The Physics of Electroweak-scale right-handed neutrinos

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- For this, one needs to introduce the concept of *Mirror Fermions*.
- Bottom-up approach: Enlarge the SM one step at a time and see what happens.

Mirror fermions

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- Doublet:

$$l_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \leftrightarrow l_R^M = \begin{pmatrix} \nu_R^M \\ e_R^M \end{pmatrix}_i$$

Singlet:

$e_R \leftrightarrow e_L^M$

Similarly for the quarks.

Mirror fermions:Why?

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- Parity can be restored at high energy above the electroweak scale $\Lambda_{EW} \sim 246\, GeV$ either by enlarging the SM gauge group to e.g. $SU(2)_L \times SU(2)_R \times U(1)$ *or* by introducing mirror fermions.

Mirror fermions:Why?

- In Left-Right models, $l_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \in SU(2)_L$ and $l_R = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_R \in SU(2)_R$

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- With $g_L = g_R$ and at $E \gg M_{W_R} \gg M_{W_L}$, the V-A interactions (exchanges of W_L) have equal strengths as the V+A interactions (exchanges of W_R) $\Rightarrow$ Parity is “restored” in that sense.

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- At $E \gg M_{mirror}$, the W and Z bosons cannot distinguish SM from mirror fermions $\Rightarrow$ $SU(2)_L$ becomes "vector-like" $\Rightarrow$ Parity is "restored" in that sense.

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- The electroweak phase transition (from $\phi^0 = 0$ to $\phi^0 = v/\sqrt{2}$) is essentially a *non-perturbative* phenomenon.
- *Non-perturbative* instanton solution in the SM at high temperature $\Rightarrow$ baryon-number violating sphaleron process. Very relevant to the problem of the baryon asymmetry of the universe!

Mirror fermions:Why?

- The appropriate framework to study *Nonperturbative phenomena* such as the electroweak phase transition (from $\phi^0 = 0$ to $\phi^0 = v/\sqrt{2}$) and related physics ("sphaleron", etc...) is lattice regularization. *Impossible* to put a chiral gauge theory such as $SU(2)_L \times U(1)_Y$ on a lattice! A *gauge-invariant* lattice formulation of the SM is possible if one introduces *mirror fermions* (Montvay, PLB 199, 89 (1987)).

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Mirror fermions:Why?

- The SM, as a chiral theory, contains gauge triangle anomalies which breaks gauge invariance. Renormalizability of the SM $\Rightarrow$ Cancellation of the triangle anomalies. Most typically, one of such cancellations is $\sum_i Q_i = 0$ for each family. For example: $-1 + 3 \times (2/3 - 1/3) = 0$.

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- Non-perturbatively, $SU(2)$ chiral gauge theories such as $SU(2)_L$ suffers the so-called Witten anomaly: the theory is trivial unless the number of doublets is even. SM: 4 per family (one lepton and three color doublets); SM with mirrors: Not a chiral gauge theory $\Rightarrow$ No Witten anomaly.

Mirror fermions $\rightarrow$ EW-scale ν_R

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- $l_R^{M,T} \sigma_2 l_R^M \Rightarrow \nu_R^{M,T} \sigma_2 \nu_R^M$. Notice the transformation under $SU(2)_L$: $\mathbf{2} \times \mathbf{2} = \mathbf{1} + \mathbf{3}$, singlet plus triplet and $Y/2 = -1 \Rightarrow$ Higgs (singlet or triplet) with $Y/2 = 1$.

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

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- $g_M\, l_R^{M,T}\, \sigma_2\, (i\tau_2\, \tilde{\chi})\, l_R^M \Rightarrow g_M(\nu_R^{M,T} \sigma_2\, \nu_R^M)\chi^0$
  $\langle\chi^0\rangle = v_M \Rightarrow$ Right-handed Majorana mass: $M = g_M v_M$!

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- How big can v_M be? Since ν_R^M is a member of a doublet, it interacts with the Z-boson (unlike the singlet case). Value of Z-boson decay width (no more than 3 light neutral fermions) $\Rightarrow M > M_Z/2 \sim 46\,GeV \Rightarrow v_M > 46\,GeV$ assuming $g_M < 1$.

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- v_M breaks $SU(2)_L \times U(1)_Y$! It will *destroy* the relationship $M_W = M_Z \cos\theta_W$ ($\rho = 1$) unless the VEV is very small! (2nd lecture!)

