The Physics of Electroweak-scale right-handed neutrinos

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The Standard Model

The Standard Model in a nutshell

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- $\alpha(x) = \frac{\vec{\tau}}{2}.\vec{\theta}(x)$ when the symmetry gauge group is $SU(2)$

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- Quarks ($SU(3)_c$ triplets) and Leptons ($SU(3)_c$ singlets) are grouped as $SU(2)_L$ left-handed doublets and right-handed singlets.

The Standard Model

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

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- e_R, u_R, d_R, ...$SU(2)_L$ singlets
- And, of course, the Higgs boson $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

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- For singlets with $U(1)_Y$ quantum number $\frac{Y}{2} = -1 \Rightarrow D_\mu\, e_R = (\partial_\mu + ig' B_\mu)e_R$
- For the Higgs with $\frac{Y}{2} = 1 \Rightarrow$ $D_\mu\, \phi = (\partial_\mu - ig\frac{\vec{\tau}}{2}.\vec{W}_\mu - ig'(\frac{1}{2})B_\mu)\phi$

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  $$\langle\phi\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$
- $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$ $(Q = T_{3L} + \frac{Y}{2}) \Rightarrow$
  $Z_\mu = \cos\theta_W W^0_\mu - \sin\theta_W B_\mu$ (Z boson);
  $A_\mu = \sin\theta_W W^0_\mu + \cos\theta_W B_\mu$ (photon).
  $\cos\theta_W = \frac{g}{\sqrt{g^2+g'^2}}$; $\sin\theta_W = \frac{g'}{\sqrt{g^2+g'^2}}$.

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  $M_\gamma = 0$; $M_{W^\pm} = \frac{1}{2} g\, v$, $M_Z = \frac{M_{W^\pm}}{\cos\theta_W}$.

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- The SM Higgs potential with Higgs doublets has a *global* $SU(2)_L \times SU(2)_R$ symmetry which breaks down to a global custodial symmetry group $SU(2)$ such that one has $\frac{1}{2} M_W^2 \vec{W}^\mu . \vec{W}_\mu$.

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- W^0 has the same mass as $W^\pm$ before mixing with B (of $U(1)_Y$) to give rise to Z and $\gamma \Rightarrow \rho = 1$!

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- Under $SU(2)_L$: l_L and ϕ: doublets; e_R: singlet. $\Rightarrow g_e\,\bar{l}_L \phi e_R = g_e\,\bar{\nu}_L \phi^+ e_R + g_e\,\bar{e}_L \phi^0 e_R$ is $SU(2)_L \otimes U(1)_Y$ invariant.

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- $\langle \phi^0 \rangle = \frac{v}{\sqrt{2}} \Rightarrow g_e \frac{v}{\sqrt{2}} \bar{e}_L e_R + H.c. \Rightarrow$ Mass of charged lepton: $m_e = g_e \frac{v}{\sqrt{2}}$; $v \approx 246\, GeV$.

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- Assessment of the SM: Doublet Higgs, no ν_R's $\Rightarrow$ No mass of the form $\bar{\nu}_L \nu_R$ (Dirac mass).
- Can one relax the particle content of the SM in order to accomodate tiny neutrino masses i.e. $m_\nu < 0.1\, eV$? Have to (boldly) go beyond the SM!

Scenarios of neutrino masses

- Lightest charged lepton, the electron: $m_e = 0.5MeV$; Lightest quark, the u-quark: $m_u \sim 4MeV$.

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- Neutrino Oscillations point to nonzero neutrino masses.
- Heaviest neutrino: $m_\nu \sim 0.1 eV$.
- Hint of a very different nature for the neutrinos! What is the nature of its mass?

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- Using notations for 2-component Weyl spinors: Majorana (lepton number violating): $\nu_L^T \sigma_2 \nu_L$.
- For the students: Show that $\nu_L^T \sigma_2 \nu_L$ is Lorentz invariant using $\Lambda_L^T \sigma_2 \Lambda_L = \sigma_2$ with $\Lambda_{L,R} = \exp(i\frac{\vec{\sigma_2}}{2}.(\vec{\omega} \mp i\vec{\nu}))$.

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- Notice $l_L^T \sigma_2 l_L = \nu_L^T \sigma_2 \nu_L + e_L^T \sigma_2 e_L$. $\Rightarrow$ $2 \times 2 = 1 + 3$ under $SU(2)_L$ and has $\frac{Y}{2} = -1$.

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- $SU(2)_L$-singlet Higgs with $\frac{Y}{2} = +1$ ϕ_S^+: $l_L^T \sigma_2 l_L \, \phi_S^+$ is allowed by gauge invariance but a VEV of ϕ_S^+ would break charge conservation! Out!

