GAUGE ANOMALY FREE U(1) AND SEESAW MODELS

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OUTLINE

- ★ Motivation
- ★ Extra $\mathbf{U(1)_X}$ gauge group
- ★ Seesaw mechanisms: **type-I** and **type-III**
- ★ Anomaly-free constraints
- ★ Texture zeroes on the effective neutrino mass matrix
- ★ Phenomenological constraints
- ★ Conclusions

In collaboration with [work in progress]:

L. M. Cebola, R. González Felipe, Phys. Rev. **D** 88 (2013) 116008
E. T. Franco, R. González Felipe, Phys. Rev. **D** 79 (2009) 115001

Motivation

- ★ 1998: Lepton Family Number Violation [Secular low violated]
- ★ Implementation of seesaw Type-I (ν_R) and Type-III (Σ)
- ★ Extending the Gauge Group: [Leike; Langacker]

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X$$

with [Ma, Roy, Sarkar]

$$X \equiv a\,B - \sum_{i=1}^{n_G} b_i L_i$$

- ★ Gauge anomaly cancellation $\Longrightarrow$ prediction of two zero textures (m_ν)
- ★ Minimal Higgs sector: doublet H (neutral) and singlet S (charged)
- ★ Richer Phenomenology:
  - If kinematically accessible: detectable at LHC
  - New gauge boson Z'
  - Nonstandard neutrino interactions

Anomaly-free Constraints

[Gross, Jackiw
Bouchiat, Illiopoulos, Meyer
Georgi, Glashow]

$$A_1 = n_G \left(2\, x_q - x_u - x_d\right) = 0$$

$$A_2 = \frac{3 n_G}{2} x_q + \frac{1}{2} \sum_{i=1}^{n_G} x_{\ell i} - 2 \sum_{i=1}^{n_\Sigma} x_{\sigma i} = 0$$

$$A_3 = n_G \left(\frac{x_q}{6} - \frac{4 x_u}{3} - \frac{x_d}{3} \right) + \sum_{i=1}^{n_G} \left(\frac{x_{\ell i}}{2} - x_{ei} \right) = 0$$

$$A_4 = n_G \left(x_q^2 - 2 x_u^2 + x_d^2 \right) + \sum_{i=1}^{n_G} \left(-x_{\ell i}^2 + x_{ei}^2 \right) = 0$$

$$A_5 = n_G \left(6\, x_q^3 - 3\, x_u^3 - 3\, x_d^3 \right) + \sum_{i=1}^{n_G} \left(2\, x_{\ell i}^3 - x_{ei}^3 \right) - \sum_{i=1}^{n_R} x_{\nu i}^3 - 3 \sum_{i=1}^{n_\Sigma} x_{\sigma i}^3 = 0$$

$$A_6 = n_G \left(6 x_q - 3 x_u - 3 x_d \right) + \sum_{i=1}^{n_G} \left(2\, x_{\ell i} - x_{ei} \right) - \sum_{i=1}^{n_R} x_{\nu i} - 3 \sum_{i=1}^{n_\Sigma} x_{\sigma i} = 0$$

Anomaly-free solutions

$$X \equiv a\,B - \sum_{i=1}^{n_G} b_i L_i$$

Under the gauge group $U(1)_X$, the charge for the quarks q_L, u_R, d_R, is universal, $x_q = x_u = x_d = a/3$, while the charged leptons ℓ_{Li}, e_{Ri} have the family nonuniversal charge assignment $x_{\ell i} = x_{ei} = -b_i$, with all b_i different

$$\sum_{k \leq n_\Sigma} b_k = 0$$

$$\sum_{i=1}^{n_G} b_i = \sum_{j \leq n_R} b_j = n_G\, a$$

$$\sum_{i=1}^{n_G} b_i^3 - \sum_{j \leq n_R} b_j^3 - 3 \sum_{k \leq n_\Sigma} b_k^3 = 0$$

