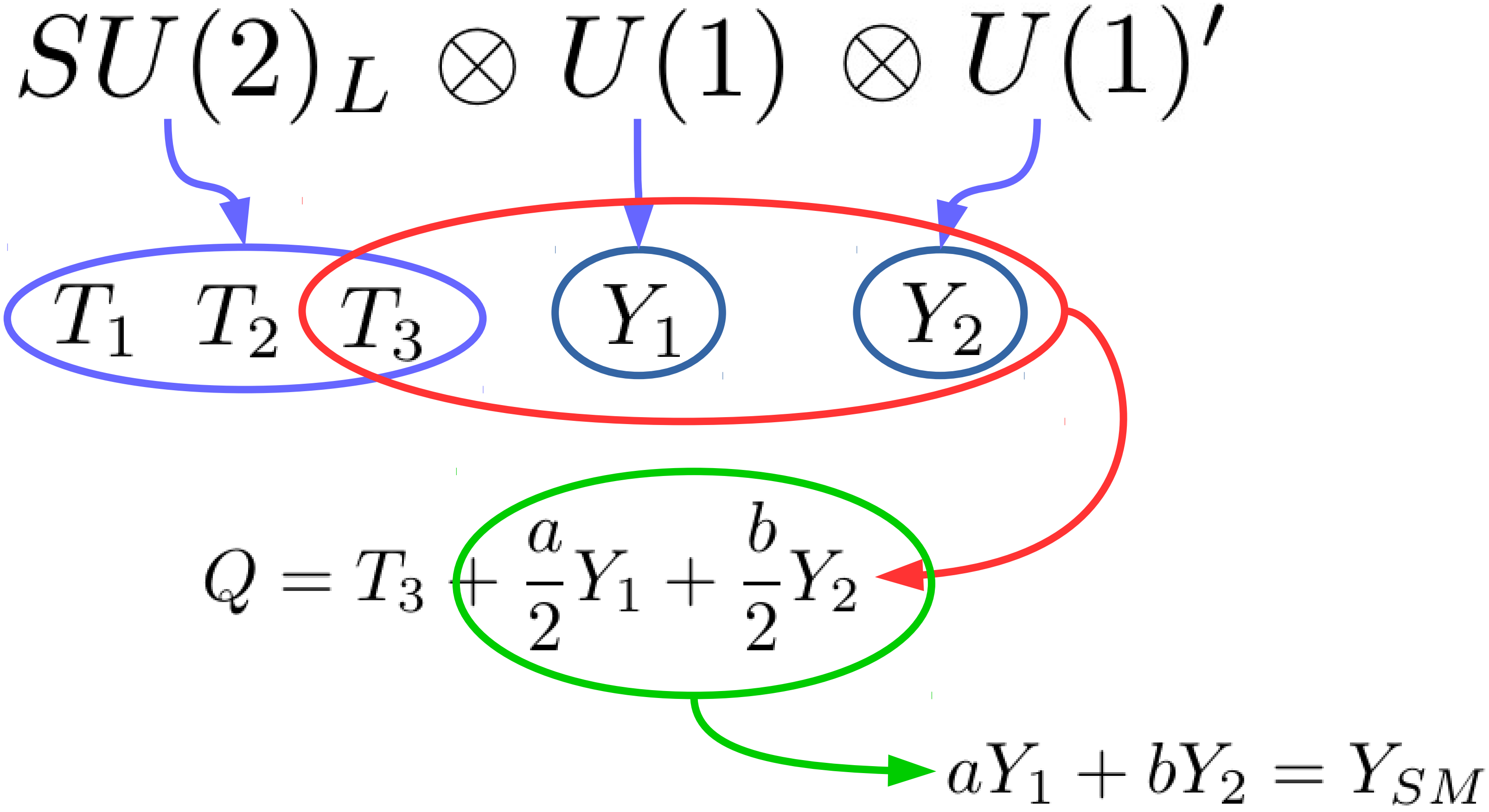
$$SU(2)_L \otimes U(1) \otimes U(1)'$$

$$T_1 \quad T_2 \quad T_3 \qquad Y_1 \qquad Y_2$$

$$Q = T_3 + \frac{a}{2} Y_1 + \frac{b}{2} Y_2$$

Building the model:

EW gauge sector



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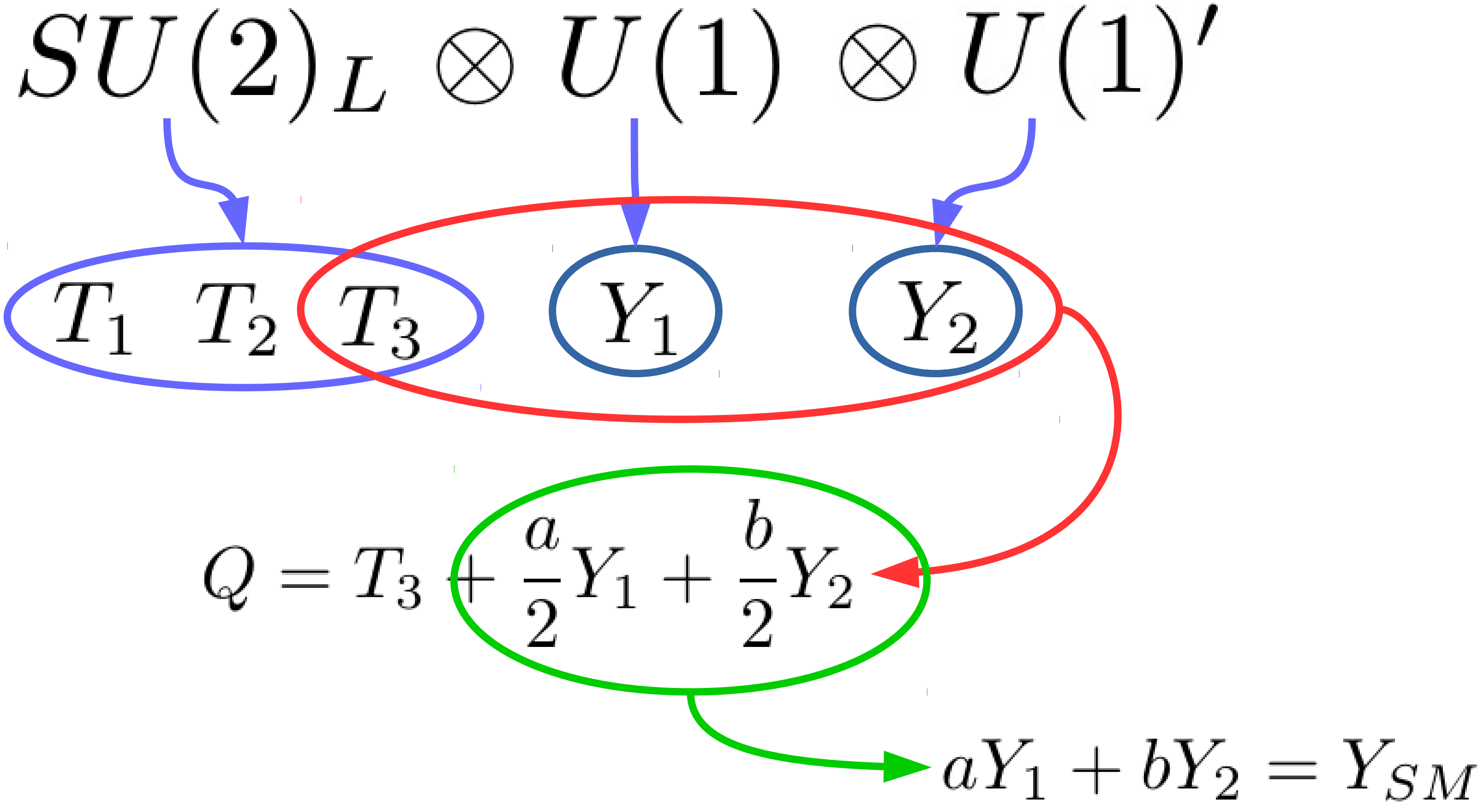
$$aY_1 + bY_2 = Y_{SM}$$

Building the model:

EW gauge sector



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$$Q = T_3 + \frac{a}{2}Y_1 + \frac{b}{2}Y_2$$

$$aY_1 + bY_2 = Y_{SM}$$

$$D_\mu = \partial_\mu - ig_L \vec{T}.\vec{A}_\mu - i\frac{g_1}{2}Y_1 B_{1\mu} - i\frac{g_2}{2}Y_2 B_{2\mu}$$

Building the model:
fermion sector

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \qquad c_R \qquad t_R$$

$$d_R \qquad s_R \qquad b_R$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$e_R \qquad \mu_R \qquad \tau_R$$

Building the model:
fermion sector

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \qquad c_R \qquad t_R$$

$$d_R \qquad s_R \qquad b_R$$

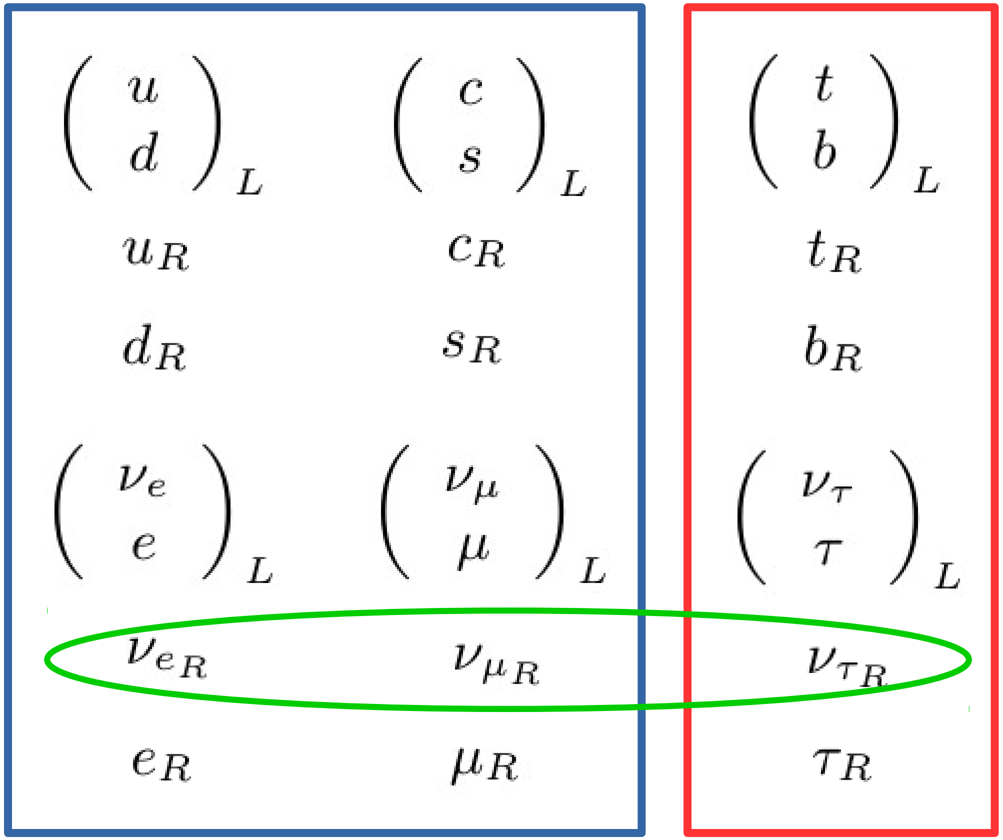
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$\boxed{\nu_{e_R} \qquad \nu_{\mu_R} \qquad \nu_{\tau_R}}$$

$$e_R \qquad \mu_R \qquad \tau_R$$

Building the model:

fermion sector



$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \quad c_R \quad t_R$$

$$d_R \quad s_R \quad b_R$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$\nu_{eR} \quad \nu_{\mu R} \quad \nu_{\tau R}$$

$$e_R \quad \mu_R \quad \tau_R$$

The limits from $K^0 - K^0$ mixing (including CP violating effects) and from μ − e conversion in muonic atoms are sufficiently strong to exclude significant Nonuniversal effects for the first two families for a TeV-scale Z' with electroweak couplings.