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- $SU(2)_L$-triplet Higgs with $\frac{Y}{2} = +1$
  $\vec{\Delta} = (\Delta^{++}, \Delta^{+}, \Delta^{0})$

Scenarios of neutrino masses

- Convenient to define:

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

with: $\Delta \rightarrow U_L \Delta U_L^\dagger$

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- Gauge-invariant Yukawa interaction:

$$i g_\Delta l_L^T \sigma_2 (\tau_2 \Delta) l_L = g_\Delta (-e_L^T \sigma_2 \frac{1}{\sqrt{2}}\,\Delta^+ \nu_L + \nu_L^T \sigma_2 \nu_L \Delta^0 - e_L^T \sigma_2 e_L \Delta^{++} - \nu_L^T \sigma_2 e_L \frac{1}{\sqrt{2}}\,\Delta^+)$$

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- $\langle \Delta^0 \rangle = v_\Delta \Rightarrow$ Majorana mass term $g_\Delta\, v_\Delta \nu_L^T \sigma_2 \nu_L$

Scenarios of neutrino masses

- In that scenario, v_Δ has to be small compared with the electroweak scale $\Lambda_{EW} \sim 246\, GeV$ because
(1) $\rho = \frac{\sum_i [T(T+1) - T_3^2]_i v_i^2}{2\sum_i T_{3i}^2 v_i^2}$ tells us that if only the Higgs triplet is present to break the SM, one would have $\rho = 1/2$! Experimentally, $\rho = 1$ to a good precision.
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(2) If g_Δ is not unnaturally small then v_Δ has to be small in order to have a *tiny* neutrino mass.
- Many problems with this scenario: light singly and doubly charged scalars are not observed, etc...

Scenarios of neutrino masses

Non-renormalizable interactions

- $\phi\, l_L \sim 1 + 3 \Rightarrow SU(2)_L \otimes U(1)_Y$ invariant $(\frac{\lambda}{M}) l_L^T \sigma_2 (\phi^T\, \phi) l_L$: Non-renormalizable term with an unknown scale M.

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- Majorana mass for the neutrino: $m_\nu = \lambda \frac{v^2}{2\,M}$. $m_\nu < 0.1\, eV$ if $\lambda v / M \sim 10^{-12} \Rightarrow M \sim 10^{14}\, GeV$ (if $\lambda \sim O(1)$) Large!

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- Not much insight. Small neutrino masses replaced by a large unknown scale M. Worse: How can we ever test this large scale?

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- For $m_D < 0.1\, eV \Rightarrow g_\nu < 10^{-12}$. Nothing wrong with that but very unnatural!

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- It is possible to obtain $g_\nu < 10^{-12}$ dynamically by enlarging the SM e.g. one-loop (or higher) radiative corrections (i.e. $g_\nu = 0$ at tree-level); or by enlarging the number of spatial dimensions: Large Extra Dimensions.

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- How can one tell whether it's Dirac or not?

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- Show that: $M\,\nu_R^T \sigma_2 \nu_R + m_D(\nu_L^\dagger \nu_R + H.c.)$ can be written as $N^T M_\nu N$ with $N \equiv \begin{pmatrix} \nu \\ \chi \end{pmatrix}$,

  $\nu \equiv \nu_L$, $\chi \equiv \sigma_2 \nu_R^*$.

  $$\Rightarrow M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \Rightarrow$$

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- In this type of scenario, M is arbitrary.

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- *Low* $M < GeV$: Light sterile (right-handed) neutrinos. Motivations: LSND experiment (most probably ruled out) ($\sim 1\, eV$ sterile); Warm Dark Matter and pulsar kicks ($\sim O(keV)$ sterile), etc...

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- Price? To have active neutrino masses less than 0.1 eV $\Rightarrow$ Very small Yukawa couplings! Why would one need seesaw then? Why can't we just have Dirac masses with small Yukawa couplings?

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- Price? To have active neutrino masses less than 0.1 eV $\Rightarrow$ Very delicate cancellation among the matrix elements of the Dirac mass matrix m_D such that *tiny non-zero eigenvalues* arise from unknown perturbations. Why would one need seesaw then? Why can't we just have Dirac masses with small Yukawa couplings?

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- For a more natural case where $m_D \sim O(GeV)$ $\Rightarrow M > 10^{13}\, GeV$!
- Physics motivation: Grand Unified Theories. Gauge coupling unification. Quarks and leptons in the same multiplet.
- Group together: $((\nu_L, e_L), (u^i_L, d^i_L), e_R, u^i_R, d^i_R, \nu_R$= 16 degrees of freedom $\Rightarrow$ 16-dimensional spinor of $SO(10)$.

Scenarios of neutrino masses

- For e.g. $SO(10) \rightarrow SU(5) \rightarrow SM \Rightarrow$ Split ν_R from the 15 SM degrees of freedom at $M_{GUT} \sim 10^{16}\, GeV \Rightarrow$ Expect the right-handed Majorana mass to be of the order of $M_{GUT} \sim 10^{16}\, GeV$!

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- Practically impossible to directly detect ν_R's and test the seesaw mechanism! Indirect test through various aspects of unification. Not there yet!

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- T. D. Lee and C. N. Yang's famous 1957 paper: "The conservation of parity is usually accepted without questions concerning its possible limit of validity beig asked. There is actually no *a priori* reason why its violation is undesirable.As is well-known, its violation implies the existence of a right-left asymmetry.

The question of parity violation

We have seen in the above some possible experimental tests of this asymmetry. These experiments test whether the present elementary particles exhibit asymmetrical behavior with respect to the right and the left. If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry..."

The question of parity violation

- The realization of Lee and Yang's dream: Mirror fermions and the natural possibility of right-handed neutrinos with electroweak-scale masses.