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- What should we do next? What we need: doublet Higgs for charged fermion masses(quarks and leptons) and triplet Higgs for right-handed Majorana neutrino mass.
- Construct the Higgs potential for doublet and triplet Higgses such that there remains a Custodial global $SU(2)$ symmetry after SSB $\Rightarrow \rho = 1$ at tree level!

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- Add $\xi = (3, Y/2 = 0)$ and group it with $\tilde{\chi} = (3, Y/2 = 1)$ in $\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}$

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- Notice the doublet Higgs can be written as $\Phi = \begin{pmatrix} \phi^0 & -\phi^+ \\ \phi^- & \phi^{0,*} \end{pmatrix}$

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- $\Phi \rightarrow U_L \Phi U_R^\dagger$, $\chi \rightarrow U_L\, \chi\, U_R^\dagger$.

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- $SU(2)_L \times SU(2)_R$-invariant potential: $V(\Phi, \chi) = \lambda_1 (Tr\Phi^\dagger\Phi - v_2^2)^2 + \lambda_2 (Tr\chi^\dagger\chi - 3v_M^2)^2 + \lambda_3 (Tr\Phi^\dagger\Phi - v_2^2 + Tr\chi^\dagger\chi - 3v_M^2)^2 + \lambda_4 (Tr\Phi^\dagger\Phi Tr\chi^\dagger\chi - 2Tr\Phi^\dagger T^i \Phi T^j . Tr\chi^\dagger T^i \chi T^j) + \lambda_5 (3Tr\chi^\dagger\chi\chi^\dagger\chi - (Tr\chi^\dagger\chi)^2)$

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- Proper **vacuum alignment** from λ_4 term when $\langle \chi^0 \rangle = \langle \xi^0 \rangle = v_M$ with $\langle \phi^0 \rangle = \frac{v_2}{\sqrt{2}}$.

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- $M_W = \frac{1}{2} g\, v = M_Z \cos\theta_W \Rightarrow \rho = 1$! Here
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  $v = \sqrt{v_2^2 + 8\, v_M^2} \approx 246\, GeV$
- Right-handed neutrino masses: $M = g_M\, v_M$
  $\Rightarrow M_Z/2 \sim 46\, GeV < M < 246\, GeV$. “Narrow” range!

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- Simplest possibility: Singlet scalar ϕ_S
$\mathcal{L}_S = g_{Sl}\, l_L^{\dagger}\, \phi_S\, l_R^M + g'_{Sl}\, e_R^{\dagger}\, \phi_S\, e_L^M + H.c.$ contains $g_{Sl}\, \nu_L^{\dagger}\, \phi_S\, \nu_R^M + H.c.$.

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- $\langle\phi_S\rangle = v_S \Rightarrow$ Neutrino Dirac Mass $m_D = g_{Sl}\, v_S$
- $M \sim O(\Lambda_{EW} \sim 246\, GeV)$, $m_\nu < 0.1\, eV$ + seesaw ($|m_\nu| = m_D^2/M$) $\Rightarrow m_D < 10^5 eV$

Mirror fermions: Dirac mass term

- If $g_{Sl} \sim O(1) \Rightarrow v_S \sim O(100\, keV) \Rightarrow$ Very light singlet scalar! (Dark Matter?) Of course, the singlet scalar mass is $\sim \sqrt{\lambda} v_S$ with λ being the quartic coupling in the singlet potential and can be either lighter or heavier than that canonical value because λ is unknown and v_S can be different from $O(100\, keV)$.

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- Cosmological consequences of electroweak-scale right-handed neutrinos and the singlet scalar field discussed in 4th lecture.

GUT vs Electroweak scale seesaw

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- Electroweak scale:
  $\sim 10^{5}\, eV = 10^{-4}\, GeV \leftrightarrow \Lambda_{EW} \sim 246\, GeV$. 6 orders of magnitude difference in scales.
  Both are accessible experimentally.

Summary of results

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- The SM with mirror fermions can be treated both perturbatively and nonperturbatively (on the lattice consistent with gauge invariance).
- Absence of perturbative and nonperturbative anomalies!
- Right-handed neutrinos which can participate in the seesaw mechanism are *active* and *light* with mass between $46\,GeV$ and $246\,GeV$ $\Rightarrow$ Accessible experimentally! Interesting signatures at the LHC (and the ILC).

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- Rich Higgs structure: Doublet and Triplet Higgses. Contains also doubly-charged scalars.
- Experimental implications in Lecture #4.