Mirror fermions, electroweak scale right-handed neutrinos and experimental implications

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Plan of Talk

- The question of parity restoration at high energies: Gauge Left-Right symmetric model vs SM with mirror fermions.

- Contrasts between these two points of view concerning the Seesaw Mechanism.

- Implications of mirror fermions: Right-handed neutrino masses, M_R, can be of the order of the electroweak scale $\Lambda_{EW} = 246\,GeV$, i.e. $M_Z/2 < M_R < \Lambda_{EW}$.

- Experimental implications of electroweak scale mirror fermions: Lepton-number violating processes at electroweak scale energies; production ν_R's at colliders and their decays into like-sign dileptons, Lepton Flavour Violating (LFV) processes such as $\mu \rightarrow e\,\gamma$, $\tau \rightarrow \mu\,\gamma$,..

- Conclusions

The question of parity restoration at high energies

- Parity is violated at "low energies". Well described by the SM $SU(2)_L \otimes U(1)_Y$. All left-handed fermions are doublets under $SU(2)_L \otimes U(1)_Y$. There are no right-handed neutrinos in the minimal SM.

  Is parity violation an intrinsic feature of nature or is it just an effect at low energies?

- If it is an effect at low energies, one might expect parity restoration at high energies. How and how high?

- Most popular model for this purpose: The gauge left-right symmetric model $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ (Mohapatra and Senjanovic). Here parity violation is manifest at low energies because the mass of the $SU(2)_L$ gauge bosons M_{W_L} is much less than the mass of the $SU(2)_R$ gauge bosons, M_{W_R}. Parity is restored for $E \gg M_{W_R} \gg M_{W_L}$. $\Rightarrow$ Implications concerning neutrino masses.

- Alternative viewpoint: The gauge group is still the SM $SU(2)_L \otimes U(1)_Y$. But now for every left-handed doublet we have a right-handed doublet, for every right-handed singlet, we have a left-handed singlet

  $\Rightarrow$ Mirror Fermions

Here parity violation is manifest at low energies because the mass of the mirror fermions will be assumed to be larger than that of their SM counterparts. Parity is restored for $E \gg M_{mirror} > M_{SM}$. $\Rightarrow$ Different implications concerning neutrino masses!

- Punchlines:

  Gauge L-R symmetric model and its GUT extensions e.g. $SO(10)$: Majorana mass of right-handed neutrinos are much larger than the electroweak scale in general.

  SM with mirror fermions: Majorana mass of right-handed neutrinos are of the order of the electroweak scale.

  $\Rightarrow$ Huge implications concerning the test of the see-saw mechanism and the Majorana nature of neutrinos!

Mirror fermions and Electroweak scale ν_R's

(hep-ph/0612004, P.L.B**649**, 275 (2007))

- This is the SM with Mirror Fermions. Mirror: same meaning as in the previous slides.

- Mirror Fermions cannot be much heavier than the electroweak scale.

- ν_R's are now not sterile i.e. non-singlet under $SU(2)_L \otimes U(1)_Y$, and can have a "low" mass of O(Λ_{EW}).

Constraints:

- A non-singlet ν_R will couple to the Z boson $\Rightarrow$ Strong constraint from the Z width!

- A Majorana bilinear $\nu_R^T \sigma_2 \nu_R$ will transform non-trivially under $SU(2)_L$ $\Rightarrow$ Strong constraint on the $SU(2)_L$ Higgs field which couples to that bilinear and which develops a non-zero vacuum expectation value, in particular one has to preserve the successful relation $M_W = M_Z \cos\theta_W$ ($\rho = 1$)!

SM with Mirror Fermions

- Gauge group: $SU(2) \otimes U(1)_Y$.

- Leptonic content:

  - $SU(2)_L$ doublets:

    SM: $l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

    Mirror: $l_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}$

    (Notice this is different from $l_R^c = i\sigma_2 l_L^*$)

    $e_R^M \neq e_R$ because neutral current experiments force e_R to be an $SU(2)_L$ singlet.

  - $SU(2)_L$ singlets:

SM: e_R

Mirror: e_L^M

- In addition to heavy mirror leptons, the model also contains heavy mirror quarks. It is amusing to note that anomaly cancellation can be done between SM fermions and their mirror counterparts. One does not need the usual cancellation between quarks and leptons. Charge quantization: sign of GUT?

