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Inverse See-saw in Supersymmetry

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hep-ph/1009.xxxx with Seong-Chan Park

See-saw is perhaps the most elegant mechanism for neutrino mass generation, n_R is well motivated from $SO(10)$ and $SU(3)_H$. but..

$$y_\nu \overline{\ell_L} n_R H_u + M_R \overline{n_R^c} n_R + M_S \overline{s_L} n_R$$

Then, in the basis of (ν_L, s_L, n_R^c)

$$\mathcal{M} = \begin{pmatrix} 0 & 0 & M_D \\ 0 & 0 & M_S \\ M_D & M_S & M_R \end{pmatrix}$$

Lightest mass eigenstate remain massless.....

- Is there any exact chiral symmetry to protect m_ν?
- Why is there an additional singlet? E_6?
- What is the Lepton number violation scale $\Lambda_{\not{L}}$?

In this talk...

Two examples that tree-level masses are suppressed but only arise radiatively.

- generate neutrino mass in a modified Wyler-Wolfenstein model from radiative corrections. *(with Seong-chan Park, hep-ph/1009.xxxx)*
- generate charged lepton masses m_e and down-type quark masses m_d radiatively from $\langle H_u \rangle$ in MSSM *(large* $\tan\beta$ *limit, see for example, Dobrescu-Fox, upper-lifted MSSM, hep-ph/1001.3147)*

So no unbroken chiral symmetry....

Lessons from Upper-lifted MSSM Dobrescu-Fox, 1001.3147

$\langle H_u \rangle \gg \langle H_d \rangle$, m_e, m_d from $\langle H_u \rangle$

Accidental symmetries in SM lagrangian

$$i\bar{Q}^i_L \not{D} Q^i_L + i\bar{u}^i_R \not{D} u^i_R + i\bar{d}^i_R \not{D} d^i_R + \ldots$$

$$Q^i_L \to U^{ij}_Q Q^j_L, \quad u^i_R \to U^{ij}_u u^j_R, \quad d^i_R \to U^{ij}_d d^j_R$$

With three generations, $U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$

$$-y^{ij}_u \bar{Q}^i_L \epsilon H^\dagger u^j_R - y^{ij}_d \bar{Q}^i_L H d^j_R + \ldots$$

break the above $[U(3)]^5$ into $U(1)_{\rm B} \times U(1)_{\rm Lep}$

$$Q^i_L \to e^{i\theta/3} Q^i_L, \quad u^i_R \to e^{i\theta/3} u^i_R, \quad d^i_R \to e^{i\theta/3} d^i_R$$

$$\ell^i_L \to e^{i\phi} \ell^i_L, \quad e^i_R \to e^{i\phi} e^i_R$$

Fermion mass is not only a electroweak symmetry breaking (EWSB) effect .

- If $y \to 0$, $U(3)$ symmetry will be restored and the corresponding fermion will be massless up to all loops.
- $m_t($ or $m_u) \neq 0 \to m_d, m_e$ must break the $U(3)$s. (for instance, topcolor model)

To eliminate the tree-level contribution, tune the *vev* .....possible in 2HDM (large $\tan\beta$)

$$\langle H_u \rangle \gg \langle H_d \rangle$$

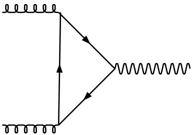
Non-zero Yukawa couplings ensure that the chiral symmetries have been broken. The masses can be generated radiatively.