Anomaly-free solutions

- ★ Minimal seesaw type I and/or type III with $n_R + n_\Sigma \leq 4$
- ★ Charged lepton mass diagonal $i \neq j \neq k$ and $b'_i \equiv b_i/a$
- ★ Purely leptonic symmetry when $a = 0$

n_R	n_Σ	Anomaly constraints	Symmetry generator X
2	0	$b_i + b_j = 3a,\ b_k = 0$	$B - 3L_j - b'_i(L_i - L_j)$
		$b_i + b_j = 0,\ b_k = 0$	$L_i - L_j$
0	2	$b_i + b_j = 0,\ b_k = 0$	$L_i - L_j$
2	1	$b_i + b_j = 3a,\ b_k = 0$	$B - 3L_j - b'_i(L_i - L_j)$
		$b_i + b_j = 0,\ b_k = 0$	$L_i - L_j$
1	2	$b_i + b_j = 0,\ b_k = 3a$	$B - 3L_k - b'_i(L_i - L_j)$
		$b_i + b_j = 0,\ b_k = 0$	$L_i - L_j$
3	0	$b_i + b_j + b_k = 3a$	$(B - L) + (1 - b'_i)(L_i - L_j) + (1 - b'_k)(L_k - L_j)$
		$b_i + b_j + b_k = 0$	$-b'_i(L_i - L_k) - b'_j(L_j - L_k)$
0	3	$b_i + b_j = 0,\ b_k = 0$	$L_i - L_j$
3	1	$b_i + b_j = 3a,\ b_k = 0$	$B - 3L_j - b'_i(L_i - L_j)$
		$b_i + b_j = 0,\ b_k = 0$	$L_i - L_j$
1	3	$b_i + b_j = 0,\ b_k = 0$	$L_i - L_j$
2	2	$b_i + b_j = 0,\ b_k = 0$	$L_i - L_j$

Yukawa interactions

$$\mathbf{Y}_u\, \overline{q_L} u_R \widetilde{H} + \mathbf{Y}_d\, \overline{q_L} d_R H + \mathbf{Y}_e\, \overline{\ell_L} e_R H + \mathbf{Y}_\nu\, \overline{\ell_L} \nu_R \widetilde{H}$$
$$+ \frac{1}{2}\mathbf{m}_R \nu_R^T C \nu_R + \mathbf{Y}_1\, \nu_R^T C \nu_R S + \mathbf{Y}_2\, \nu_R^T C \nu_R S^*$$
$$+ \frac{1}{2}\mathbf{m}_\Sigma \mathrm{Tr}\left(\Sigma^T C\, \Sigma\right) + \mathbf{Y}_T\, \overline{\ell_L} i\tau_2 \Sigma\, H$$
$$+ \mathbf{Y}_3\, \mathrm{Tr}\left(\Sigma^T C\, \Sigma\right) S + \mathbf{Y}_4\, \mathrm{Tr}\left(\Sigma^T C\, \Sigma\right) S^* + \text{H.c.}$$

Seesaw type-I and type-II

$$\mathbf{m}_\nu \simeq -\mathbf{m}_D\, \mathbf{M}_R^{-1}\, \mathbf{m}_D^T - \mathbf{m}_T\, \mathbf{M}_\Sigma^{-1}\, \mathbf{m}_T^T$$

where

$$\mathbf{m}_D = \mathbf{Y}_\nu \langle H \rangle, \quad \mathbf{M}_R = \mathbf{m}_R + 2\mathbf{Y}_1 \langle S \rangle + 2\mathbf{Y}_2 \langle S^* \rangle$$
$$\mathbf{m}_T = \mathbf{Y}_T \langle H \rangle, \quad \mathbf{M}_\Sigma = \mathbf{m}_\Sigma + 2\mathbf{Y}_3 \langle S \rangle + 2\mathbf{Y}_4 \langle S^* \rangle$$

Neutrino two-zero textures

[Frampton, Glashow, Marfatia]

$$\mathbf{A}_1 : \begin{pmatrix} 0 & 0 & * \\ 0 & * & * \\ * & * & * \end{pmatrix} \quad \mathbf{A}_2 : \begin{pmatrix} 0 & * & 0 \\ * & * & * \\ 0 & * & * \end{pmatrix} \quad \mathbf{D}_1 : \begin{pmatrix} * & * & * \\ * & 0 & 0 \\ * & 0 & * \end{pmatrix} \quad \mathbf{D}_2 : \begin{pmatrix} * & * & * \\ * & * & 0 \\ * & 0 & 0 \end{pmatrix}$$