Building the model:
scalar sector

$$\phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}$$

Building the model:

scalar sector

$$\phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \longrightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \longrightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}$$

$$v_1 < v_2$$

Building the model:

scalar sector

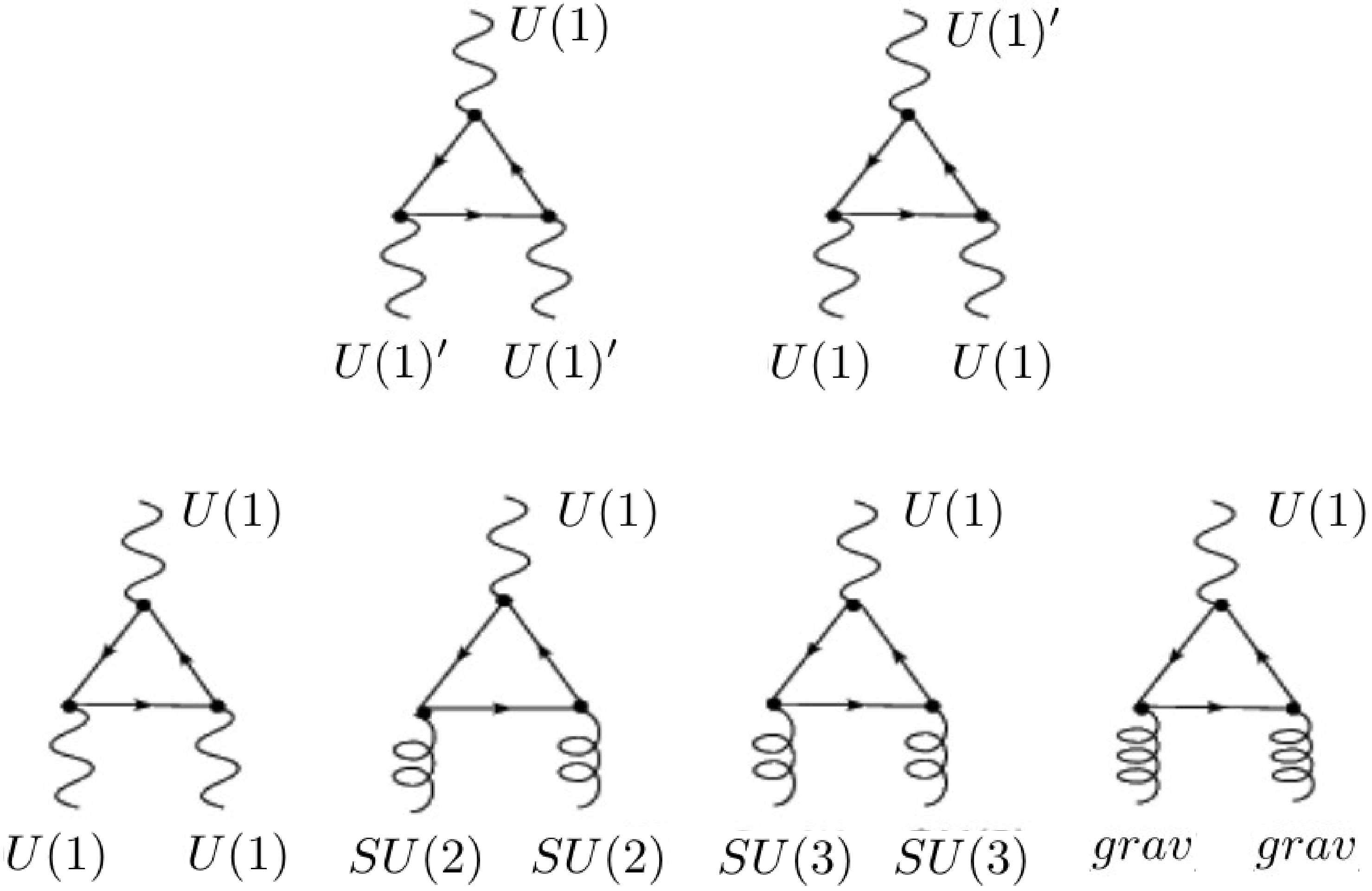
$$\phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \longrightarrow \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix} \Rightarrow B_{1\mu} + B_{2\mu} \longrightarrow B_\mu + Z'_\mu$$

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \longrightarrow \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \Rightarrow B_\mu + A_{3\mu} \longrightarrow Z_\mu + A_\mu$$

$$v_1 < v_2$$

Building the model:
conditions

- ✔ Triangular anomalies



Building the model:

conditions

- ✓ Yukawa couplings

$$
\begin{aligned}
\mathcal{L}_Y \supset & \overline{\psi}_{1L}\tilde{\phi}_1\nu_{1R} + \overline{\psi}_{1L}\phi_1 e_{1R} + \overline{\psi'}_{1L}\tilde{\phi}_1 u_{1R} + \overline{\psi'}_{1L}\phi_1 d_{1R} + \\
& \overline{\psi}_{3L}\tilde{\phi}_2\nu_{3R} + \overline{\psi}_{3L}\phi_2 e_{3R} + \overline{\psi'}_{3L}\tilde{\phi}_2 u_{3R} + \overline{\psi'}_{3L}\phi_2 d_{3R} + h.c
\end{aligned}
$$

Building the model:
conditions

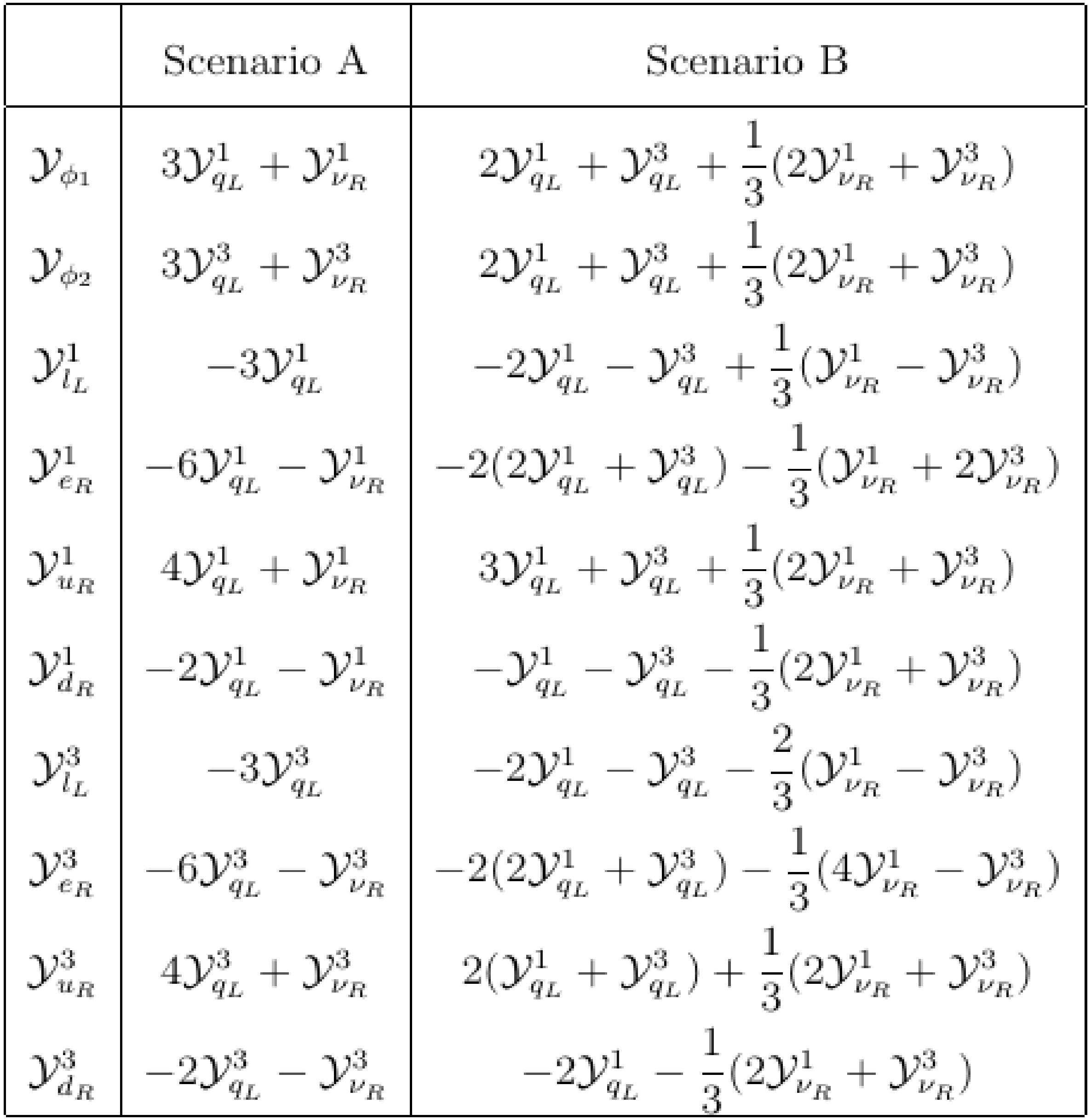
- ✓ Yukawa couplings

$$\mathcal{L}_Y \supset \overline{\psi}_{1L}\tilde{\phi}_1\nu_{1R} + \overline{\psi}_{1L}\phi_1 e_{1R} + \overline{\psi'}_{1L}\tilde{\phi}_1 u_{1R} + \overline{\psi'}_{1L}\phi_1 d_{1R} +$$
$$\overline{\psi}_{3L}\tilde{\phi}_2\nu_{3R} + \overline{\psi}_{3L}\phi_2 e_{3R} + \overline{\psi'}_{3L}\tilde{\phi}_2 u_{3R} + \overline{\psi'}_{3L}\phi_2 d_{3R} + h.c$$

$$\begin{aligned} Y_{\phi 1} - Y^R_{\nu 1} + Y^L_1 &= 0, \\ Y_{\phi 1} + Y^R_{e 1} - Y^L_1 &= 0, \\ Y_{\phi 1} - Y^R_{u 1} + Y^{\prime L}_1 &= 0, \\ Y_{\phi 1} + Y^R_{d 1} - Y^{\prime L}_1 &= 0, \end{aligned}$$

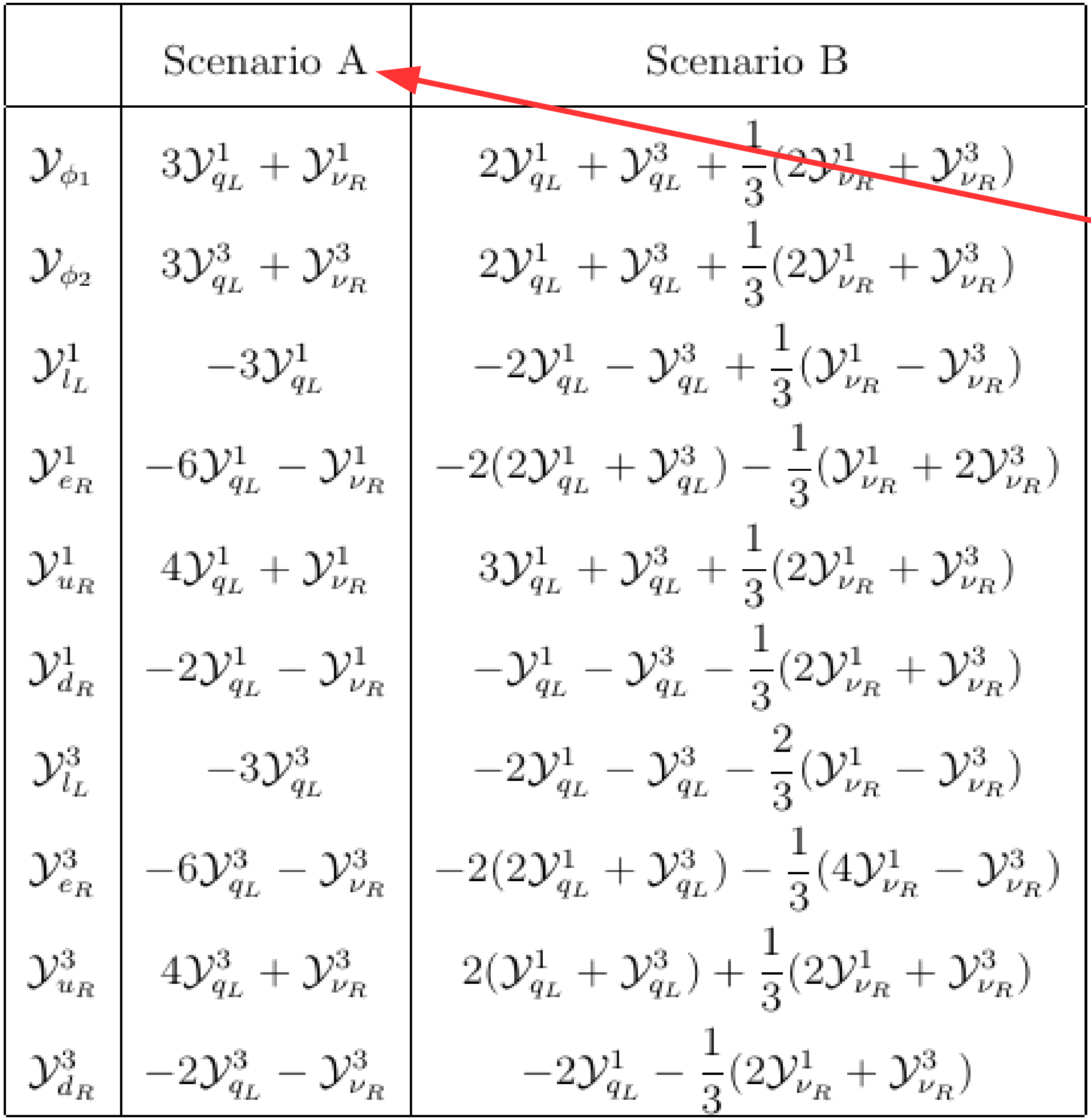
$$\begin{aligned} Y_{\phi 2} - Y^R_{\nu 3} + Y^L_3 &= 0, \\ Y_{\phi 2} + Y^R_{e 3} - Y^L_3 &= 0, \\ Y_{\phi 2} - Y^R_{u 3} + Y^{\prime L}_3 &= 0, \\ Y_{\phi 2} + Y^R_{d 3} - Y^{\prime L}_3 &= 0, \end{aligned}$$

Building the model: two scenarios



	Scenario A	Scenario B
$\mathcal{Y}_{\phi_1}$	$3\mathcal{Y}^1_{q_L} + \mathcal{Y}^1_{\nu_R}$	$2\mathcal{Y}^1_{q_L} + \mathcal{Y}^3_{q_L} + \frac{1}{3}(2\mathcal{Y}^1_{\nu_R} + \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}_{\phi_2}$	$3\mathcal{Y}^3_{q_L} + \mathcal{Y}^3_{\nu_R}$	$2\mathcal{Y}^1_{q_L} + \mathcal{Y}^3_{q_L} + \frac{1}{3}(2\mathcal{Y}^1_{\nu_R} + \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{l_L}$	$-3\mathcal{Y}^1_{q_L}$	$-2\mathcal{Y}^1_{q_L} - \mathcal{Y}^3_{q_L} + \frac{1}{3}(\mathcal{Y}^1_{\nu_R} - \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{e_R}$	$-6\mathcal{Y}^1_{q_L} - \mathcal{Y}^1_{\nu_R}$	$-2(2\mathcal{Y}^1_{q_L} + \mathcal{Y}^3_{q_L}) - \frac{1}{3}(\mathcal{Y}^1_{\nu_R} + 2\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{u_R}$	$4\mathcal{Y}^1_{q_L} + \mathcal{Y}^1_{\nu_R}$	$3\mathcal{Y}^1_{q_L} + \mathcal{Y}^3_{q_L} + \frac{1}{3}(2\mathcal{Y}^1_{\nu_R} + \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{d_R}$	$-2\mathcal{Y}^1_{q_L} - \mathcal{Y}^1_{\nu_R}$	$-\mathcal{Y}^1_{q_L} - \mathcal{Y}^3_{q_L} - \frac{1}{3}(2\mathcal{Y}^1_{\nu_R} + \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{l_L}$	$-3\mathcal{Y}^3_{q_L}$	$-2\mathcal{Y}^1_{q_L} - \mathcal{Y}^3_{q_L} - \frac{2}{3}(\mathcal{Y}^1_{\nu_R} - \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{e_R}$	$-6\mathcal{Y}^3_{q_L} - \mathcal{Y}^3_{\nu_R}$	$-2(2\mathcal{Y}^1_{q_L} + \mathcal{Y}^3_{q_L}) - \frac{1}{3}(4\mathcal{Y}^1_{\nu_R} - \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{u_R}$	$4\mathcal{Y}^3_{q_L} + \mathcal{Y}^3_{\nu_R}$	$2(\mathcal{Y}^1_{q_L} + \mathcal{Y}^3_{q_L}) + \frac{1}{3}(2\mathcal{Y}^1_{\nu_R} + \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{d_R}$	$-2\mathcal{Y}^3_{q_L} - \mathcal{Y}^3_{\nu_R}$	$-2\mathcal{Y}^1_{q_L} - \frac{1}{3}(2\mathcal{Y}^1_{\nu_R} + \mathcal{Y}^3_{\nu_R})$