MSSM is a natural 2HDM

- Superpotential is holomorphic and ϵH^* is forbidden in superpotential.
- $\tilde{H}_u$, $\tilde{H}_d$ contributes to anomaly $[SU(2)_L]^2 U(1)_Y$,.... and Witten Anomaly

$$W = y_u Q u^c H_u + y_d Q d^c H_d + y_e \ell e^c H_d + \mu H_u H_d$$

2HDM has Peccei-Quinn symmetry (DFSZ axion, 1981).



$$A_{[SU(3)_C]^2U(1)} = 3\alpha + \frac{3}{2}(2(q-\alpha)+(u-\alpha)+(d-\alpha))$$
$$= 3\alpha - \frac{3}{2}(h_u + h_d)$$

$$q+u+h_u = 2\alpha, q+d+h_d = 2\alpha$$

$M_{\mathrm{PQ}} \sim M_{\mathrm{Intermediate}}$, Kim-Nilles

$$\mathbf{10}\cdot\mathbf{10}H_u + \mathbf{10}\cdot\bar{\mathbf{5}}H_d$$

Field	$\mathbf{10}$	$\bar{\mathbf{5}}$	H_u	H_d	θ
R-charge	$\frac{1}{5}$	$\frac{3}{5}$	$\frac{4}{5}$	$\frac{6}{5}$	1
PQ	0	-1	0	1	0

$$\mathbf{10}\cdot\bar{\mathbf{5}}H_u^* : \quad \cancel{R} : \frac{1}{5}+\frac{3}{5}-\frac{4}{5} = 0 \neq 2, \quad \cancel{\mathrm{PQ}}$$

$$W = \mu H_u H_d \qquad \cancel{\mathrm{PQ}}$$

$$\begin{aligned}\mathcal{L}_{\mathrm{soft}} \quad \ni & \quad m_{\tilde{f}}^2 \mid \tilde{f} \mid^2 \qquad R-\text{invariant} \\ + & \quad M_{\frac{1}{2}} \lambda\lambda + A_u \tilde{Q} \tilde{u} H_u + \ldots \qquad \cancel{R} \\ + & \quad B\mu H_u H_d \qquad \cancel{R}, \cancel{\mathrm{PQ}}\end{aligned}$$

If $\cancel{\mathrm{PQ}}$, $\cancel{R}$ and $\cancel{[U3]^5}$,

$$\mathbf{10} \cdot \bar{\mathbf{5}} H_u^* \rightarrow m_e, m_d \neq 0$$

Another $\cancel{\mathrm{PQ}}$ source, (proportional to μ)

$$F_{H_d} = \frac{\partial W}{\partial H_d} = y_d Q d^c + y_e \ell e^c + \mu H_u$$

$$V \ni \mid F_{H_d} \mid^2 = y_d \mu^* H_u^* \tilde{Q} \tilde{d} + y_e \mu^* H_u^* \tilde{\ell} \tilde{e}$$

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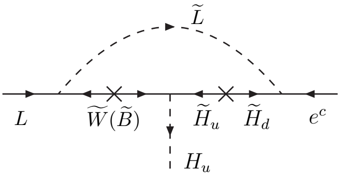
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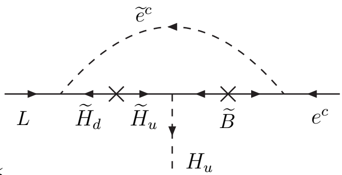
$\widetilde{H}_u$
$\widetilde{H}_d$
e^c
H_u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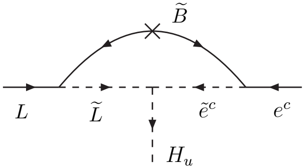
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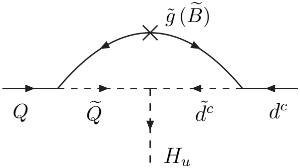
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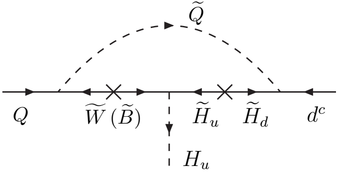
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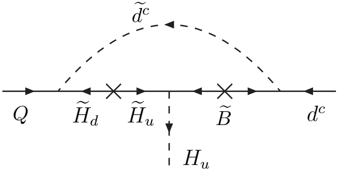
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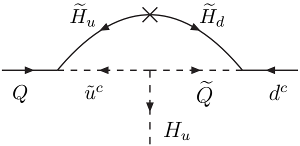
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d^c
H_u

Physics Implications

- If all Yukawa couplings in MSSM are perturbative at M_{GUT}, $2 \lesssim \tan\beta \lesssim 50$.