$$\mathbf{B}_1 : \begin{pmatrix} * & * & 0 \\ * & 0 & * \\ 0 & * & * \end{pmatrix} \quad \mathbf{B}_2 : \begin{pmatrix} * & 0 & * \\ 0 & * & * \\ * & * & 0 \end{pmatrix} \quad \mathbf{E}_1 : \begin{pmatrix} 0 & * & * \\ * & 0 & * \\ * & * & * \end{pmatrix} \quad \mathbf{E}_2 : \begin{pmatrix} 0 & * & * \\ * & * & * \\ * & * & 0 \end{pmatrix}$$

$$\mathbf{B}_3 : \begin{pmatrix} * & 0 & * \\ 0 & 0 & * \\ * & * & * \end{pmatrix} \quad \mathbf{B}_4 : \begin{pmatrix} * & * & 0 \\ * & * & * \\ 0 & * & 0 \end{pmatrix} \quad \mathbf{E}_3 : \begin{pmatrix} 0 & * & * \\ * & * & 0 \\ * & 0 & * \end{pmatrix} \quad \mathbf{F}_1 : \begin{pmatrix} * & 0 & 0 \\ 0 & * & * \\ 0 & * & * \end{pmatrix}$$

$$\mathbf{C} : \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix} \quad \mathbf{F}_2 : \begin{pmatrix} * & 0 & * \\ 0 & * & 0 \\ * & 0 & * \end{pmatrix} \quad \mathbf{F}_3 : \begin{pmatrix} * & * & 0 \\ * & * & 0 \\ 0 & 0 & * \end{pmatrix}$$

$$\mathcal{P}_1 \equiv (\mathbf{A}_1, \mathbf{A}_2, \mathbf{B}_3, \mathbf{B}_4, \mathbf{D}_1, \mathbf{D}_2),$$
$$\mathcal{P}_2 \equiv (\mathbf{B}_1, \mathbf{B}_2, \mathbf{E}_3),$$
$$\mathcal{P}_3 \equiv (\mathbf{C}, \mathbf{E}_1, \mathbf{E}_2),$$
$$\mathcal{P}_4 \equiv (\mathbf{F}_1, \mathbf{F}_2, \mathbf{F}_3).$$

Two-zero textures compatible with data

$$A_1 : \begin{pmatrix} 0 & 0 & * \\ 0 & * & * \\ * & * & * \end{pmatrix} \quad A_2 : \begin{pmatrix} 0 & * & 0 \\ * & * & * \\ 0 & * & * \end{pmatrix}$$

$$B_1 : \begin{pmatrix} * & * & 0 \\ * & 0 & * \\ 0 & * & * \end{pmatrix} \quad B_2 : \begin{pmatrix} * & 0 & * \\ 0 & * & * \\ * & * & 0 \end{pmatrix}$$

$$B_3 : \begin{pmatrix} * & 0 & * \\ 0 & 0 & * \\ * & * & * \end{pmatrix} \quad B_4 : \begin{pmatrix} * & * & 0 \\ * & * & * \\ 0 & * & 0 \end{pmatrix}$$

$$C : \begin{pmatrix} * & * & * \\ * & 0 & * \\ * & * & 0 \end{pmatrix}$$

[Frampton, Glashow, Marfatia
Z.-z. Xing
W. Grimus, Ludl
Ludl, S. Morisi, E. Peinado
Meloni, Blankenburg
Frigerio, Villanova del Moral
Fritzsch, Xing, Zhou]

- m_ℓ is diagonal with proper ordering
- This textures are viable and imply correlations among the data

Viable type I (type III) two-zero textures

- ★ Case: $n_R = 3$ $(n_\Sigma = 3)$ with $\mathbf{m}_D$ $(\mathbf{m}_T)$ diagonal
- ★ All cases belong to the permutation set $\mathcal{P}_1$

$\mathbf{M}_{R,\Sigma}$	$\mathbf{D}_2$ $\begin{pmatrix} 0 & * & * \\ * & * & 0 \\ * & 0 & 0 \end{pmatrix}$	$\mathbf{B}_4$ $\begin{pmatrix} * & * & 0 \\ * & 0 & * \\ 0 & * & 0 \end{pmatrix}$
$\mathbf{m}_\nu$	$\mathbf{A}_1$	$\mathbf{A}_2$