- Also the requirement of the vanishing of the non-perturbative Witten anomaly for $SU(2)_L \Rightarrow$ Even number of doublets can be accomplished with just leptons or just quarks!

Mass terms for neutrinos: (other charged fermions receive masses by coupling to the SM Higgs doublet.)

- Lepton-number conserving Dirac mass:

  $\mathcal{L}_S = g_{Sl}\,\bar{l}_L\,\phi_S\,l_R^M + g'_{Sl}\,\bar{l}_L^M\,\phi_S\,l_R + H.c.$

  $\langle\phi_S\rangle = v_S \Rightarrow m_D = g_{Sl}\,v_S \Rightarrow$ Unrelated to the electroweak scale i.e. does not break the SM.

- Lepton-number violating Majorana mass:

  The relevant bilinear is $l_R^{M,T}\,\sigma_2 l_R^M$. This cannot couple to a singlet Higgs field since its VEV would break charge conservation $\Rightarrow$ Only option: an $SU(2)_L$ triplet Higgs $\tilde{\chi} = (3, Y/2 = 1)$.

$$\tilde{\chi} = \frac{1}{\sqrt{2}} \vec{\tau} . \vec{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}} \chi^+ & \chi^{++} \\ \chi^0 & -\frac{1}{\sqrt{2}} \chi^+ \end{pmatrix}$$

$$\Rightarrow \mathcal{L}_M = g_M \, l_R^{M,T} \, \sigma_2 \, \tau_2 \, \tilde{\chi} \, l_R^M$$

$$\langle \chi^0 \rangle = v_M \Rightarrow M_R = g_M \, v_M$$

Although a $U(1)_M$ global symmetry is imposed to avoid a Majorana mass term for the L-H neutrinos at the lowest order, it is not necessary and other options are possible.

This VEV also breaks $SU(2)_L$!

The successful relation $M_W = M_Z \cos \theta_W$ ($\rho = 1$) which relies primarily on $SU(2)_L$ Higgs fields being doublets would be spoiled unless $v_M \ll \Lambda_{EW}$. Trouble!! The Z-width constraint requires $M_R > M_Z/2$.

With just $\tilde{\chi}$, $\rho = 1/2$. ρ can be significantly different from 1 at tree-level when both doublet and triplet with comparable V.E.V's are present!

Elegant solution (Chanowitz and Golden, Georgi and Machacek):

$\rho \approx 1$ is a manifestation of an approximate custodial global $SU(2)$ symmetry of the Higgs potential. (Recall: In the SM with Higgs doublets, the W mass term is $\frac{1}{2}M_W^2 \vec{W}_\mu \vec{W}^\mu$ with $M_W^2 = \frac{1}{4}g^2v^2$, reflecting that custodial symmetry.) To maintain that custodial symmetry, one can add an additional Higgs triplet $\xi = (3, Y/2 = 0)$ which can be grouped with $\tilde{\chi} = (3, Y/2 = 1)$ to form

$$\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}$$

$\Rightarrow$ Global $SU(2)_L \otimes SU(2)_R$ symmetry of the Higgs potential with χ being $(3,3)$ of that global symmetry. The complex Higgs doublet belong to a $(2,2)$ representation: $\Phi = \begin{pmatrix} \phi^0 & -\phi^+ \\ \phi^- & \phi^{0,*} \end{pmatrix}$

With

$$\langle \chi \rangle = \begin{pmatrix} v_M & 0 & 0 \\ 0 & v_M & 0 \\ 0 & 0 & v_M \end{pmatrix}$$

and

$$\langle \Phi \rangle = \begin{pmatrix} v_2 & 0 \\ 0 & v_2 \end{pmatrix}$$

breaking global $SU(2)_L \otimes SU(2)_R$ down to a custodial $SU(2)$ symmetry with $M_W = g\, v/2$ and $M_Z = M_W/\cos\theta_W$, where $v = \sqrt{v_2^2 + 8\, v_M^2} \approx 246\, GeV$.

$\Rightarrow$ $\rho = 1$ even if $v_M \sim O(\Lambda_{EW})$!!

$\Rightarrow$ $M_R \sim O(\Lambda_{EW})$!

Two questions:

- How low can M_R be?

  Answer: $M_Z/2$ from the constraint of the Z width.

  $\Rightarrow$ $M_Z/2 < M_R < O(\Lambda_{EW})$

A rather "narrow" range!

- What about m_D or rather the VEV v_S of the singlet Higgs field?