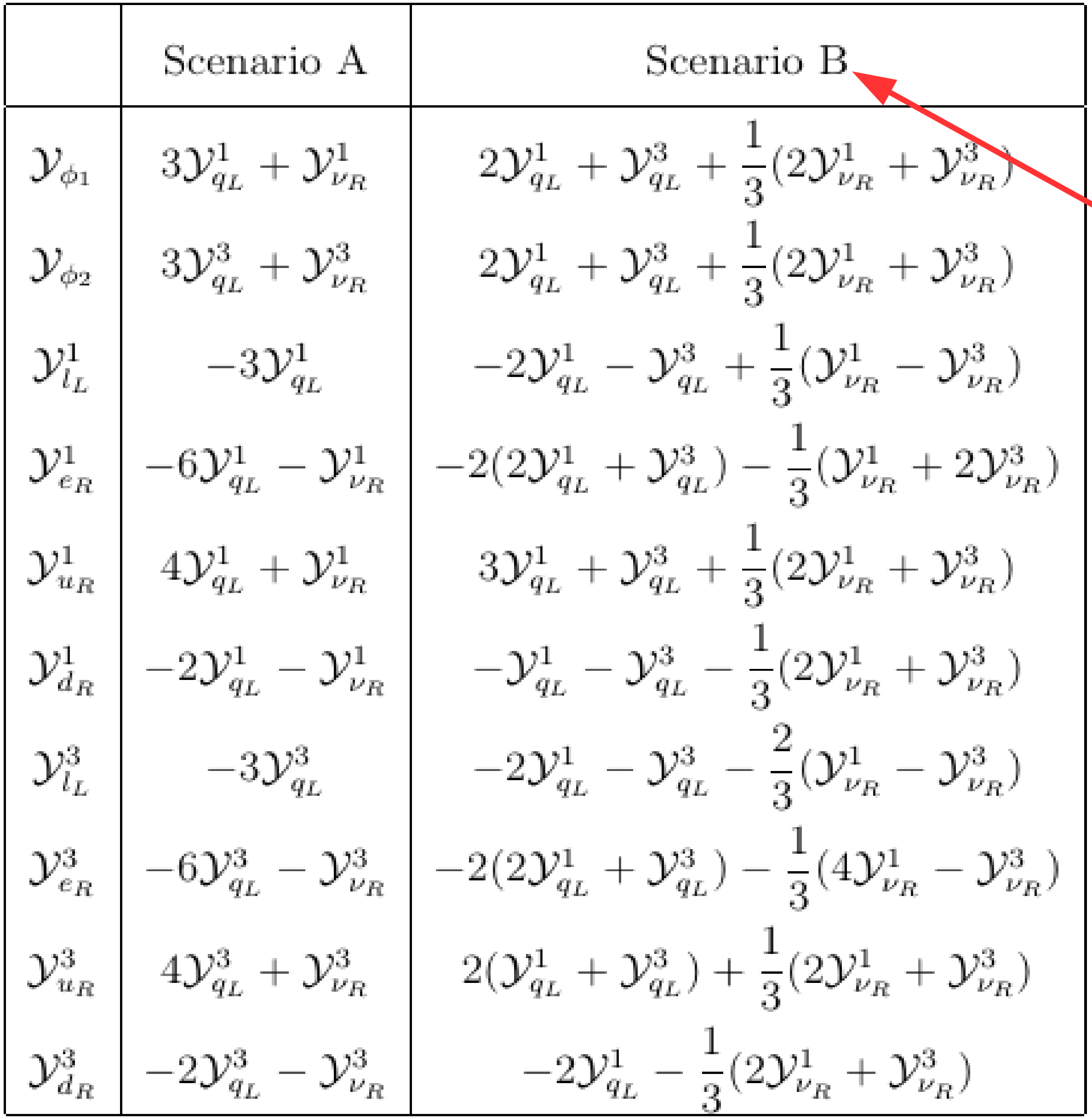
Building the model: two scenarios



	Scenario A	Scenario B
$\mathcal{Y}_{\phi_1}$	$3\mathcal{Y}^1_{q_L}+\mathcal{Y}^1_{\nu_R}$	$2\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L}+\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}_{\phi_2}$	$3\mathcal{Y}^3_{q_L}+\mathcal{Y}^3_{\nu_R}$	$2\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L}+\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{l_L}$	$-3\mathcal{Y}^1_{q_L}$	$-2\mathcal{Y}^1_{q_L}-\mathcal{Y}^3_{q_L}+\frac{1}{3}(\mathcal{Y}^1_{\nu_R}-\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{e_R}$	$-6\mathcal{Y}^1_{q_L}-\mathcal{Y}^1_{\nu_R}$	$-2(2\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L})-\frac{1}{3}(\mathcal{Y}^1_{\nu_R}+2\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{u_R}$	$4\mathcal{Y}^1_{q_L}+\mathcal{Y}^1_{\nu_R}$	$3\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L}+\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{d_R}$	$-2\mathcal{Y}^1_{q_L}-\mathcal{Y}^1_{\nu_R}$	$-\mathcal{Y}^1_{q_L}-\mathcal{Y}^3_{q_L}-\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{l_L}$	$-3\mathcal{Y}^3_{q_L}$	$-2\mathcal{Y}^1_{q_L}-\mathcal{Y}^3_{q_L}-\frac{2}{3}(\mathcal{Y}^1_{\nu_R}-\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{e_R}$	$-6\mathcal{Y}^3_{q_L}-\mathcal{Y}^3_{\nu_R}$	$-2(2\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L})-\frac{1}{3}(4\mathcal{Y}^1_{\nu_R}-\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{u_R}$	$4\mathcal{Y}^3_{q_L}+\mathcal{Y}^3_{\nu_R}$	$2(\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L})+\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{d_R}$	$-2\mathcal{Y}^3_{q_L}-\mathcal{Y}^3_{\nu_R}$	$-2\mathcal{Y}^1_{q_L}-\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$

Anomaly cancellation takes place between fermions in each family.

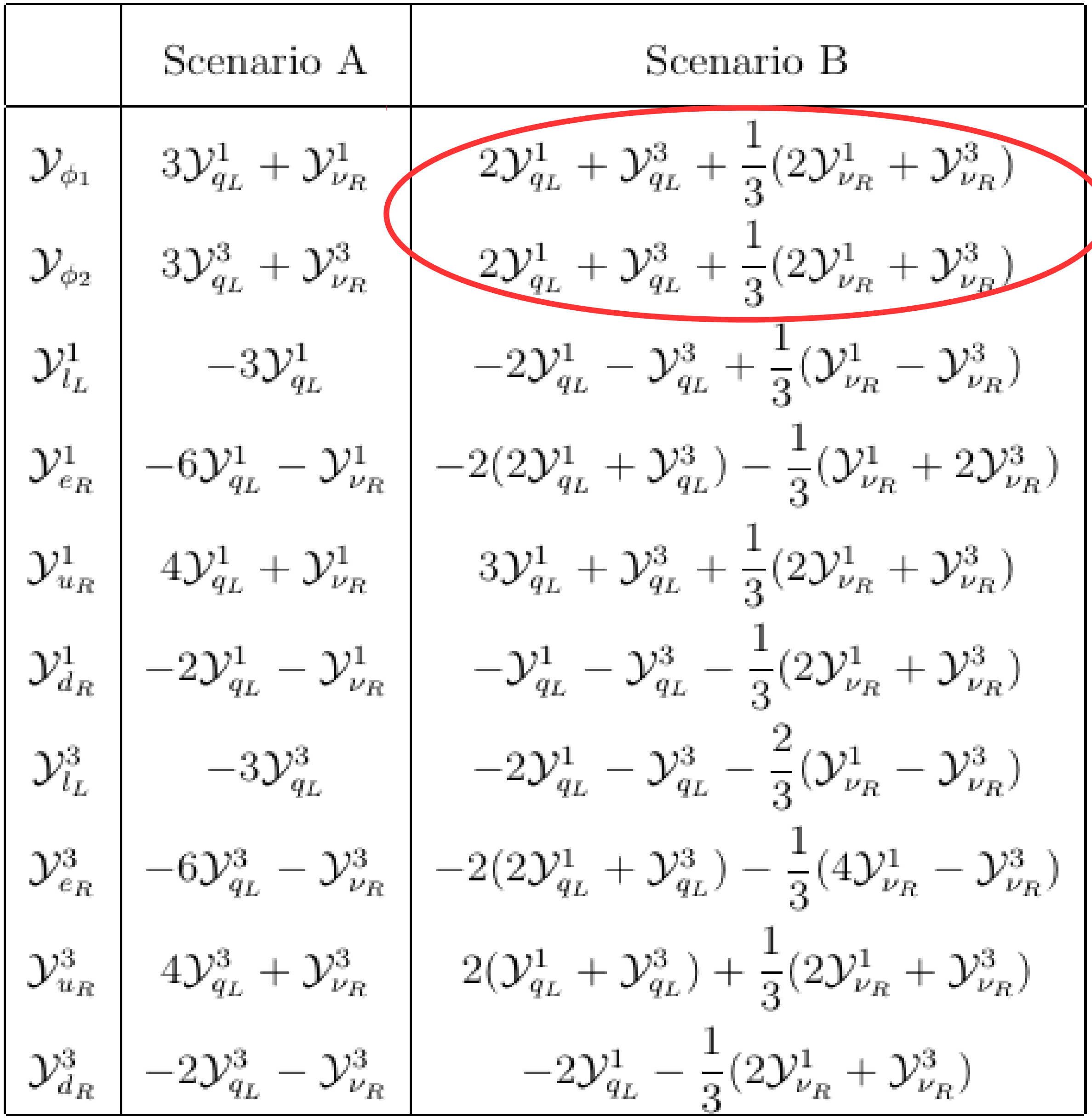
Building the model: two scenarios



	Scenario A	Scenario B
$\mathcal{Y}_{\phi_1}$	$3\mathcal{Y}^1_{q_L}+\mathcal{Y}^1_{\nu_R}$	$2\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L}+\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}_{\phi_2}$	$3\mathcal{Y}^3_{q_L}+\mathcal{Y}^3_{\nu_R}$	$2\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L}+\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{l_L}$	$-3\mathcal{Y}^1_{q_L}$	$-2\mathcal{Y}^1_{q_L}-\mathcal{Y}^3_{q_L}+\frac{1}{3}(\mathcal{Y}^1_{\nu_R}-\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{e_R}$	$-6\mathcal{Y}^1_{q_L}-\mathcal{Y}^1_{\nu_R}$	$-2(2\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L})-\frac{1}{3}(\mathcal{Y}^1_{\nu_R}+2\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{u_R}$	$4\mathcal{Y}^1_{q_L}+\mathcal{Y}^1_{\nu_R}$	$3\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L}+\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{d_R}$	$-2\mathcal{Y}^1_{q_L}-\mathcal{Y}^1_{\nu_R}$	$-\mathcal{Y}^1_{q_L}-\mathcal{Y}^3_{q_L}-\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{l_L}$	$-3\mathcal{Y}^3_{q_L}$	$-2\mathcal{Y}^1_{q_L}-\mathcal{Y}^3_{q_L}-\frac{2}{3}(\mathcal{Y}^1_{\nu_R}-\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{e_R}$	$-6\mathcal{Y}^3_{q_L}-\mathcal{Y}^3_{\nu_R}$	$-2(2\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L})-\frac{1}{3}(4\mathcal{Y}^1_{\nu_R}-\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{u_R}$	$4\mathcal{Y}^3_{q_L}+\mathcal{Y}^3_{\nu_R}$	$2(\mathcal{Y}^1_{q_L}+\mathcal{Y}^3_{q_L})+\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{d_R}$	$-2\mathcal{Y}^3_{q_L}-\mathcal{Y}^3_{\nu_R}$	$-2\mathcal{Y}^1_{q_L}-\frac{1}{3}(2\mathcal{Y}^1_{\nu_R}+\mathcal{Y}^3_{\nu_R})$

Anomaly cancellation takes Place between fermions in different families.