$\mathbf{M}_{R,\Sigma}$	$\mathbf{B}_4$ $\begin{pmatrix} * & * & 0 \\ * & 0 & * \\ 0 & * & 0 \end{pmatrix}$	$\mathbf{B}_3$ $\begin{pmatrix} * & 0 & * \\ 0 & 0 & * \\ * & * & 0 \end{pmatrix}$
$\mathbf{m}_\nu$	$\mathbf{B}_3$	$\mathbf{B}_4$

★ Case: $n_R = 3$ ($n_\Sigma = 3$) with $\mathbf{m}_D$ ($\mathbf{m}_T$) non-diagonal

★ All cases belong to the permutation set $\mathcal{P}_1$

$\mathbf{m}_{D,T}$	$\mathbf{M}_{R,\Sigma}$	$\mathbf{m}_\nu$
$\mathbf{A}_1$	$\mathbf{A}_1$ $\begin{pmatrix} 0 & 0 & * \\ 0 & * & 0 \\ * & 0 & * \end{pmatrix}$ $\begin{pmatrix} 0 & 0 & * \\ 0 & * & * \\ * & * & 0 \end{pmatrix}$ $\begin{pmatrix} 0 & 0 & * \\ 0 & * & 0 \\ * & 0 & 0 \end{pmatrix}$	$\mathbf{A}_1$
$\mathbf{A}_2$	$\mathbf{A}_2$ $\begin{pmatrix} 0 & * & 0 \\ * & 0 & * \\ 0 & * & * \end{pmatrix}$ $\begin{pmatrix} 0 & * & 0 \\ * & * & 0 \\ 0 & 0 & * \end{pmatrix}$ $\begin{pmatrix} 0 & * & 0 \\ * & 0 & 0 \\ 0 & 0 & * \end{pmatrix}$	$\mathbf{A}_2$
$\mathbf{B}_3$	$\mathbf{B}_3$ $\begin{pmatrix} * & 0 & 0 \\ 0 & 0 & * \\ 0 & * & * \end{pmatrix}$ $\begin{pmatrix} * & 0 & * \\ 0 & 0 & * \\ * & * & 0 \end{pmatrix}$ $\begin{pmatrix} * & 0 & 0 \\ 0 & 0 & * \\ 0 & * & 0 \end{pmatrix}$	$\mathbf{B}_3$
$\mathbf{B}_4$	$\mathbf{B}_4$ $\begin{pmatrix} * & 0 & 0 \\ 0 & * & * \\ 0 & * & 0 \end{pmatrix}$ $\begin{pmatrix} * & * & 0 \\ * & 0 & * \\ 0 & * & 0 \end{pmatrix}$ $\begin{pmatrix} * & 0 & 0 \\ 0 & 0 & * \\ 0 & * & 0 \end{pmatrix}$	$\mathbf{B}_4$

★ The cases with $n_R = 2$ $(n_\Sigma = 2)$ and $n_R = 3$ $(n_\Sigma = 3)$

$\mathbf{m}_{D,T}$	$\mathbf{M}_{R,\Sigma}$	$\mathbf{m}_\nu$
$\begin{pmatrix} \ast & \ast \\ 0 & \ast \\ \ast & 0 \end{pmatrix}$ $\begin{pmatrix} \ast & \ast \\ \ast & 0 \\ 0 & \ast \end{pmatrix}$	$\begin{pmatrix} 0 & \ast \\ \ast & 0 \end{pmatrix}$	$\mathbf{C}$ with $\det \mathbf{C} = 0$
$\begin{pmatrix} \ast & \ast & \ast \\ 0 & 0 & \ast \\ \ast & 0 & 0 \end{pmatrix}$ $\begin{pmatrix} \ast & \ast & \ast \\ \ast & 0 & 0 \\ 0 & 0 & \ast \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & \ast \\ 0 & \ast & 0 \\ \ast & 0 & 0 \end{pmatrix}$	
$\begin{pmatrix} \ast & \ast & \ast \\ 0 & \ast & 0 \\ \ast & 0 & 0 \end{pmatrix}$ $\begin{pmatrix} \ast & \ast & \ast \\ \ast & 0 & 0 \\ 0 & \ast & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \ast & 0 \\ \ast & 0 & 0 \\ 0 & 0 & \ast \end{pmatrix}$	$\mathbf{C}$
$\begin{pmatrix} \ast & \ast & \ast \\ 0 & 0 & \ast \\ 0 & \ast & 0 \end{pmatrix}$ $\begin{pmatrix} \ast & \ast & \ast \\ 0 & \ast & 0 \\ 0 & 0 & \ast \end{pmatrix}$	$\begin{pmatrix} \ast & 0 & 0 \\ 0 & 0 & \ast \\ 0 & \ast & 0 \end{pmatrix}$	