  Answer: With the light neutrino mass $m_\nu \leq 1\, eV$ and $M_R \sim O(\Lambda_{EW}) \Rightarrow m_D \sim 10^5\, eV \Rightarrow v_S \sim 10^5\, eV$ if we assume $g_{Sl} \sim O(1)$ or e.g. $v_S \sim 10^8\, eV$ if $g_{Sl} \sim 10^{-3}$.

  (Possible cosmological implications of a singlet scalar field e.g. the possibility of of the link between Mass-Varying Neutrinos (MaVans) and Dark Energy: Hung; Gu, Wang and Zhang; Fardon, Nelson and Weiner. Also, constraints from CMB? Other astrophysical implications?)

Implications at colliders

Majorana neutrinos with electroweak scale masses $\Rightarrow$ lepton-number violating processes at electroweak scale energies. (For singlet ν_R's, the issue is much more complex, involving delicate cancellations to keep the light neutrinos light (Kersten and Smirnov).)

In particular, we should be able to produce ν_R's and observe their decays at colliders (LHC, etc...) $\Rightarrow$ Characteristic signatures: like-sign dilepton events $\Rightarrow$ A high-energy equivalent of neutrinoless double beta decay. (This was discussed in the context of L-R model by Keung and Senjanovic (83).) That could be the smoking gun for Majorana neutrinos! Another interesting model with electroweak scale lepton triplet with zero hypercharge was proposed by Bajc and Senjanovic (Type III see-saw).

- From $l_R^M = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}$, ν_R's interact with the Z and W bosons at tree level!

  Recall $M_Z/2 < M_R < \Lambda_{EW}$.

- Production of ν_R's:

  $q + \bar{q} \rightarrow \text{Z} \rightarrow \nu_R + \nu_R$

  and e.g.

$u + \bar{d} \rightarrow W^+ \rightarrow \nu_R + l_R^{M,+}$

Production cross section: $\sigma \approx 400\, fb$ at LHC for $M_R \sim 100\, GeV \Rightarrow N = L\,\sigma \approx 60000\, events/year$ with maximal luminosity $L = 10^{34}\, cm^{-2}\, s^{-1}$.

– ν_R's are Majorana and can have transitions $\nu_R \rightarrow l_R^{M,\mp} + W^{\pm}$.

– A heavier ν_R can decay into a lighter l_R^M and

  * $\nu_R + \nu_R \rightarrow l_R^{M,\mp} + l_R^{M,\mp} + W^{\pm} + W^{\pm} \rightarrow l_L^{\mp} + l_L^{\mp} + W^{\pm} + W^{\pm} + \phi_S + \phi_S$, where ϕ_S would be missing energy.

  * $\nu_R + l_R^{M,+} \rightarrow l_R^{M,+} + l_R^{M,+} + W^- \rightarrow l_L^+ + l_L^+ + W^- + \phi_S + \phi_S$.

  Interesting like-sign dilepton events! One can look for like-sign dimuons for example.

Since this involves missing energies $\Rightarrow$ Careful with background! For example one of such backgound could be a production of $W^{\pm}W^{\pm}W^{\mp}W^{\mp}$ with 2 like-sign W's decaying into a charged lepton plus a neutrino ("missing energy").

But...This is of O(α_W^2) in amplitude smaller than the above process. Another background: $H+W \rightarrow WWW$. In addition, depending on the lifetime of the mirror leptons, the SM leptons appear at a displaced vertex.

- Lepton-number violating process with like-sign dileptons can also occur with ν_R's in the intermediate state (from $W^{\pm}W^{\pm} \rightarrow l_L^{\pm}+l_L^{\pm}$) but that involves very small mixing angles of the order $\frac{m_\nu}{M_R}$.

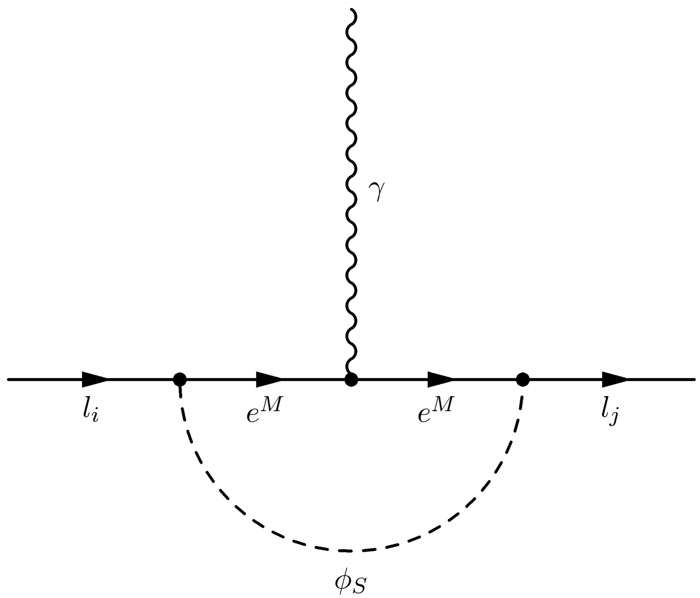
- Detailed phenomenological analyses are in preparation: SM background, event reconstructions, etc...