  But what if m_b arise from $\langle H_u \rangle$ radiatively.....

ν_L does not carry any unbroken gauge symmetry ($SU(3)_C \times U(1)_{\rm EM}$)....

$$-\frac{1}{2} M_\nu^{ij} \nu_L^{iT} C v_L^j$$

Type-I see-saw

$$y_\nu \overline{\ell_L} n_R H_u + M_R \overline{n_R^c} n_R + h.c. \ ,$$

For one generation y_ν break $U(1)_\ell \times U(1)_n \to U(1)_{\rm Lep}$

$M_R \to \cancel{U(1)}_{\rm Lep}$

$$m_\nu = M_D^T M_R^{-1} M_D$$

- Without tuning dimensionless y_ν, tiny m_ν from $M_{\rm GUT}$
- $U(1)_{B-L}$ becomes anomaly free, easily embedded into $SO(10)$

Pati-Salam(Wyler-Wolfenstein)

$$y_\nu \overline{\ell_L} n_R H_u + M_S \overline{s_L} n_R + h.c.$$

In basis (ν_L, s_L, n_R^c)

$$\mathcal{M} = \begin{pmatrix} 0 & 0 & M_D \\ 0 & 0 & M_S \\ M_D & M_S & 0 \end{pmatrix}$$

$$m_\nu = 0$$

Inverse see-saw (Mohapatra, Valle)

$$y_\nu \overline{\ell_L} n_R H_u + M_S \overline{s_L} n_R + \epsilon \overline{s_L^c} s_L$$

In basis (ν_L, s_L, n_R^c)

$$\mathcal{M} = \begin{pmatrix} 0 & 0 & M_D \\ 0 & \epsilon & M_S \\ M_D & M_S & 0 \end{pmatrix}$$

$$m_\nu \simeq \epsilon \frac{M_D^2}{M_D^2 + M_S^2}$$

Tuning: Dimensionless y_ν or dimension-one M

$y_e \sim 10^{-6}$, $y_\nu \sim 10^{-12}$?

Dimension One: see-saw vs inverse

- In see-saw, M_R breaks $U(1)_{B-L}$ gauge symmetry at ultra-high scale, for instance, $M_{\rm GUT}$.
- Now n, s are both SM gauge singlet...., the scale vanishes to restore the $U(1)_{\rm Lep}$, can be identified as soft breaking of $U(1)_{\rm Lep}$.

$$y_\nu \overline{\ell_L} n_R H_u + M_S \overline{s_L} n_R + M_R \overline{n_R^c} n_R$$

In basis (ν_L, s_L, n_R^c)

$$\mathcal{M} = \begin{pmatrix} 0 & 0 & M_D \\ 0 & 0 & M_S \\ M_D & M_S & M_R \end{pmatrix}$$

$$\begin{aligned} \nu &= -\frac{M_S}{\sqrt{M_D^2 + M_S^2}} \nu_L + \frac{M_D}{\sqrt{M_D^2 + M_S^2}} s_L \\ N_\pm &= \frac{1}{\sqrt{M_\pm^2 + M_D^2 + M_S^2}} (M_D \nu_L + M_S s_L - M_\pm n_R^c) \end{aligned}$$

with mass eigenvalues as

$$m_\nu = 0, \quad M_\pm = \frac{1}{2}\left(M_R \pm \sqrt{4M_D^2 + M_R^2 + 4M_S^2}\right)$$

Why no $M_R^* \overline{s_L^c} s_L$? SUSY

$$W = y_\nu \ell n^c H_u + M_S s n^c + M_R n^c n^c$$

Field	ℓ	e^c	n^c	s	H_u	H_d	θ
R-charge	$\frac{1}{5}$	$\frac{3}{5}$	1	1	$\frac{4}{5}$	$\frac{6}{5}$	1
$U(1)_L$	1	-1	-1	1	0	0	0