★ The cases of type I/III mixed seesaw with $n_R = n_\Sigma = 2$

★ $\mathbf{m}_D$ and $\mathbf{m}_T$ contain the maximum 4 zeroes elements

$\mathbf{m}_D$	$\mathbf{M}_R$	$\mathbf{m}_T, \mathbf{M}_\Sigma$	$\mathbf{m}_\nu$
$\begin{pmatrix} 0 & 0 \\ 0 & \ast \\ \ast & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \ast \\ \ast & \ast \end{pmatrix}$	$\begin{pmatrix} 0 & \ast \\ \ast & 0 \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} \ast & \ast \\ \ast & 0 \end{pmatrix}$ or $\begin{pmatrix} \ast & 0 \\ 0 & \ast \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & \ast \\ \ast & \ast \end{pmatrix}$	$\mathbf{B}_1$
$\begin{pmatrix} 0 & 0 \\ \ast & 0 \\ 0 & \ast \end{pmatrix}$	$\begin{pmatrix} \ast & \ast \\ \ast & 0 \end{pmatrix}$		
$\begin{pmatrix} 0 & 0 \\ 0 & \ast \\ \ast & 0 \end{pmatrix}$	$\begin{pmatrix} \ast & \ast \\ \ast & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \ast \\ 0 & 0 \\ \ast & 0 \end{pmatrix}, \begin{pmatrix} \ast & \ast \\ \ast & 0 \end{pmatrix}$ or $\begin{pmatrix} \ast & 0 \\ 0 & 0 \\ 0 & \ast \end{pmatrix}, \begin{pmatrix} 0 & \ast \\ \ast & \ast \end{pmatrix}$	$\mathbf{B}_2$
$\begin{pmatrix} 0 & 0 \\ \ast & 0 \\ 0 & \ast \end{pmatrix}$	$\begin{pmatrix} 0 & \ast \\ \ast & \ast \end{pmatrix}$		

Anomaly-free and viable two-zero textures

Symmetry generator X	$\lvert x_s \rvert$	$\mathbf{M}_R$	$\mathbf{m}_\nu$
$B + L_e - L_\mu - 3L_\tau$	2	$\mathbf{D}_2$	$\mathbf{A}_1$
$B + 3L_e - L_\mu - 5L_\tau$	2	$(\mathbf{M}_R)_{11} = (\mathbf{M}_R)_{23} = (\mathbf{M}_R)_{33} = 0$	
$B + 3L_e - 6L_\tau$	3		
$B + 9L_e - 3L_\mu - 9L_\tau$	6		
$B + L_e - 3L_\mu - L_\tau$	2	$\mathbf{D}_1$	$\mathbf{A}_2$
$B + 3L_e - 5L_\mu - L_\tau$	2	$(\mathbf{M}_R)_{11} = (\mathbf{M}_R)_{22} = (\mathbf{M}_R)_{23} = 0$	
$B + 3L_e - 6L_\mu$	3		
$B + 9L_e - 9L_\mu - 3L_\tau$	6		
$B - L_e + L_\mu - 3L_\tau$	2	$\mathbf{B}_4$	$\mathbf{B}_3$
$B - L_e + 3L_\mu - 5L_\tau$	2	$(\mathbf{M}_R)_{13} = (\mathbf{M}_R)_{22} = (\mathbf{M}_R)_{33} = 0$	
$B + 3L_\mu - 6L_\tau$	3		
$B - 3L_e + 9L_\mu - 9L_\tau$	6		
$B - L_e - 3L_\mu + L_\tau$	2	$\mathbf{B}_3$	$\mathbf{B}_4$
$B - L_e - 5L_\mu + 3L_\tau$	2	$(\mathbf{M}_R)_{12} = (\mathbf{M}_R)_{22} = (\mathbf{M}_R)_{33} = 0$	
$B - 6L_\mu + 3L_\tau$	3		
$B - 3L_e - 9L_\mu + 9L_\tau$	6		