LFV processes: $\mu \to e\,\gamma$, $\tau \to \mu\,\gamma$

(arXiv:0711.0733 [hep-ph], P. L. B. **659**, 585 (2008))

Mixing between SM leptons and Mirror leptons $\Rightarrow$ LFV processes.

For example:



Dominant diagram for $l_i \to l_j + \gamma$

- Lagrangians:
  - Doublet sector:

    $e_L^0 = U_L^l e_L \,;\, e_R^{0,M} = U_R^{l^M} e_R^M$

$$\mathcal{L}_{S,charged} = -(\bar{e}_L\, U^L\, e_R^M)\, \phi_S + H.c.$$

$$U^L = U_L^{l,\dagger}\, g_{Sl}\, U_R^{l^M}$$

- Singlet sector:

$$e_R^0 = U_R^l e_R\, ;\; e_L^{0,M} = U_L^{l^M} e_L^M$$

$$\mathcal{L}_S' = -(\bar{e}_R\, U^R\, e_L^M)\, \phi_S + H.c.$$

$$U^R = U_R^{l,\dagger}\, g_{Sl}'\, U_L^{l^M}$$

- Connection with the (Dirac) neutrino mass matrix:

$$m_\nu^D = v_S\, g_{Sl}$$

$$\frac{m_\nu^D}{v_S} = U_L^l\, U^L\, U_R^{l^M,\dagger}$$

If $g_{Sl}' = g_{Sl}$:

$$\frac{m_\nu^D}{v_S} = U_R^l\, U^R\, U_L^{l^M,\dagger}$$

⇒ Deep connection between the Dirac part of the neutrino mass matrix, m_ν^D. and the matrices which are involved in LFV processes in our model, namely U^L and U^R.

- The processes $\mu \to e\,\gamma$ and $\tau \to \mu\,\gamma$:
  - Amplitude:

$$T(l_i \to l_j\,\gamma) \;=\; \epsilon^\lambda \bar{u}_{l_j}(p-q)\{i\,q^\nu\,\sigma_{\lambda\nu}\,[c_L^{(l_i)}(\frac{1-\gamma_5}{2}) \\ +c_R^{(l_i)}(\frac{1+\gamma_5}{2})]\}u_{l_i}(p)\,.$$

  - Decay rate:

$$\Gamma(l_i \to l_j\,\gamma) = \frac{m_{l_i}^3}{16\,\pi}(|c_L^{(l_i)} + c_R^{(l_i)}|^2 + |c_L^{(l_i)} - c_R^{(l_i)}|^2)$$

– Branching ratios:

$$\begin{aligned} B(\mu \to e\,\gamma) &= \frac{\Gamma(\mu \to e\,\gamma)}{\Gamma(\mu \to e\bar{\nu}_e\nu_\mu)} \\ &= \frac{12\pi^2}{m_\mu^2 G_F^2}(|c_L^{(\mu)} + c_R^{(\mu)}|^2 + |c_L^{(\mu)} - c_R^{(\mu)}|^2)\,. \end{aligned}$$

$$\begin{aligned} \frac{B(\tau \to \mu\,\gamma)}{B(\tau \to \mu\bar{\nu}_\mu\nu_\tau)} &= \frac{\Gamma(\tau \to \mu\,\gamma)}{\Gamma(\tau \to \mu\bar{\nu}_\mu\nu_\tau)} \\ &= \frac{12\pi^2}{m_\tau^2 G_F^2}(|c_L^{(\tau)} + c_R^{(\tau)}|^2 + |c_L^{(\tau)} - c_R^{(\tau)}|^2)\,. \end{aligned}$$

– $c_L^{(\mu)}$, $c_R^{(\mu)}$, $c_L^{(\tau)}$ and $c_R^{(\tau)}$ at one loop:

$c_L^{(\mu)} = \frac{1}{64\,\pi^2} \sum_i \frac{U_{i\mu}^{R*}\, U_{ei}^{L}}{m_i}$; $c_R^{(\mu)} = \frac{1}{64\,\pi^2} \sum_i \frac{U_{i\mu}^{L*}\, U_{ei}^{R}}{m_i}$

$c_L^{(\tau)} = \frac{1}{64\,\pi^2} \sum_i \frac{U_{i\tau}^{R*}\, U_{\mu i}^{L}}{m_i}$; $c_R^{(\tau)} = \frac{1}{64\,\pi^2} \sum_i \frac{U_{i\tau}^{L*}\, U_{\mu i}^{R}}{m_i}$

m_i: masses of mirror charged leptons.

To gain(?) some insights, go to some special cases.

- Special cases:

$g_{Sl} = g'_{Sl}$, $U_L^l = U_R^l$ and $U_R^{l^M} = U_L^{l^M}$.

$\Rightarrow U^L = U^R = U^E$

$\Rightarrow$

$c_L^{(\mu)} = c_R^{(\mu)} = \frac{1}{64\,\pi^2} \frac{1}{m_E} \sum_i (\frac{m_E}{m_i})(U_{i\mu}^{E*}\, U_{ei}^{E})$,

$$c_L^{(\tau)} = c_R^{(\tau)} = \frac{1}{64\,\pi^2}\frac{1}{m_E}\sum_i (\frac{m_E}{m_i})(U_{i\tau}^{E*}\,U_{\mu i}^{E})$$

$$m_i = m_E + \delta m_i.$$

- Matrix elements of $U^E \Rightarrow$ Determination of lifetime and decay length of mirror charged leptons.

- Experimental constraints:

  $B(\tau \to \mu\,\gamma)_{exp} < 6.8 \times 10^{-8}$ (BaBar)

  $B(\tau \to \mu\,\gamma)_{exp} < 4.5 \times 10^{-8}$ (Belle)

  $B(\mu \to e\,\gamma)_{exp} < 1.2 \times 10^{-11}$ (PDG)

- Constraints on mixings:

$$|\sum_i (\frac{m_E}{m_i})(U^{E*}_{i\mu} U^E_{ei})|^2 < 1.25 \times 10^{-15}, 5.0 \times 10^{-15}$$

$$|\sum_i (\frac{m_E}{m_i})(U^{E*}_{i\tau} U^E_{\mu i})|^2 < \left\{ \begin{array}{c} 7.1 \\ 4.7 \end{array} \right\} \times 10^{-12}, \left\{ \begin{array}{c} 28.4 \\ 18.8 \end{array} \right\} \times 10^{-12}$$

for $m_E = 100\, GeV$, $200\, GeV$ respectively.

- Depending on U^E, there are several possibilities: both processes are observed, one is observed and not the other; none is observed

  $\Rightarrow$ Implications on lifetime and decay length of mirror charged leptons.

- Some examples with e.g. $m_E = 100\, GeV$:

- Case I: $U^E_{i\,e} \sim \lambda^3\,;\, U^E_{i\,\mu} \sim \lambda^2\,;\, U^E_{i\,\tau} \sim \lambda$

  $\Rightarrow B(\mu \to e\,\gamma) \approx 1.6 \times 10^3\,\lambda^4\,B(\tau \to \mu\,\gamma)$

  $B(\tau \to \mu\,\gamma) \Rightarrow \lambda < 0.009$

  $\Rightarrow B(\mu \to e\,\gamma) < 4 \times 10^{-16}$: Two orders of magnitude below the MEG proposal.

- Case II: $U^E_{i\,e} \sim \lambda^3\,;\, U^E_{i\,\mu} \sim \lambda\,;\, U^E_{i\,\tau} \sim \lambda^2$

  $\Rightarrow B(\mu \to e\,\gamma) \approx 1.6 \times 10^3\,\lambda^2\,B(\tau \to \mu\,\gamma)$

  Again $\lambda < 0.009$

  $\Rightarrow B(\mu \to e\,\gamma) < 5 \times 10^{-12}$: Well within the range of the MEG proposal.