Building the model: two scenarios



	Scenario A	Scenario B
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$\mathcal{Y}_{\phi 2}$	$3\mathcal{Y}^3_{q_L} + \mathcal{Y}^3_{\nu_R}$	$2\mathcal{Y}^1_{q_L} + \mathcal{Y}^3_{q_L} + \frac{1}{3}(2\mathcal{Y}^1_{\nu_R} + \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{l_L}$	$-3\mathcal{Y}^1_{q_L}$	$-2\mathcal{Y}^1_{q_L} - \mathcal{Y}^3_{q_L} + \frac{1}{3}(\mathcal{Y}^1_{\nu_R} - \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{e_R}$	$-6\mathcal{Y}^1_{q_L} - \mathcal{Y}^1_{\nu_R}$	$-2(2\mathcal{Y}^1_{q_L} + \mathcal{Y}^3_{q_L}) - \frac{1}{3}(\mathcal{Y}^1_{\nu_R} + 2\mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{u_R}$	$4\mathcal{Y}^1_{q_L} + \mathcal{Y}^1_{\nu_R}$	$3\mathcal{Y}^1_{q_L} + \mathcal{Y}^3_{q_L} + \frac{1}{3}(2\mathcal{Y}^1_{\nu_R} + \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^1_{d_R}$	$-2\mathcal{Y}^1_{q_L} - \mathcal{Y}^1_{\nu_R}$	$-\mathcal{Y}^1_{q_L} - \mathcal{Y}^3_{q_L} - \frac{1}{3}(2\mathcal{Y}^1_{\nu_R} + \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{l_L}$	$-3\mathcal{Y}^3_{q_L}$	$-2\mathcal{Y}^1_{q_L} - \mathcal{Y}^3_{q_L} - \frac{2}{3}(\mathcal{Y}^1_{\nu_R} - \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{e_R}$	$-6\mathcal{Y}^3_{q_L} - \mathcal{Y}^3_{\nu_R}$	$-2(2\mathcal{Y}^1_{q_L} + \mathcal{Y}^3_{q_L}) - \frac{1}{3}(4\mathcal{Y}^1_{\nu_R} - \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{u_R}$	$4\mathcal{Y}^3_{q_L} + \mathcal{Y}^3_{\nu_R}$	$2(\mathcal{Y}^1_{q_L} + \mathcal{Y}^3_{q_L}) + \frac{1}{3}(2\mathcal{Y}^1_{\nu_R} + \mathcal{Y}^3_{\nu_R})$
$\mathcal{Y}^3_{d_R}$	$-2\mathcal{Y}^3_{q_L} - \mathcal{Y}^3_{\nu_R}$	$-2\mathcal{Y}^1_{q_L} - \frac{1}{3}(2\mathcal{Y}^1_{\nu_R} + \mathcal{Y}^3_{\nu_R})$

Φ_1 and Φ_2 have the same quantum numbers, so that Φ_2 also couples to first and second family fermions!

A Z_2 symmetry can resolve this problem

Building the model:
parameters

All chiral charges can be expressed in terms of only four (4) independent parameters

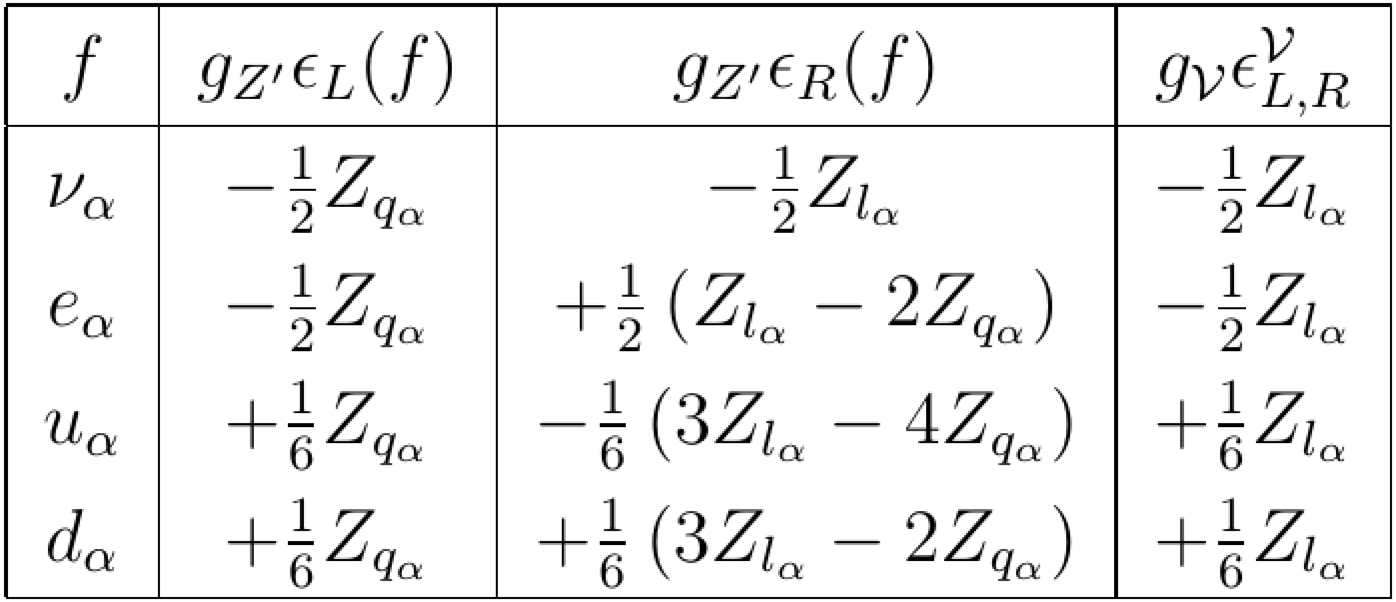
$$
\begin{aligned}
Z_{l_1} &\equiv Y^1_{\nu_R} D, \\
Z_{l_3} &\equiv Y^3_{\nu_R} D, \\
Z_{q_1} &\equiv C - 3Y^1_{q_L} D, \\
Z_{q_3} &\equiv C - 3Y^3_{q_L} D,
\end{aligned}
$$

$$C, D = f(a, b, g_1, g_2, \theta)$$

Mixing angle between B_1 and B_2

Building the model:

chiral charges (A)

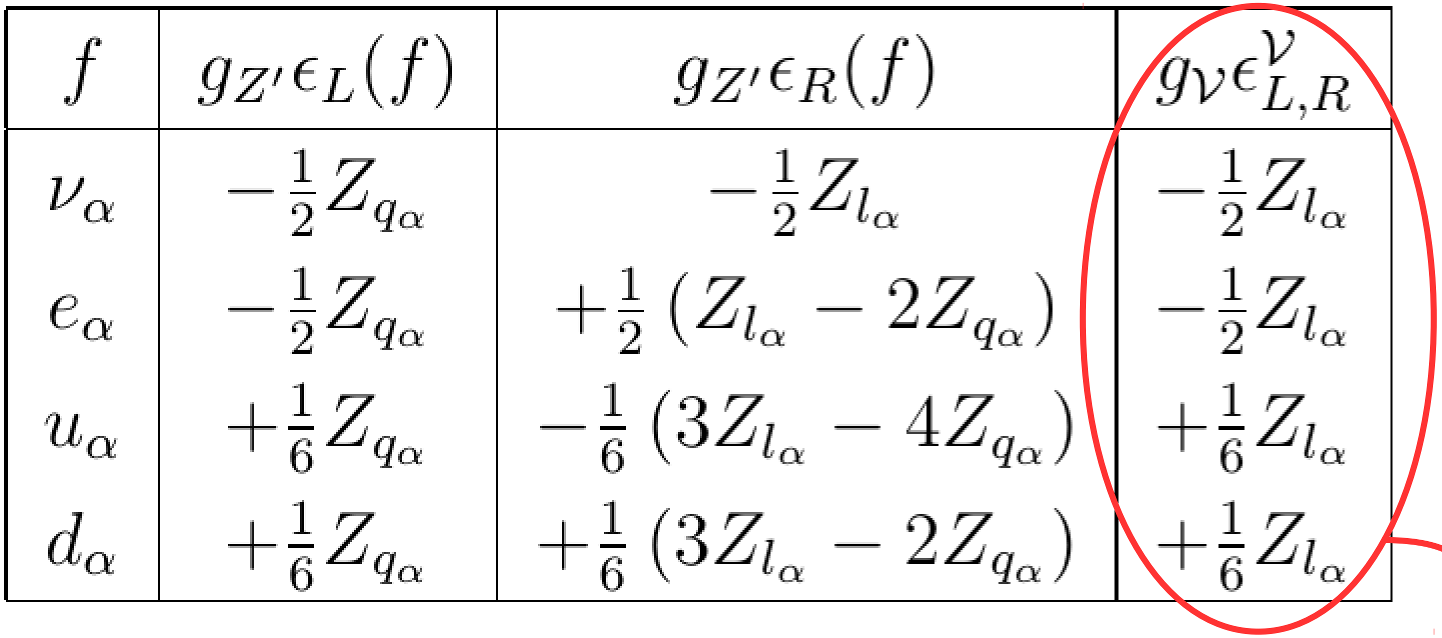


f	$g_{Z'}\epsilon_L(f)$	$g_{Z'}\epsilon_R(f)$	$g_{\mathcal{V}}\epsilon^{\mathcal{V}}_{L,R}$
ν_α	$-\frac{1}{2}Z_{q_\alpha}$	$-\frac{1}{2}Z_{l_\alpha}$	$-\frac{1}{2}Z_{l_\alpha}$
e_α	$-\frac{1}{2}Z_{q_\alpha}$	$+\frac{1}{2}\left(Z_{l_\alpha}-2Z_{q_\alpha}\right)$	$-\frac{1}{2}Z_{l_\alpha}$
u_α	$+\frac{1}{6}Z_{q_\alpha}$	$-\frac{1}{6}\left(3Z_{l_\alpha}-4Z_{q_\alpha}\right)$	$+\frac{1}{6}Z_{l_\alpha}$
d_α	$+\frac{1}{6}Z_{q_\alpha}$	$+\frac{1}{6}\left(3Z_{l_\alpha}-2Z_{q_\alpha}\right)$	$+\frac{1}{6}Z_{l_\alpha}$

$$\alpha = 1, 3$$

Building the model:

chiral charges (A)



f	$g_{Z'}\epsilon_L(f)$	$g_{Z'}\epsilon_R(f)$	$g_{\mathcal{V}}\epsilon^{\mathcal{V}}_{L,R}$
ν_α	$-\frac{1}{2}Z_{q_\alpha}$	$-\frac{1}{2}Z_{l_\alpha}$	$-\frac{1}{2}Z_{l_\alpha}$
e_α	$-\frac{1}{2}Z_{q_\alpha}$	$+\frac{1}{2}\left(Z_{l_\alpha}-2Z_{q_\alpha}\right)$	$-\frac{1}{2}Z_{l_\alpha}$
u_α	$+\frac{1}{6}Z_{q_\alpha}$	$-\frac{1}{6}\left(3Z_{l_\alpha}-4Z_{q_\alpha}\right)$	$+\frac{1}{6}Z_{l_\alpha}$
d_α	$+\frac{1}{6}Z_{q_\alpha}$	$+\frac{1}{6}\left(3Z_{l_\alpha}-2Z_{q_\alpha}\right)$	$+\frac{1}{6}Z_{l_\alpha}$

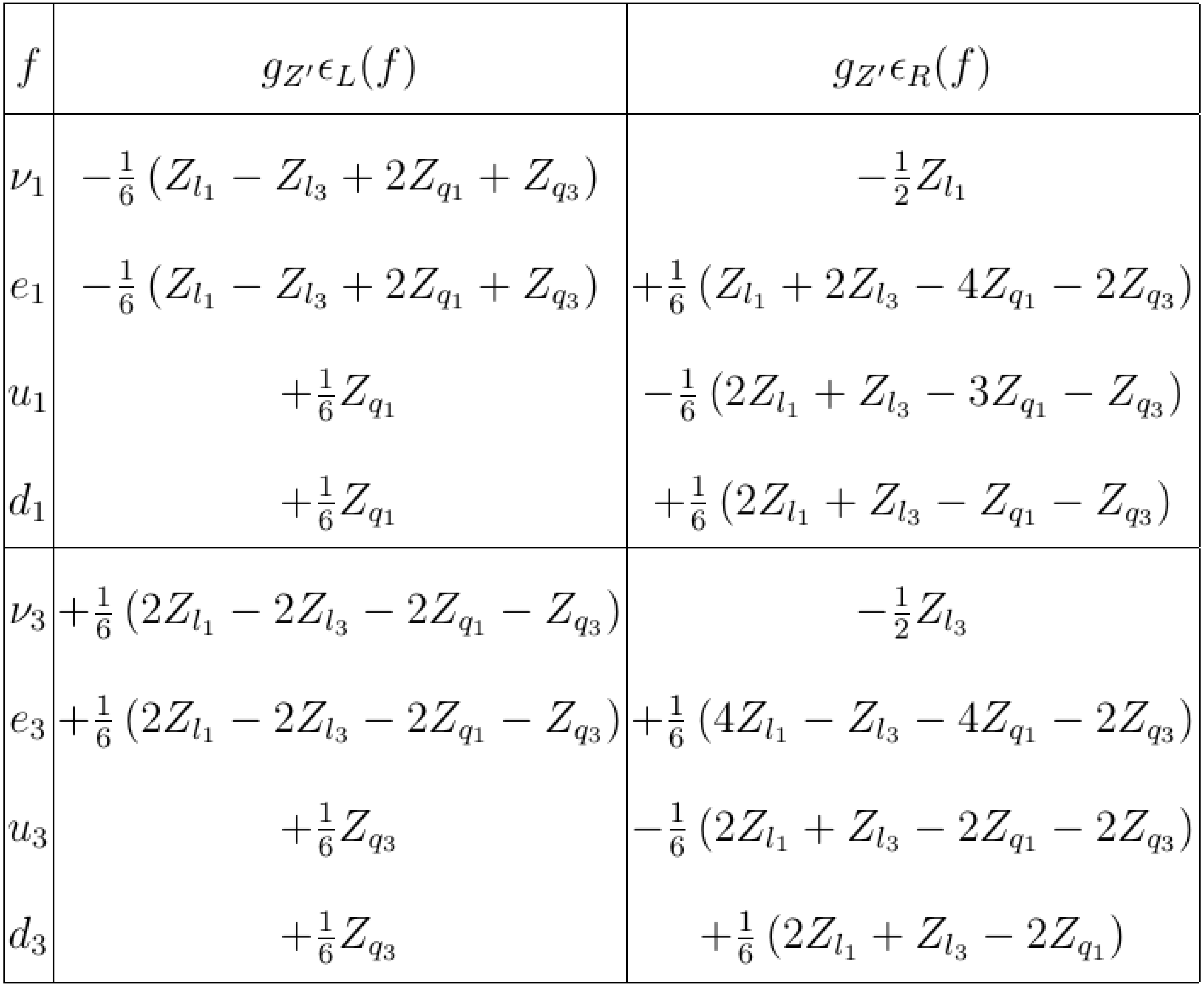
$$\alpha = 1, 3$$

$$Z_{l_\alpha} = Z_{q_\alpha}$$

The most general vector model

Building the model:

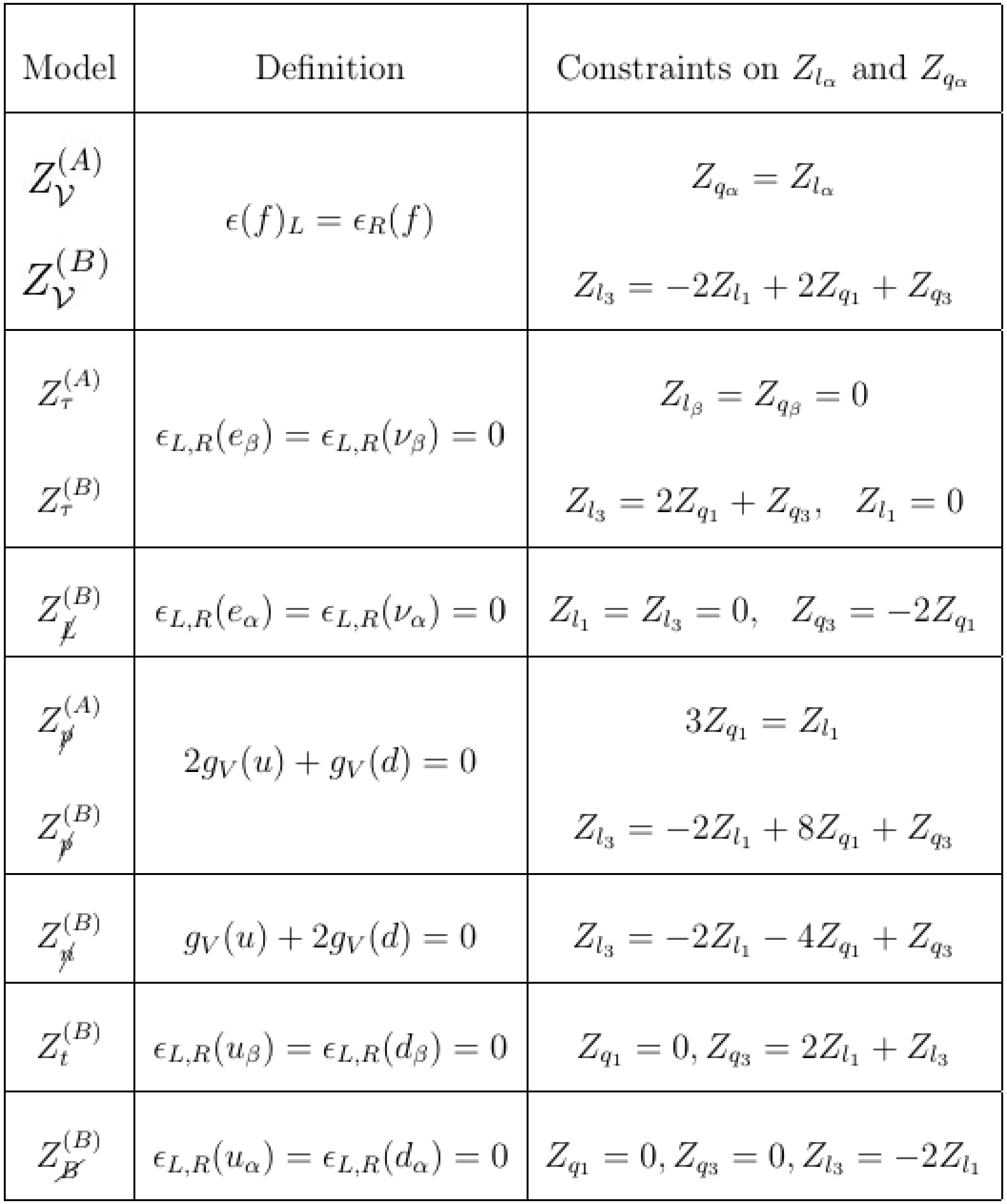
chiral charges (B)



f	$g_{Z'}\epsilon_L(f)$	$g_{Z'}\epsilon_R(f)$
ν_1	$-\frac{1}{6}\left(Z_{l_1} - Z_{l_3} + 2Z_{q_1} + Z_{q_3}\right)$	$-\frac{1}{2}Z_{l_1}$
e_1	$-\frac{1}{6}\left(Z_{l_1} - Z_{l_3} + 2Z_{q_1} + Z_{q_3}\right)$	$+\frac{1}{6}\left(Z_{l_1} + 2Z_{l_3} - 4Z_{q_1} - 2Z_{q_3}\right)$
u_1	$+\frac{1}{6}Z_{q_1}$	$-\frac{1}{6}\left(2Z_{l_1} + Z_{l_3} - 3Z_{q_1} - Z_{q_3}\right)$
d_1	$+\frac{1}{6}Z_{q_1}$	$+\frac{1}{6}\left(2Z_{l_1} + Z_{l_3} - Z_{q_1} - Z_{q_3}\right)$
ν_3	$+\frac{1}{6}\left(2Z_{l_1} - 2Z_{l_3} - 2Z_{q_1} - Z_{q_3}\right)$	$-\frac{1}{2}Z_{l_3}$
e_3	$+\frac{1}{6}\left(2Z_{l_1} - 2Z_{l_3} - 2Z_{q_1} - Z_{q_3}\right)$	$+\frac{1}{6}\left(4Z_{l_1} - Z_{l_3} - 4Z_{q_1} - 2Z_{q_3}\right)$
u_3	$+\frac{1}{6}Z_{q_3}$	$-\frac{1}{6}\left(2Z_{l_1} + Z_{l_3} - 2Z_{q_1} - 2Z_{q_3}\right)$
d_3	$+\frac{1}{6}Z_{q_3}$	$+\frac{1}{6}\left(2Z_{l_1} + Z_{l_3} - 2Z_{q_1}\right)$

Phenomenological analysis:

benchmark models



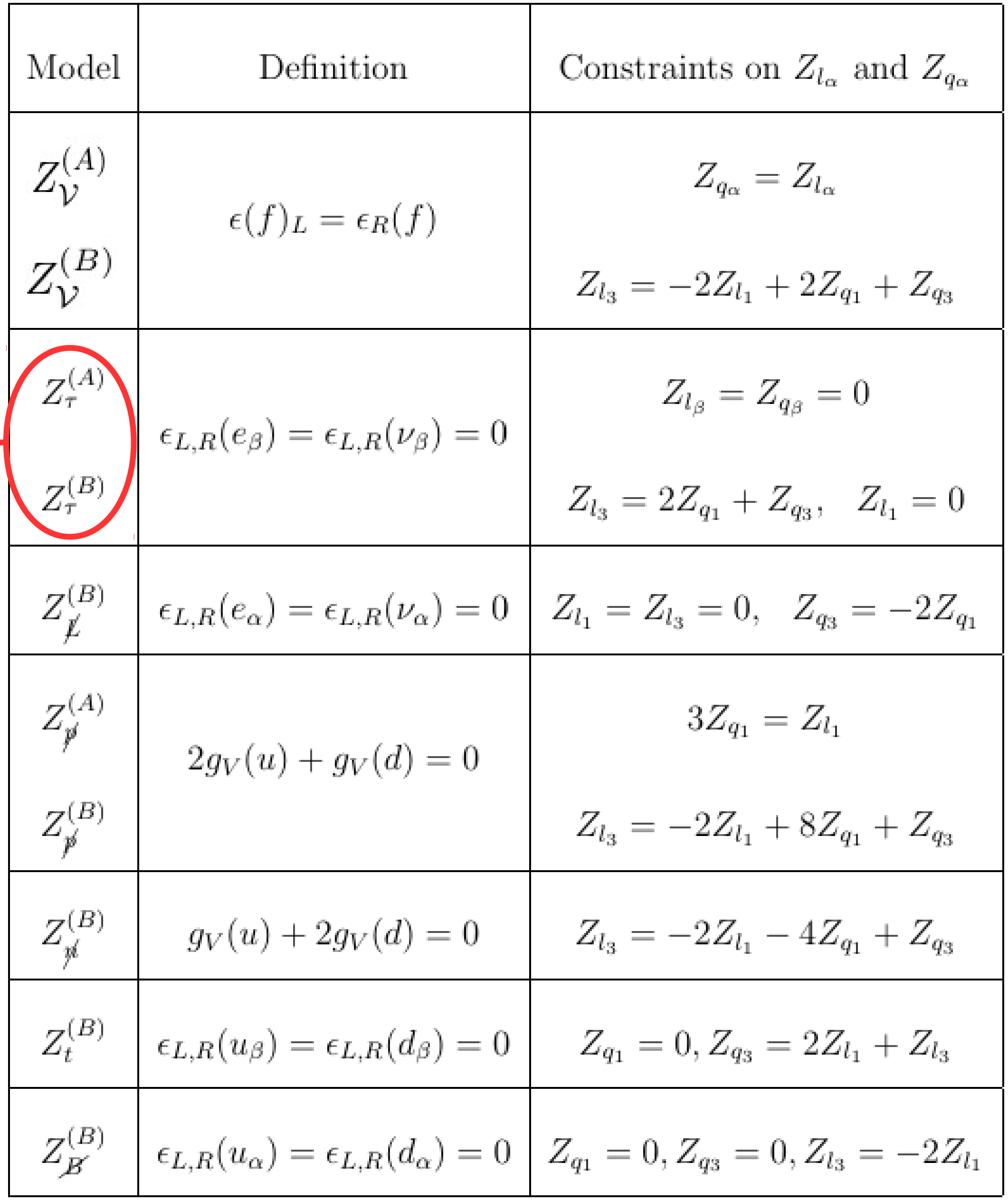
Model	Definition	Constraints on Z_{l_α} and Z_{q_α}
$Z_{\mathcal{V}}^{(A)}$	$\epsilon(f)_L = \epsilon_R(f)$	$Z_{q_\alpha} = Z_{l_\alpha}$
$Z_{\mathcal{V}}^{(B)}$		$Z_{l_3} = -2Z_{l_1} + 2Z_{q_1} + Z_{q_3}$
$Z_{\tau}^{(A)}$	$\epsilon_{L,R}(e_\beta) = \epsilon_{L,R}(\nu_\beta) = 0$	$Z_{l_\beta} = Z_{q_\beta} = 0$
$Z_{\tau}^{(B)}$		$Z_{l_3} = 2Z_{q_1} + Z_{q_3}, \quad Z_{l_1} = 0$
$Z_{\not L}^{(B)}$	$\epsilon_{L,R}(e_\alpha) = \epsilon_{L,R}(\nu_\alpha) = 0$	$Z_{l_1} = Z_{l_3} = 0, \quad Z_{q_3} = -2Z_{q_1}$
$Z_{\not p}^{(A)}$	$2g_V(u) + g_V(d) = 0$	$3Z_{q_1} = Z_{l_1}$
$Z_{\not p}^{(B)}$		$Z_{l_3} = -2Z_{l_1} + 8Z_{q_1} + Z_{q_3}$
$Z_{\not n}^{(B)}$	$g_V(u) + 2g_V(d) = 0$	$Z_{l_3} = -2Z_{l_1} - 4Z_{q_1} + Z_{q_3}$
$Z_{t}^{(B)}$	$\epsilon_{L,R}(u_\beta) = \epsilon_{L,R}(d_\beta) = 0$	$Z_{q_1} = 0, Z_{q_3} = 2Z_{l_1} + Z_{l_3}$
$Z_{\not B}^{(B)}$	$\epsilon_{L,R}(u_\alpha) = \epsilon_{L,R}(d_\alpha) = 0$	$Z_{q_1} = 0, Z_{q_3} = 0, Z_{l_3} = -2Z_{l_1}$

Phenomenological analysis:
benchmark models

Model	Definition	Constraints on Z_{l_α} and Z_{q_α}
$Z_{\mathcal{V}}^{(A)}$ $Z_{\mathcal{V}}^{(B)}$	$\epsilon(f)_L = \epsilon_R(f)$	$Z_{q_\alpha} = Z_{l_\alpha}$ $Z_{l_3} = -2Z_{l_1} + 2Z_{q_1} + Z_{q_3}$
$Z_{\tau}^{(A)}$ $Z_{\tau}^{(B)}$	$\epsilon_{L,R}(e_\beta) = \epsilon_{L,R}(\nu_\beta) = 0$	$Z_{l_\beta} = Z_{q_\beta} = 0$ $Z_{l_3} = 2Z_{q_1} + Z_{q_3}, \quad Z_{l_1} = 0$
$Z_{\not L}^{(B)}$	$\epsilon_{L,R}(e_\alpha) = \epsilon_{L,R}(\nu_\alpha) = 0$	$Z_{l_1} = Z_{l_3} = 0, \quad Z_{q_3} = -2Z_{q_1}$
$Z_{\not p}^{(A)}$ $Z_{\not p}^{(B)}$	$2g_V(u) + g_V(d) = 0$	$3Z_{q_1} = Z_{l_1}$ $Z_{l_3} = -2Z_{l_1} + 8Z_{q_1} + Z_{q_3}$
$Z_{\not n}^{(B)}$	$g_V(u) + 2g_V(d) = 0$	$Z_{l_3} = -2Z_{l_1} - 4Z_{q_1} + Z_{q_3}$
$Z_{t}^{(B)}$	$\epsilon_{L,R}(u_\beta) = \epsilon_{L,R}(d_\beta) = 0$	$Z_{q_1} = 0, Z_{q_3} = 2Z_{l_1} + Z_{l_3}$
$Z_{\not B}^{(B)}$	$\epsilon_{L,R}(u_\alpha) = \epsilon_{L,R}(d_\alpha) = 0$	$Z_{q_1} = 0, Z_{q_3} = 0, Z_{l_3} = -2Z_{l_1}$