For a mixed type I/III seesaw scenario with $n_R = 3$ and $n_\Sigma = 1$ only the solutions with $\lvert x_s \rvert = 3$ remain viable

Phenomenology

★ Minimal scalar content: a doublet H and a complex singlet S :

$$V = -\, m^2\, H^\dagger H + \lambda (H^\dagger H)^2 - m_S^2\, S^\dagger S + \lambda_S\, (S^\dagger S)^2 + \beta\, (S^\dagger S)(H^\dagger H)$$

★ Spontaneous breaking of the gauge group ($v \simeq 246$ GeV)

$$H = \begin{pmatrix} 0 \\ \dfrac{h+v}{\sqrt{2}} \end{pmatrix} \qquad S = \frac{s + v_S}{\sqrt{2}}$$

with $m^2 > 0$ and $m_S^2 > 0$

★ For V to be positive-definitive $\lambda, \lambda_S > 0$ and $\beta^2 < 4\lambda\lambda_S$

★ Massive gauge bosons: $W^\pm$, Z and Z'

★ The massive h and s mixes (limit $v_S \gg v$ and $\lambda_S v_S^2 \gg \lambda v^2$)

$$m_1^2 \simeq 2\left(\lambda - \frac{\beta^2}{4\lambda_S}\right) v^2 \quad m_2^2 \simeq 2\lambda_S\, v_S^2 \quad \theta \simeq \frac{\beta v}{2\lambda_S v_S}$$

- ★ The mass of the new Z' gauge boson

$$m_{Z'} = |x_s|\, g_X v_S$$

- ★ An indirect constraint on $m_{Z'}$ from analyses of LEP2 precision electroweak data:

$$\frac{m_{Z'}}{g_X} = |x_s|\, v_S \gtrsim 13.5\ \text{TeV}$$

- ★ Depending on the charge x_s, different lower bounds on the breaking scale of the $U(1)_X$ gauge symmetry are obtained are

$$|x_s| = 2,\ 3,\ 6 \quad \Longrightarrow \quad v_S \gtrsim 6.75\ \text{TeV}, 4.5\ \text{TeV}, 2.25\ \text{TeV}$$

- ★ To put limits on the $m_{Z'}$ the gauge coupling strength must be known

$$g_X \sim 0.1 \quad \Longrightarrow \quad m_{Z'} \gtrsim 1.4\ \text{TeV}$$

- ★ Could be probed through the search of dilepton Z' resonances at the final stage of the LHC, $\sqrt{s} = 14$ TeV TeV and $L \simeq 100\ \text{fb}^{-1}$
- ★ pp collisions (ATLAS and CMS) at $\sqrt{s} = 8$ TeV and integrated luminosity of about $20\,\text{fb}^{-1}$ requires $m_{Z'} > 3$ TeV

Non Standard Interactions

[Wolfenstein]

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\, G_F\, \varepsilon^{fP}_{\alpha\beta}\, (\bar{\nu}_\alpha \gamma_\mu L \nu_\beta)(\bar{f}\gamma^\mu P f)$$

- ★ The dimensionless couplings $\varepsilon^{fP}_{\alpha\beta}$ encode the deviations from SI
- ★ If NSI are mediated by intermediate particles: $m_{\rm NSI} \sim 1\,(10)$ TeV

$$|\varepsilon| \sim m_W^2 / m_{\rm NSI}^2 \implies |\varepsilon| \sim 10^{-2}\,(10^{-4})$$

- ★ For the extra $U(1)_X$ model one has

$$\varepsilon^{fP}_{\alpha\beta} = \frac{v^2}{2\,v_S^2}\frac{x_f\, x_{\nu_\alpha}}{x_s^2}\,\delta_{\alpha\beta}$$

- ★ Model-independent bounds [Ohlsson]

$$|\varepsilon^{\oplus}_{ee}| < 4.2\; |\varepsilon^{\oplus}_{\mu\mu}| < 0.068\; |\varepsilon^{\oplus}_{\tau\tau}| < 21.0$$

$$|\varepsilon^{\odot}_{ee}| < 2.5\; |\varepsilon^{\odot}_{\mu\mu}| < 0.046\; |\varepsilon^{\odot}_{\tau\tau}| < 9.0$$