- Case III: $U^E_{i\,e} \sim \lambda\,;\, U^E_{i\,\mu} \sim \lambda^2\,;\, U^E_{i\,\tau} \sim \lambda^3$

$B(\mu \to e\,\gamma) \propto \lambda^6$ and $B(\tau \to \mu\,\gamma) \propto \lambda^{10}$. To satisfy both constraints $\lambda < 0.006$

$\Rightarrow B(\tau \to \mu\,\gamma) < 10^{-25}$: Hopelessly small!

– Summary:

	$\lambda \leq$	$B(\tau \to \mu\,\gamma) \leq$	$B(\mu \to e\,\gamma) \leq$
Case I:	0.009	4.5×10^{-8}	4×10^{-16}
Case II:	0.009	4.5×10^{-8}	5×10^{-12}
Case III:	0.002	1.2×10^{-25}	1.2×10^{-11}

- Connection between LFV processes (low energy) and the decay length of mirror charged lepton (high energy):

  Take Case II just as an example:

$\Gamma(e_3^M \to \mu + \phi_S) \sim m_E \lambda^2/(32\,\pi) \Rightarrow l = 1/\Gamma(e_3^M \to \mu + \phi_S) \sim 2445\, fm$ for $\lambda \sim 0.009$ Microscopic!

In general, in this model, macroscopic decay lengths $\Rightarrow$ tiny $\lambda \Rightarrow$ Unobservable LFV processes.

- Future measurements of LFV processes at MEG and B factories will further test the model. This is linked to the search for electroweak scale right-handed neutrinos.

Conclusions

- A model with mirror fermions can lead to a scenario in which the right-handed neutrinos have electroweak scale masses.

- Lepton-number violating processes, such as like-sign dileptons, coming from electroweak scale SM non-singlet ν_R's can now be accessible experimentally at colliders!

- LFV processes such as $B(\tau \to \mu\,\gamma)$ and $B(\mu \to e\,\gamma)$ which are low energy processes are linked to high energy processes such as the production of electroweak scale right-handed neutrinos and their detections through the decay lengths of charged mirror leptons.

- The scalar sector is much richer than that in the SM $\Rightarrow$ search for doubly-charged Higgs scalars e.g., etc..

Backup slides

- Actually, since $v = \sqrt{v_2^2 + 8\,v_M^2} \sim 246\,GeV$, this can have a quite interesting implication on the form of the quark mass matrices themselves since the top quark mass is $\sim 171\,GeV$ and quarks couple only to the Higgs doublet. In fact, with $v_M > M_Z/2 \sim 46\,GeV$, the scale that appears in front of the Up-quark mass matrix, namely $g_U\,v_2/\sqrt{2}$ is constrained such that, for $g_U \sim O(1)$, $v_2/\sqrt{2} < 147\,GeV$ $\Rightarrow$ the mass matrix of the Up-quark sector might be of the almost democratic type for example. This also would imply that mirror fermions cannot be too heavy.

- Some kind of “see-saw” among the charged leptons and their mirror counterparts as well as in the quark sector. However, the mass eigenvalues are, e.g. the charged leptons:

  $$\tilde{m}_l = m_l - \frac{m_D^2}{m_{lM} - m_l} \sim m_l$$

  $$\tilde{m}_{lM} = m_{lM} - \frac{m_D^2}{m_{lM} - m_l} \sim m_{lM}$$

  because $m_D \ll m_{lM} - m_l \Rightarrow$ Practically impossible to detect SM and mirror mixing among the charged sectors.

- Last but not least: It is possible to avoid the imposition of the $U(1)_M$ global symmetry. The see-saw mechanism will look however very different from the above $\Rightarrow$ Interesting implications concerning the see-saw matrix $\Rightarrow$ Possibility of dynamical electroweak symmetry breaking. Work in preparation.

- Triplet Higgs scalars:
  - Doubly charged scalars in $\tilde{\chi}$!
  - $\tilde{\chi}$ can be produced at colliders.
  - $\tilde{\chi}$ couples to W and Z and to right-handed neutrinos and mirror charged leptons which subsequently decay into SM leptons.
  - ξ does not couple to fermions but to W and Z. Can look for them through W and Z.

- Mirror fermions:

  The charged mirror fermions decay into SM charged fermions plus (missing energy) ϕ_S. The decay length will depend primarily on the coupling g_{Sl}!

- Singlet scalar ϕ_S:

  ϕ_S can be as light as few hundreds keV's. Possible cosmological and astrophysical implications? e.g. $\phi_S + \phi_S^* \rightarrow l^+ + l^-$ with a charged mirror lepton in the t-channel.