Vector models

Phenomenological analysis:
benchmark models

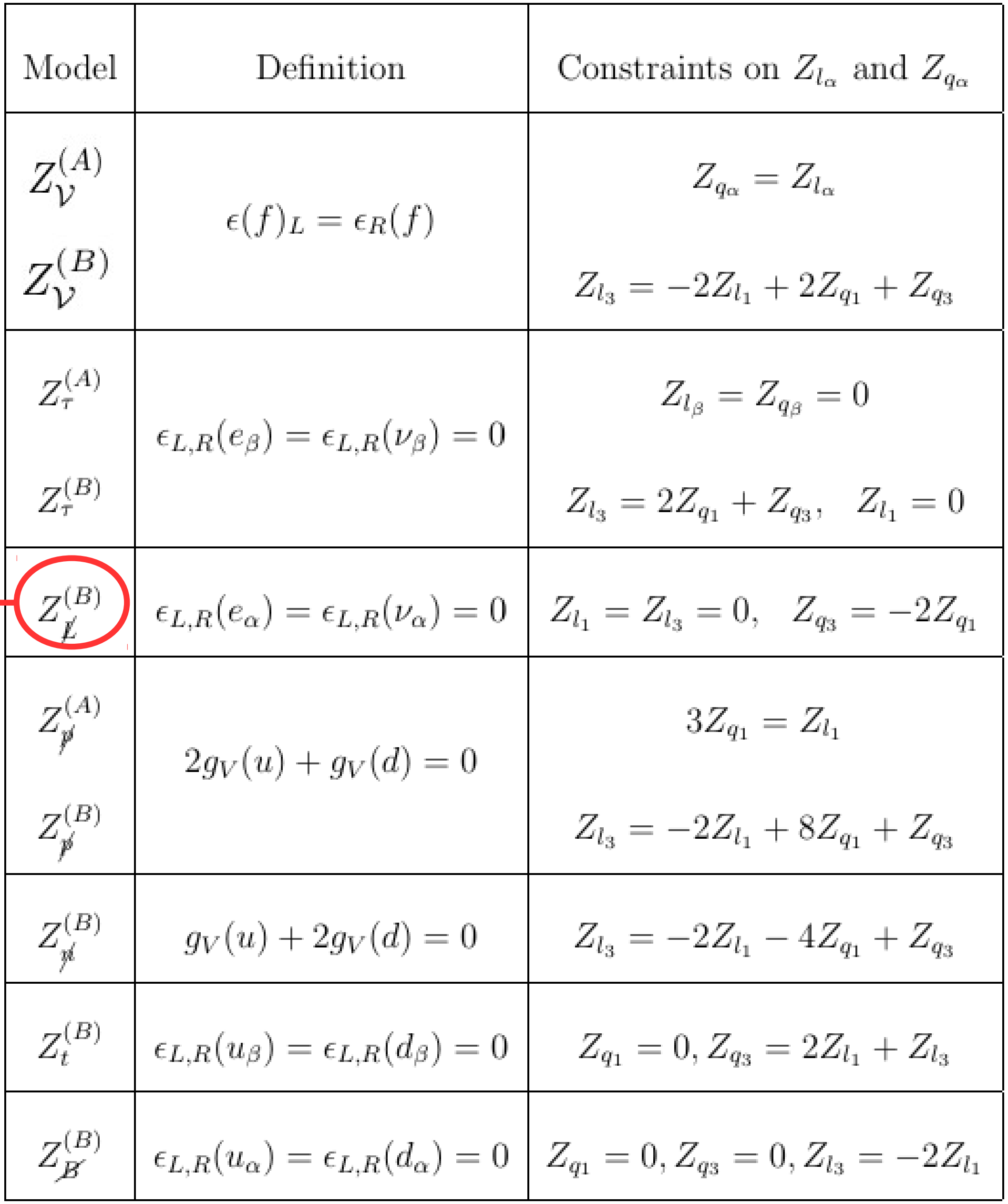


Model	Definition	Constraints on Z_{l_α} and Z_{q_α}
$Z_{\mathcal{V}}^{(A)}$	$\epsilon(f)_L = \epsilon_R(f)$	$Z_{q_\alpha} = Z_{l_\alpha}$
$Z_{\mathcal{V}}^{(B)}$		$Z_{l_3} = -2Z_{l_1} + 2Z_{q_1} + Z_{q_3}$
$Z_{\tau}^{(A)}$	$\epsilon_{L,R}(e_\beta) = \epsilon_{L,R}(\nu_\beta) = 0$	$Z_{l_\beta} = Z_{q_\beta} = 0$
$Z_{\tau}^{(B)}$		$Z_{l_3} = 2Z_{q_1} + Z_{q_3}, \quad Z_{l_1} = 0$
$Z_{\not{L}}^{(B)}$	$\epsilon_{L,R}(e_\alpha) = \epsilon_{L,R}(\nu_\alpha) = 0$	$Z_{l_1} = Z_{l_3} = 0, \quad Z_{q_3} = -2Z_{q_1}$
$Z_{\not{p}}^{(A)}$	$2g_V(u) + g_V(d) = 0$	$3Z_{q_1} = Z_{l_1}$
$Z_{\not{p}}^{(B)}$		$Z_{l_3} = -2Z_{l_1} + 8Z_{q_1} + Z_{q_3}$
$Z_{\not{n}}^{(B)}$	$g_V(u) + 2g_V(d) = 0$	$Z_{l_3} = -2Z_{l_1} - 4Z_{q_1} + Z_{q_3}$
$Z_{t}^{(B)}$	$\epsilon_{L,R}(u_\beta) = \epsilon_{L,R}(d_\beta) = 0$	$Z_{q_1} = 0, Z_{q_3} = 2Z_{l_1} + Z_{l_3}$
$Z_{\not{B}}^{(B)}$	$\epsilon_{L,R}(u_\alpha) = \epsilon_{L,R}(d_\alpha) = 0$	$Z_{q_1} = 0, Z_{q_3} = 0, Z_{l_3} = -2Z_{l_1}$

Tau-philic models

Phenomenological analysis:
benchmark models

Lepto-phobic models



Model	Definition	Constraints on Z_{l_α} and Z_{q_α}
$Z_{\mathcal{V}}^{(A)}$ $Z_{\mathcal{V}}^{(B)}$	$\epsilon(f)_L = \epsilon_R(f)$	$Z_{q_\alpha} = Z_{l_\alpha}$ $Z_{l_3} = -2Z_{l_1} + 2Z_{q_1} + Z_{q_3}$
$Z_{\tau}^{(A)}$ $Z_{\tau}^{(B)}$	$\epsilon_{L,R}(e_\beta) = \epsilon_{L,R}(\nu_\beta) = 0$	$Z_{l_\beta} = Z_{q_\beta} = 0$ $Z_{l_3} = 2Z_{q_1} + Z_{q_3}, \quad Z_{l_1} = 0$
$Z_{\not{L}}^{(B)}$	$\epsilon_{L,R}(e_\alpha) = \epsilon_{L,R}(\nu_\alpha) = 0$	$Z_{l_1} = Z_{l_3} = 0, \quad Z_{q_3} = -2Z_{q_1}$
$Z_{\not{p}}^{(A)}$ $Z_{\not{p}}^{(B)}$	$2g_V(u) + g_V(d) = 0$	$3Z_{q_1} = Z_{l_1}$ $Z_{l_3} = -2Z_{l_1} + 8Z_{q_1} + Z_{q_3}$
$Z_{\not{n}}^{(B)}$	$g_V(u) + 2g_V(d) = 0$	$Z_{l_3} = -2Z_{l_1} - 4Z_{q_1} + Z_{q_3}$
$Z_{t}^{(B)}$	$\epsilon_{L,R}(u_\beta) = \epsilon_{L,R}(d_\beta) = 0$	$Z_{q_1} = 0, Z_{q_3} = 2Z_{l_1} + Z_{l_3}$
$Z_{\not{B}}^{(B)}$	$\epsilon_{L,R}(u_\alpha) = \epsilon_{L,R}(d_\alpha) = 0$	$Z_{q_1} = 0, Z_{q_3} = 0, Z_{l_3} = -2Z_{l_1}$

Phenomenological analysis:

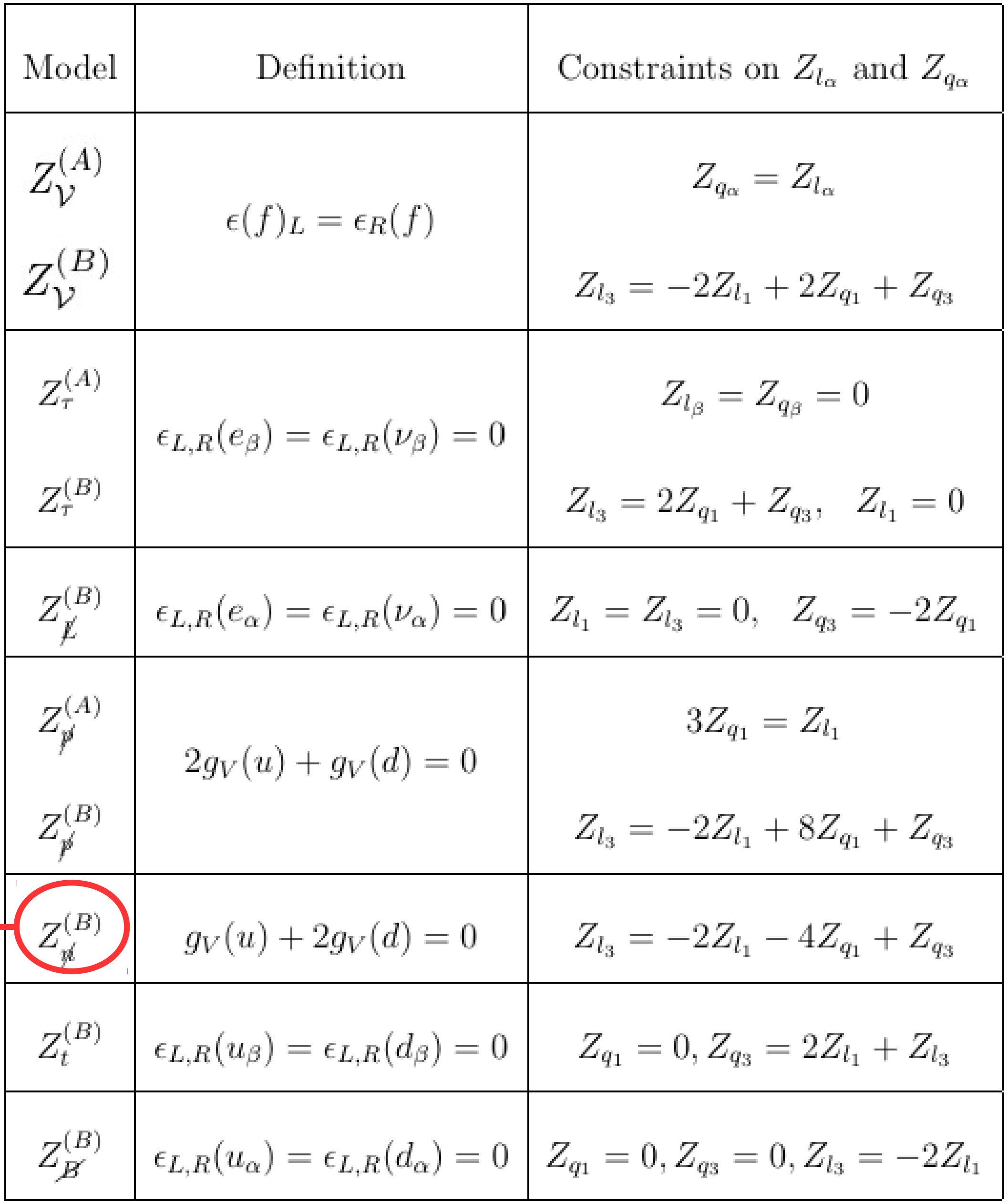
benchmark models

Proton-phobic models

Model	Definition	Constraints on Z_{l_α} and Z_{q_α}
$Z_{\mathcal{V}}^{(A)}$ $Z_{\mathcal{V}}^{(B)}$	$\epsilon(f)_L = \epsilon_R(f)$	$Z_{q_\alpha} = Z_{l_\alpha}$ $Z_{l_3} = -2Z_{l_1} + 2Z_{q_1} + Z_{q_3}$
$Z_{\tau}^{(A)}$ $Z_{\tau}^{(B)}$	$\epsilon_{L,R}(e_\beta) = \epsilon_{L,R}(\nu_\beta) = 0$	$Z_{l_\beta} = Z_{q_\beta} = 0$ $Z_{l_3} = 2Z_{q_1} + Z_{q_3}, \quad Z_{l_1} = 0$
$Z_{\not L}^{(B)}$	$\epsilon_{L,R}(e_\alpha) = \epsilon_{L,R}(\nu_\alpha) = 0$	$Z_{l_1} = Z_{l_3} = 0, \quad Z_{q_3} = -2Z_{q_1}$
$Z_{\not p}^{(A)}$ $Z_{\not p}^{(B)}$	$2g_V(u) + g_V(d) = 0$	$3Z_{q_1} = Z_{l_1}$ $Z_{l_3} = -2Z_{l_1} + 8Z_{q_1} + Z_{q_3}$
$Z_{\not n}^{(B)}$	$g_V(u) + 2g_V(d) = 0$	$Z_{l_3} = -2Z_{l_1} - 4Z_{q_1} + Z_{q_3}$
$Z_{t}^{(B)}$	$\epsilon_{L,R}(u_\beta) = \epsilon_{L,R}(d_\beta) = 0$	$Z_{q_1} = 0, Z_{q_3} = 2Z_{l_1} + Z_{l_3}$
$Z_{\not B}^{(B)}$	$\epsilon_{L,R}(u_\alpha) = \epsilon_{L,R}(d_\alpha) = 0$	$Z_{q_1} = 0, Z_{q_3} = 0, Z_{l_3} = -2Z_{l_1}$