Non Standard Interactions

Lower bounds: breaking scale v_S, Earth-like ($v_S^{\oplus}$) and solar-like ($v_S^{\odot}$) matter

(x_e, x_μ, x_τ)	$\lvert x_s \rvert$	$v_S^{\oplus}$ [GeV]	$v_S^{\odot}$ [GeV]
$(1, -1, -3)$	2	522	539
$(3, -1, -5)$	2	723	849
$(3, 0, -6)$	3	106	133
$(9, -3, -9)$	6	692	837
$(1, -3, -1)$	2	905	934
$(3, -5, -1)$	2	1617	1898
$(3, -6, 0)$	3	1181	1386
$(9, -9, -3)$	6	1198	1451
$(-1, 1, -3)$	2	522	539
$(-1, 3, -5)$	2	905	934
$(0, 3, -6)$	3	545	481
$(-3, 9, -9)$	6	723	849
$(-1, -3, 1)$	2	905	934
$(-1, -5, 3)$	2	1168	1205
$(0, -6, 3)$	3	771	680
$(-3, -9, 9)$	6	723	849

Branching Ratio Plane

[Diener, Godfrey, Martin]

★ Flavour model discrimination

$$\Gamma(Z' \to f\bar{f}) \simeq \frac{g_X^2}{24\pi} m_{Z'} \left(x_{fL}^2 + x_{fR}^2 \right),$$

in the limit $m_f << m_{Z'}$

$$R_{b/\mu} = \frac{\sigma(pp \to Z' \to b\,\bar{b})}{\sigma(pp \to Z' \to \mu^+\mu^-)} \simeq \frac{K_b}{3} \frac{a^2}{b_2^2}$$

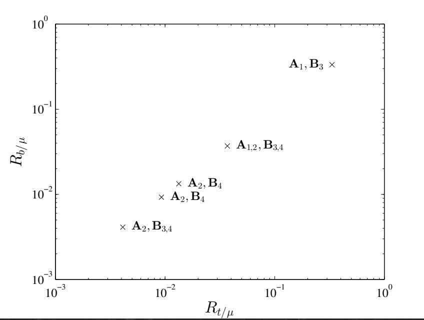
$$R_{t/\mu} = \frac{\sigma(pp \to Z' \to t\,\bar{t})}{\sigma(pp \to Z' \to \mu^+\mu^-)} \simeq \frac{K_t}{3} \frac{a^2}{b_2^2}$$

$$R_{\tau/\mu} = \frac{\sigma(pp \to Z' \to \tau^+\tau^-)}{\sigma(pp \to Z' \to \mu^+\mu^-)} \simeq K_\tau \frac{b_3^2}{b_2^2}$$

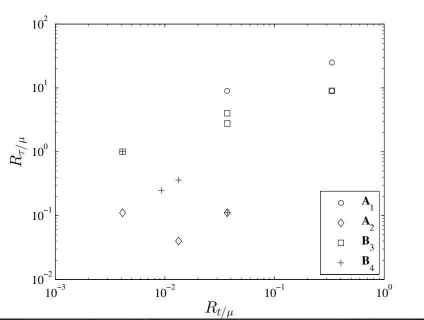
★ $K_{b,t} \sim \mathcal{O}(1)$ factors incorporate the QCD and QED next-to-leading order corrections

Branching Ratio Plane

Leading to neutrino mass matrix patterns of type $\mathbf{A}_{1,2}$ and $\mathbf{B}_{3,4}$



$R_{t/\mu} - R_{b/\mu}$



$R_{t/\mu} - R_{\tau/\mu}$

Conclusions

- ★ Extensions of the SM based on Abelian gauge symmetries $U(1)_X$

$$X \equiv a\,B - \sum_{i=1}^{n_G} b_i L_i$$

- ★ We looked the possible charge assignments that lead to cancellation of gauge anomalies and to a predictive flavor structure for m_ν
- ★ We restricted the charges so charged leptons are diagonal and therefore m_ν is directly linked to low-energy parameter
- ★ We found that only a limited set of solutions are viable, leading to two-zero textures of the neutrino mass matrix with a minimal extra fermion and scalar content
- ★ All allowed patterns were obtained in the framework of the type I seesaw mechanism with three right-handed neutrinos (or in a mixed type I/III seesaw framework with three right-handed neutrinos and one fermion triplet), extending the SM scalar sector with a complex scalar singlet field