W_{eff}	m	R-charge of m	$U(1)_L$ charge
$n^c n^c$	$\overline{n_R^c} n_R$	$1+1-2\theta=0$	-2
$\ell s H_u$	$\overline{\nu_L^c} s_L$	$\frac{1}{5}+1+\frac{4}{5}-2\theta=0$	2
$\ell \ell H_u H_u$	$\overline{\nu_L^c} \nu_L$	$\frac{1}{5}+\frac{1}{5}+\frac{4}{5}+\frac{4}{5}-2\theta=0$	2
ss	$\overline{s_L^c} s_L$	$1+1-2\theta=0$	2

New gauge interaction?

Under E_6

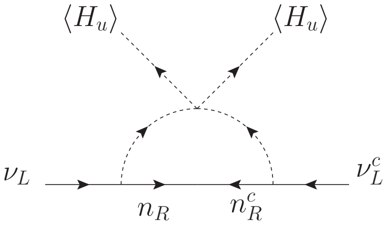
$$27 = 16 + 10 + 1$$

s_L is completely gauge singlet and any term involving s_L will be only gravitationally induced in

- Kähler potential
- Lepton number violation B-terms in soft-breaking lagrangian

R-invariant piece

$U(1)_{B-L}$ becomes anomalous so the leading is Yukawa interaction induced $\ell\ell H_u H_u$ Non-SUSY contribution



$$\begin{aligned}(M_\nu^{1-\mathrm{loop}})_{ij} &= \sum_{k=1}^{3} \frac{1}{16\pi^2} M_R^k \sum_{\phi=h,H} \frac{Y_{ik}^* Y_{jk}^* M_\phi^2}{M_\phi^2 - {M_R^k}^2} \ln\left(\frac{M_\phi^2}{{M_R^k}^2}\right) \\ &- \frac{Y_{ik}^* Y_{jk}^* M_A^2}{M_A^2 - {M_R^k}^2} \ln\left(\frac{M_A^2}{{M_R^k}^2}\right)\end{aligned}$$

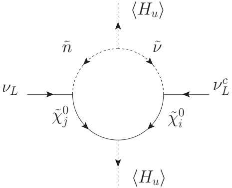
$$M_R \frac{M_\phi^2}{M_\phi^2 - {M_R}^2} \ln\left(\frac{M_\phi^2}{{M_R}^2}\right)$$

- $M_R \gg M_{h,H}$ restore the see-saw, $M_R < 10^{12}$ GeV
- $M_R \ll M_{h,H}$, inverse see-saw limit, $M_R \sim$ KeV

We take the inverse see-saw limit (non-canonical Kälher potential) to ensure light neutrino mass.

$$
\begin{aligned}
V &= \left|\frac{\partial W}{\partial n_R}\right|^2 = |(\ell H_u + M_s s_L + M_R n_R)|^2 \\
&= M_R^* \tilde{n}_R^* \tilde{\ell} H_u + M_R^* M_s \tilde{n}_R^* \tilde{s}_L
\end{aligned}
$$

After $M_{\rm susy}$,



$$
m_{\tilde{n}}^2 \sim M_{\rm susy}^2 + M_R^2
$$

- $M_R \gg M_{\rm susy}$
- $M_R \ll M_{\rm susy}$

$\not{R}$ Contribution

The effective operators do not break R-symmetry

$$\mathcal{L}_{soft} \ni B_R M_R \tilde{n}_R \tilde{n}_R + B_S \epsilon_s \tilde{s}_L \tilde{s}_L + A_s M_R \tilde{\ell}_L \tilde{s}_L H_u + B_\nu M_\nu \tilde{\nu}_L \tilde{\nu}_L$$

m_ν only arise with gaugino mass insertion.
Soft SUSY breaking terms that also violate $U(1)_{\mathrm{Lep}}$ but $1/M_{\mathrm{Pl}}$ suppression.

Conclusions

- I present two examples that the fermion masses arise from radiative correction where the tree level masses are suppressed but all the chiral symmetries are broken.