Phenomenological analysis:
benchmark models

Neutron-phobic models



Model	Definition	Constraints on Z_{l_α} and Z_{q_α}
$Z_{\mathcal{V}}^{(A)}$ $Z_{\mathcal{V}}^{(B)}$	$\epsilon(f)_L = \epsilon_R(f)$	$Z_{q_\alpha} = Z_{l_\alpha}$ $Z_{l_3} = -2Z_{l_1} + 2Z_{q_1} + Z_{q_3}$
$Z_{\tau}^{(A)}$ $Z_{\tau}^{(B)}$	$\epsilon_{L,R}(e_\beta) = \epsilon_{L,R}(\nu_\beta) = 0$	$Z_{l_\beta} = Z_{q_\beta} = 0$ $Z_{l_3} = 2Z_{q_1} + Z_{q_3}, \quad Z_{l_1} = 0$
$Z_{\not{L}}^{(B)}$	$\epsilon_{L,R}(e_\alpha) = \epsilon_{L,R}(\nu_\alpha) = 0$	$Z_{l_1} = Z_{l_3} = 0, \quad Z_{q_3} = -2Z_{q_1}$
$Z_{\not{p}}^{(A)}$ $Z_{\not{p}}^{(B)}$	$2g_V(u) + g_V(d) = 0$	$3Z_{q_1} = Z_{l_1}$ $Z_{l_3} = -2Z_{l_1} + 8Z_{q_1} + Z_{q_3}$
$Z_{\not{n}}^{(B)}$	$g_V(u) + 2g_V(d) = 0$	$Z_{l_3} = -2Z_{l_1} - 4Z_{q_1} + Z_{q_3}$
$Z_{t}^{(B)}$	$\epsilon_{L,R}(u_\beta) = \epsilon_{L,R}(d_\beta) = 0$	$Z_{q_1} = 0, Z_{q_3} = 2Z_{l_1} + Z_{l_3}$
$Z_{\not{B}}^{(B)}$	$\epsilon_{L,R}(u_\alpha) = \epsilon_{L,R}(d_\alpha) = 0$	$Z_{q_1} = 0, Z_{q_3} = 0, Z_{l_3} = -2Z_{l_1}$

Phenomenological analysis:
benchmark models

Model	Definition	Constraints on Z_{l_α} and Z_{q_α}
$Z_{\mathcal{V}}^{(A)}$ $Z_{\mathcal{V}}^{(B)}$	$\epsilon(f)_L = \epsilon_R(f)$	$Z_{q_\alpha} = Z_{l_\alpha}$ $Z_{l_3} = -2Z_{l_1} + 2Z_{q_1} + Z_{q_3}$
$Z_{\tau}^{(A)}$ $Z_{\tau}^{(B)}$	$\epsilon_{L,R}(e_\beta) = \epsilon_{L,R}(\nu_\beta) = 0$	$Z_{l_\beta} = Z_{q_\beta} = 0$ $Z_{l_3} = 2Z_{q_1} + Z_{q_3}, \quad Z_{l_1} = 0$
$Z_{\not L}^{(B)}$	$\epsilon_{L,R}(e_\alpha) = \epsilon_{L,R}(\nu_\alpha) = 0$	$Z_{l_1} = Z_{l_3} = 0, \quad Z_{q_3} = -2Z_{q_1}$
$Z_{\not p}^{(A)}$ $Z_{\not p}^{(B)}$	$2g_V(u) + g_V(d) = 0$	$3Z_{q_1} = Z_{l_1}$ $Z_{l_3} = -2Z_{l_1} + 8Z_{q_1} + Z_{q_3}$
$Z_{\not n}^{(B)}$	$g_V(u) + 2g_V(d) = 0$	$Z_{l_3} = -2Z_{l_1} - 4Z_{q_1} + Z_{q_3}$
$Z_{t}^{(B)}$	$\epsilon_{L,R}(u_\beta) = \epsilon_{L,R}(d_\beta) = 0$	$Z_{q_1} = 0, Z_{q_3} = 2Z_{l_1} + Z_{l_3}$
$Z_{\not B}^{(B)}$	$\epsilon_{L,R}(u_\alpha) = \epsilon_{L,R}(d_\alpha) = 0$	$Z_{q_1} = 0, Z_{q_3} = 0, Z_{l_3} = -2Z_{l_1}$

Top-philic models

Phenomenological analysis:

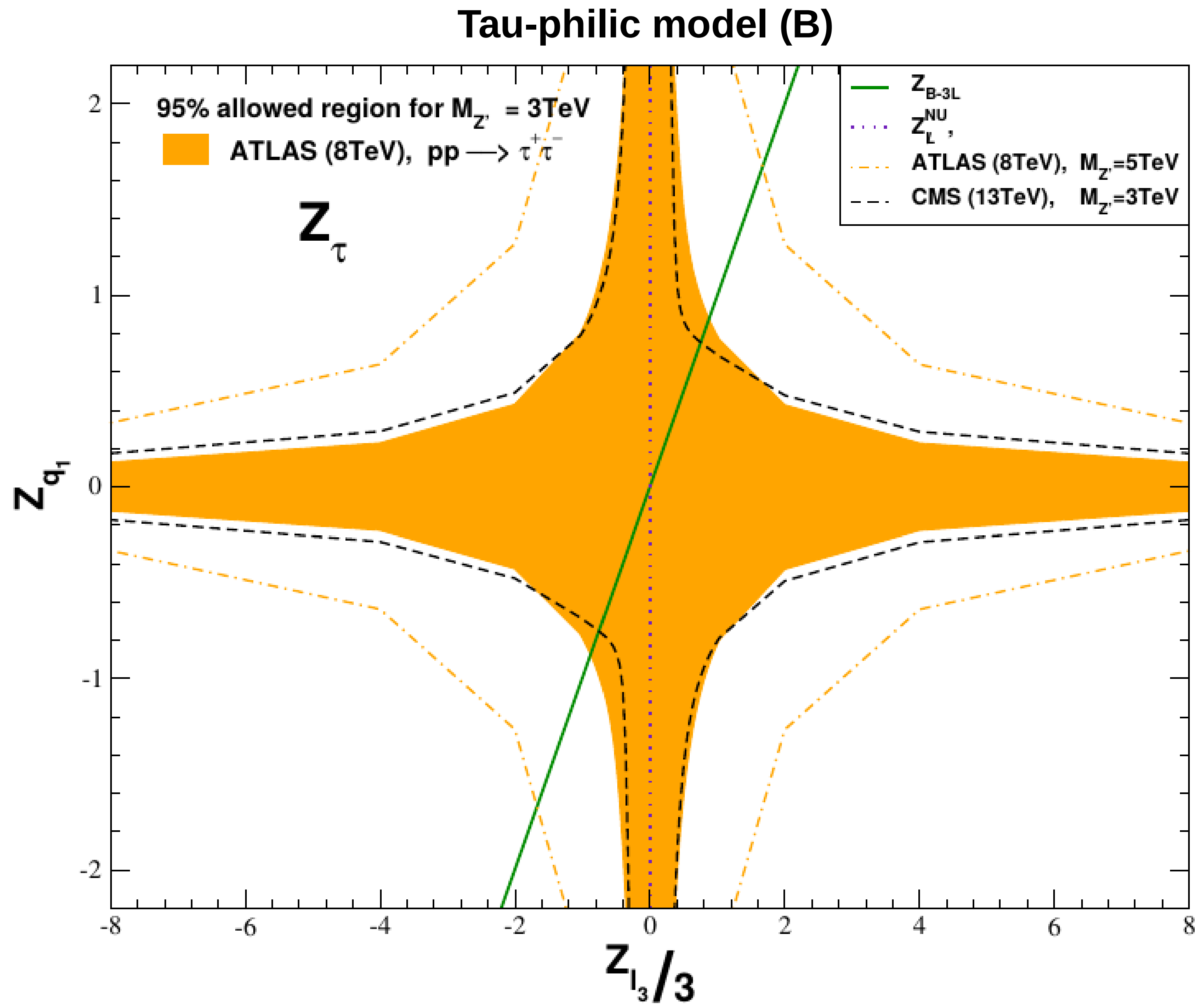
benchmark models

Model	Definition	Constraints on Z_{l_α} and Z_{q_α}
$Z_{\mathcal{V}}^{(A)}$ $Z_{\mathcal{V}}^{(B)}$	$\epsilon(f)_L = \epsilon_R(f)$	$Z_{q_\alpha} = Z_{l_\alpha}$ $Z_{l_3} = -2Z_{l_1} + 2Z_{q_1} + Z_{q_3}$
$Z_{\tau}^{(A)}$ $Z_{\tau}^{(B)}$	$\epsilon_{L,R}(e_\beta) = \epsilon_{L,R}(\nu_\beta) = 0$	$Z_{l_\beta} = Z_{q_\beta} = 0$ $Z_{l_3} = 2Z_{q_1} + Z_{q_3}, \quad Z_{l_1} = 0$
$Z_{\not L}^{(B)}$	$\epsilon_{L,R}(e_\alpha) = \epsilon_{L,R}(\nu_\alpha) = 0$	$Z_{l_1} = Z_{l_3} = 0, \quad Z_{q_3} = -2Z_{q_1}$
$Z_{\not p}^{(A)}$ $Z_{\not p}^{(B)}$	$2g_V(u) + g_V(d) = 0$	$3Z_{q_1} = Z_{l_1}$ $Z_{l_3} = -2Z_{l_1} + 8Z_{q_1} + Z_{q_3}$
$Z_{\not n}^{(B)}$	$g_V(u) + 2g_V(d) = 0$	$Z_{l_3} = -2Z_{l_1} - 4Z_{q_1} + Z_{q_3}$
$Z_{t}^{(B)}$	$\epsilon_{L,R}(u_\beta) = \epsilon_{L,R}(d_\beta) = 0$	$Z_{q_1} = 0, Z_{q_3} = 2Z_{l_1} + Z_{l_3}$
$Z_{\not B}^{(B)}$	$\epsilon_{L,R}(u_\alpha) = \epsilon_{L,R}(d_\alpha) = 0$	$Z_{q_1} = 0, Z_{q_3} = 0, Z_{l_3} = -2Z_{l_1}$

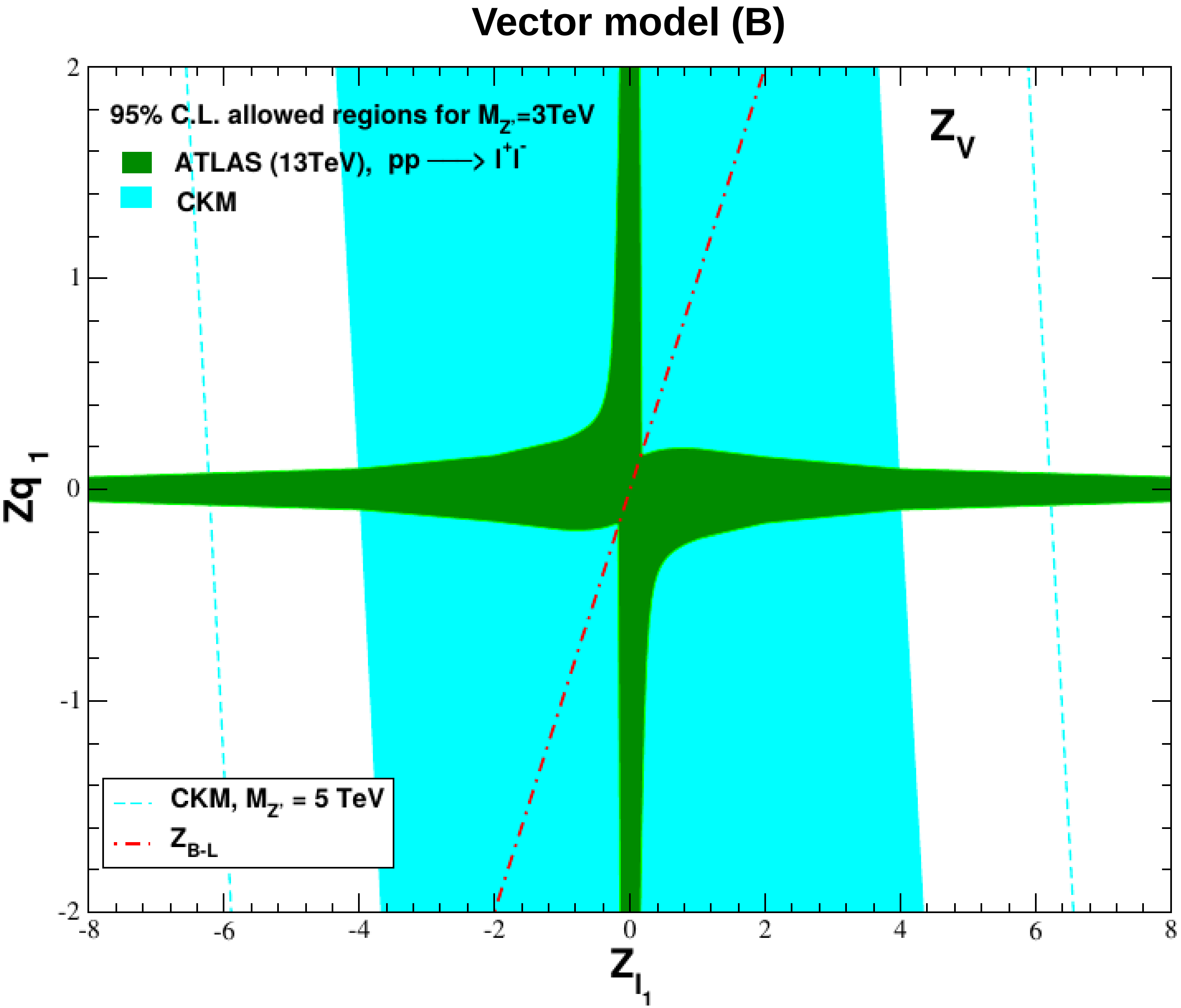
Hadron-phobic models

Phenomenological analysis:

results

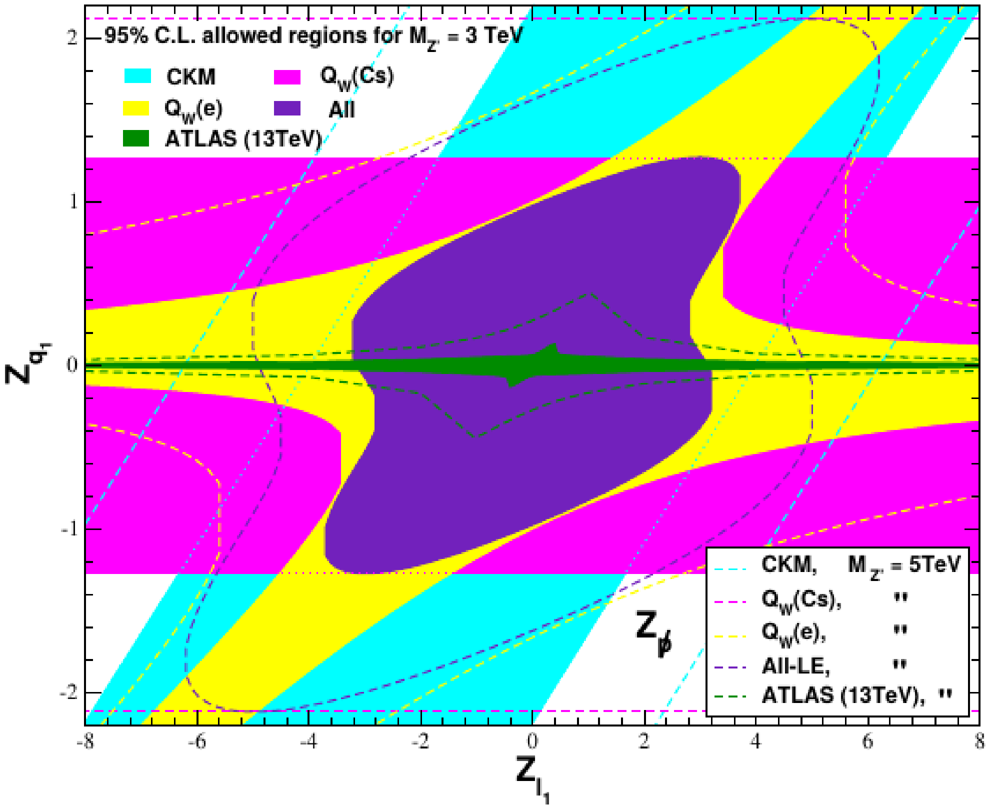


Phenomenological analysis:
results

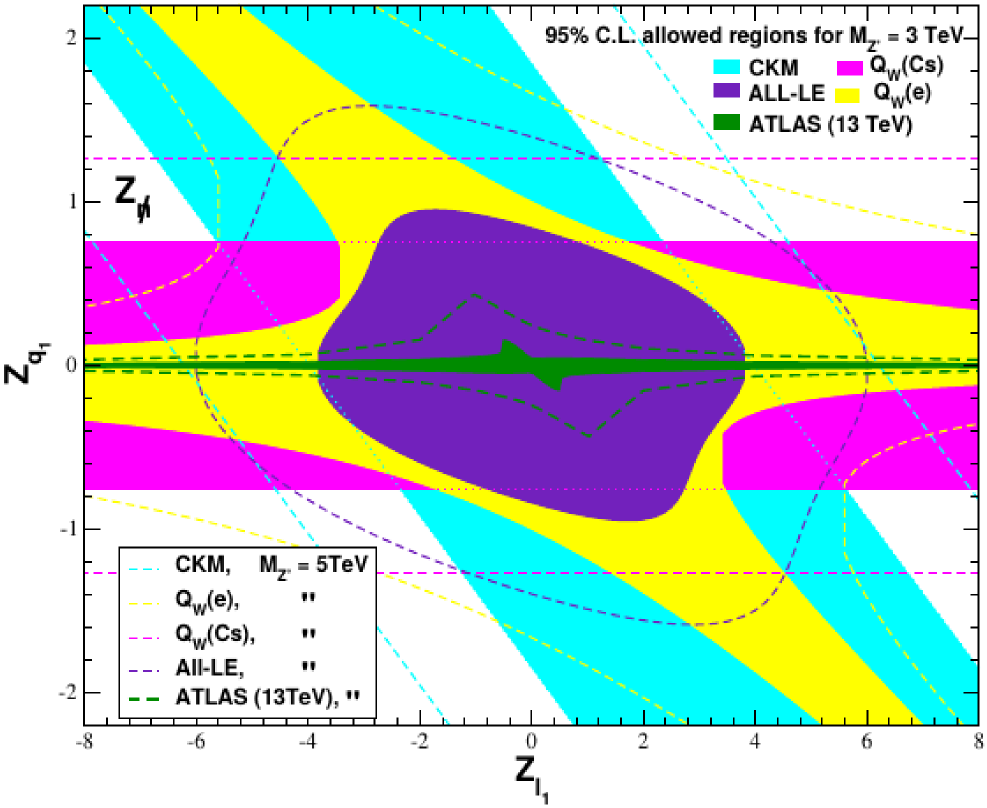


Phenomenological analysis:
results

Proton-phobic model (B)

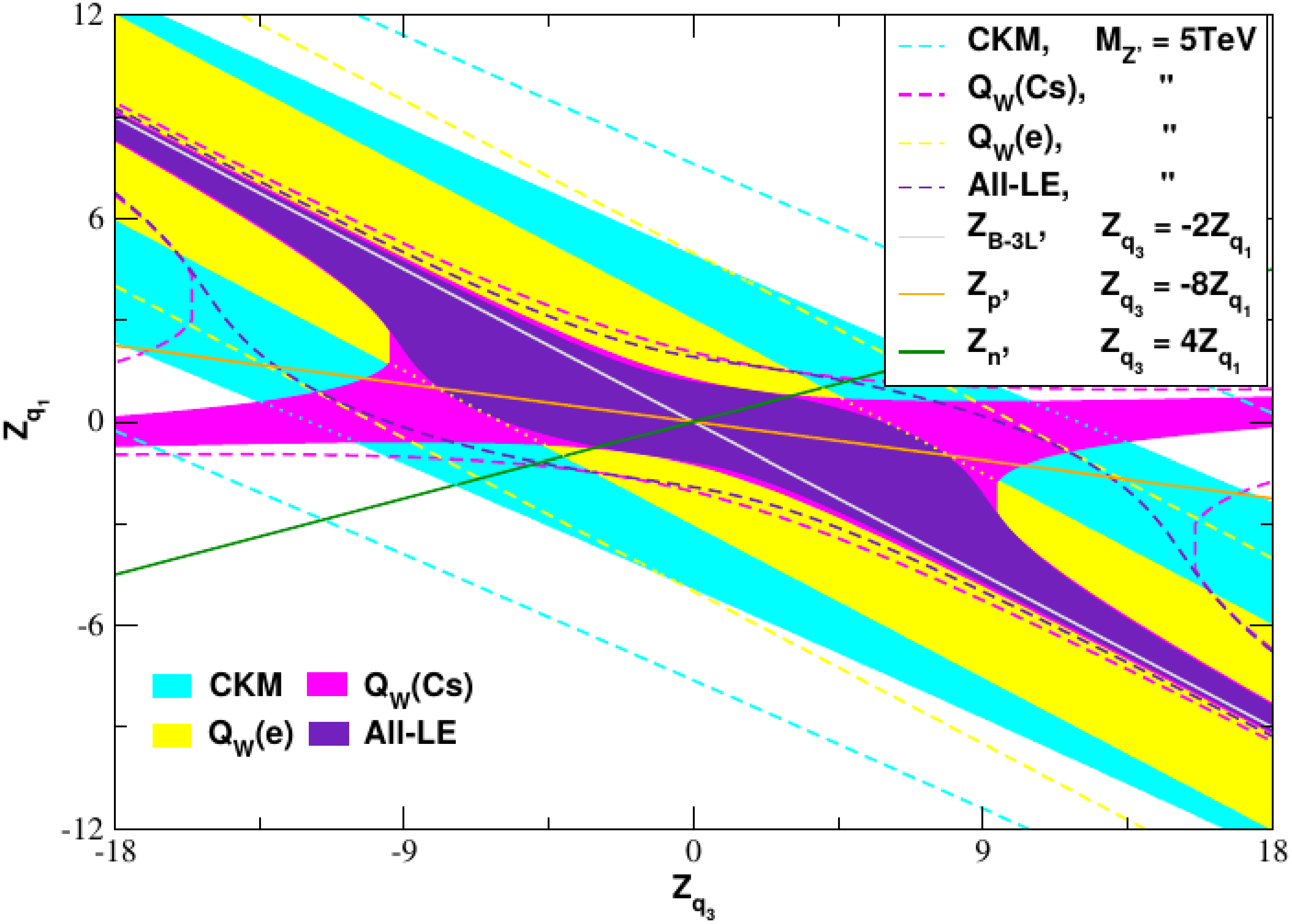


Neutron-phobic model (B)



Phenomenological analysis:
results

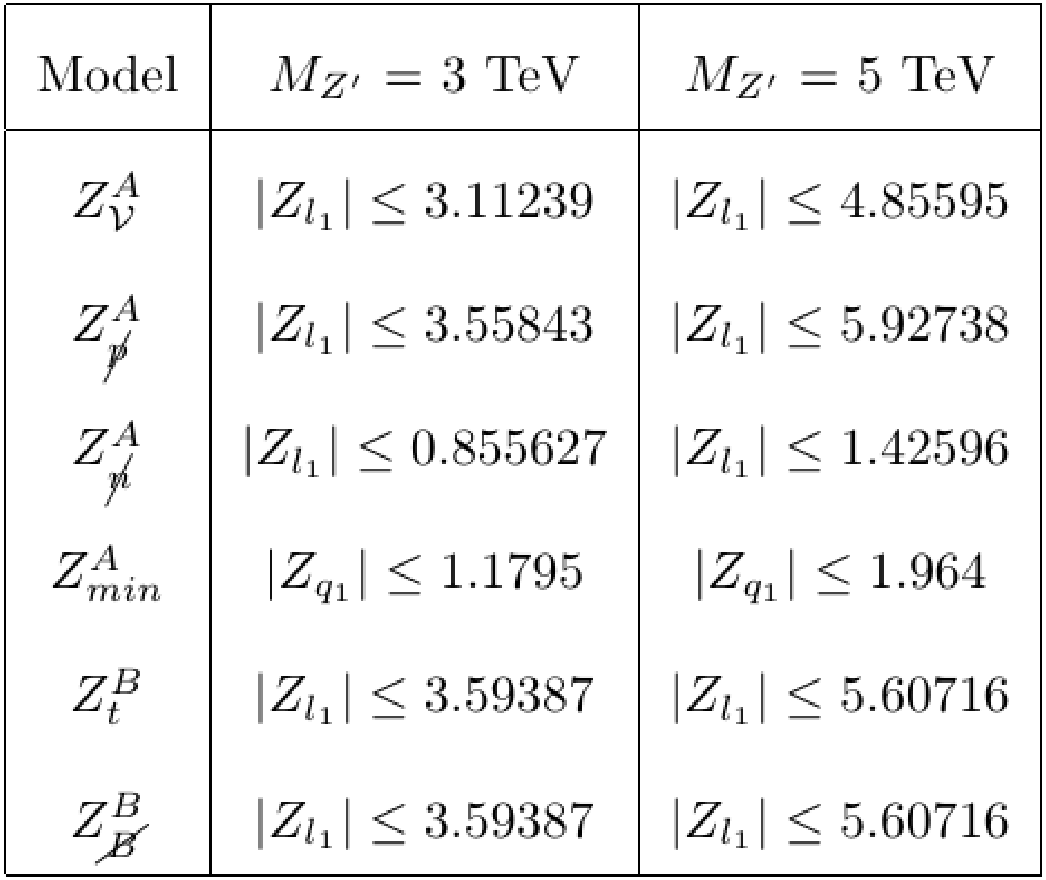
Minimal Model (B) (*“without” right-handed neutrinos*)



Phenomenological analysis:

results

Scenario A



Model	$M_{Z'} = 3$ TeV	$M_{Z'} = 5$ TeV
$Z^A_{\mathcal{V}}$	$\lvert Z_{l_1} \rvert \leq 3.11239$	$\lvert Z_{l_1} \rvert \leq 4.85595$
$Z^A_{\not p}$	$\lvert Z_{l_1} \rvert \leq 3.55843$	$\lvert Z_{l_1} \rvert \leq 5.92738$
$Z^A_{\not n}$	$\lvert Z_{l_1} \rvert \leq 0.855627$	$\lvert Z_{l_1} \rvert \leq 1.42596$
Z^A_{min}	$\lvert Z_{q_1} \rvert \leq 1.1795$	$\lvert Z_{q_1} \rvert \leq 1.964$
Z^B_t	$\lvert Z_{l_1} \rvert \leq 3.59387$	$\lvert Z_{l_1} \rvert \leq 5.60716$
$Z^B_{\not B}$	$\lvert Z_{l_1} \rvert \leq 3.59387$	$\lvert Z_{l_1} \rvert \leq 5.60716$

Conclusions

- ✓ **The minimal EW extension of the SM with a minimal content of fermions was considered. The complete model can be parameterized by just four independent continuous parameters. By imposing conditions on these parameters a great variety of specific models can be derived. For some of these models low-energy constraints were calculated and compared with the most recent LHC constraints.**

- ✓ **Non-universal models are well motivated and can be used to explain the number of families and the hierarchies observed in the fermion mass spectrum.**

- ✓ **By demanding an anomaly-free model and imposing constraints from Yukawa couplings, two versions (scenarios) of the model are possible: one where the anomaly cancellation takes place between fermions in each family, and other where the anomalies cancel out between fermions in different families.**

- ✓ **It is possible to obtain, as particular cases, universal models.**

- ✓ **To prevent FCNC constraints the charges of the first and second family were assumed to be identical, but not necessarily the same as those of the third one.**

- ✓ **Unitarity constraints on the CKM are able to exclude some regions in the parameter space which are difficult to exclude by using only LHC data. This shows the complementarity between experiments carried out at low and high energies.**

Perspectives

- ✓ What about DM?
- ✓ What about neutrino physics?

Thank you!