The classically conformal B-L extended Ma model

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The Classically conformal B-L extended Ma model solves 2 hierarchy problems

① Neutrino mass scale and EW scale ② EW(TeV) scale and Planck scale

Ma model

E. Ma, Phys.Rev.D73, 077301 (2006)

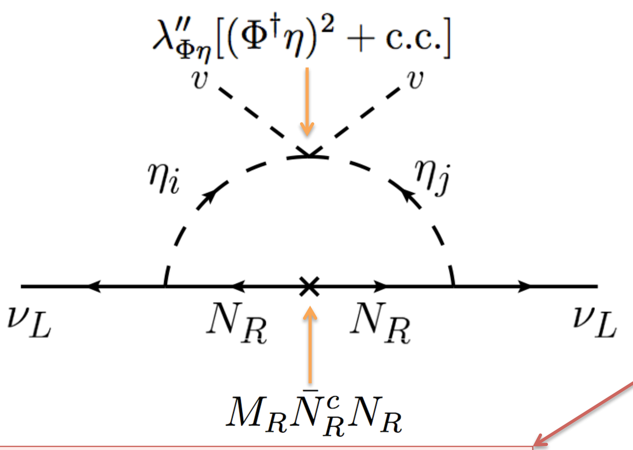
Ma model is minimal radiative see-saw model with DM

Fermion	L_L	e_R	N_R
$(SU(2)_L, U(1)_Y)$	$(\mathbf{2}, -1/2)$	$(\mathbf{1}, -1)$	$(\mathbf{1}, 0)$
Z_2	+	+	−

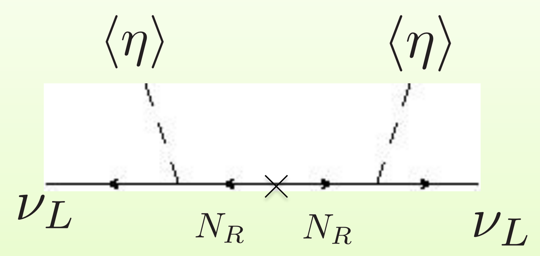
Boson	Φ	η
$(SU(2)_L, U(1)_Y)$	$(\mathbf{2}, 1/2)$	$(\mathbf{2}, 1/2)$
Z_2	+	−

If $\lambda''_{\Phi\eta}$ is zero, neutrino masses are zero

$$(\mathcal{M}_\nu)_{ab} = \frac{(y_\eta)_{ak}(y_\eta)_{bk}M_k}{(4\pi)^2}\left[\frac{m_R^2}{m_R^2-M_k^2}\ln\frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2-M_k^2}\ln\frac{m_I^2}{M_k^2}\right] \qquad m_R^2 - m_I^2 = 2\lambda''_{\Phi\eta}v^2$$



If Majorana mass is forbidden, this diagram can't draw



If η has non-zero VEV, neutrino mass is generated by tree level

Classically conformal model

W.A. Bardeen, FERMILAB-CONF-95-391-T

Classically conformal theory with no intermediate scale can be an alternative solution to the naturalness problem

Hierarchy problem

$$m^2(\mu) = m_0^2 + \frac{3\Lambda^2}{8\pi^2 v^2}\left(m_Z^2 + 2m_W^2 + m^2 - 4m_t^2\right) + \mathcal{O}\left(\ln\frac{\Lambda}{\mu}\right)$$

subtracted at UV scale
Once subtracted, no longer appears

Classically conformal invariance

Natural boundary condition is no mass terms at Planck scale

$$m^2(\Lambda) = m_0^2 + \frac{3\Lambda^2}{8\pi^2 v^2}\left(m_Z^2 + 2m_W^2 + m^2 - 4m_t^2\right) = 0$$

Ma model	Classically conformal
M1. Majorana mass	C1. No mass term
M2. $\lambda''_{\Phi\eta}$ is non-zero	C2. No intermediate scale
M3. η is inert doublet	C3. CW type EWSB

If large new scale exists, Higgs mass has large correction.

$$\delta m^2 \sim \lambda_{mix} m_{new}^2$$

Effective potential

$$V_{eff}(\phi) = \frac{\lambda_\Phi(\phi)}{4}\phi^4$$

① $\frac{dV_{eff}}{d\phi} = \frac{M^4}{4}\left(\frac{d\lambda_\Phi}{dt} + 4\lambda_\Phi\right) = 0$

$\Rightarrow \lambda_\Phi = -\frac{1}{4}\frac{d\lambda_\Phi}{dt} \sim -\frac{1}{64\pi^2}\left(96g'^4 - Y_N^4\right)$

λ_Φ is generated by loop effect

② $\frac{d^2V_{eff}}{d\phi^2} = -4\lambda_\Phi M^2 > 0 \Rightarrow \lambda_\Phi < 0$

λ_Φ is negative

M1, C1

Majorana mass term is forbidden by Classically conformal invariance

B-L gauged extension

Majorana mass is generated by B-L symmetry breaking

$$\frac{1}{2}y_N\varphi\bar{N}_R^c N_R \Rightarrow M_R\bar{N}_R^c N_R$$

Fermion	L_L	e_R	N_R
$(SU(2)_L, U(1)_Y)$	$(\mathbf{2}, -1/2)$	$(\mathbf{1}, -1)$	$(\mathbf{1}, 0)$
$U(1)_{B-L}$	−1	−1	−1
Z_2	+	+	−

Boson	Φ	η	φ
$(SU(2)_L, U(1)_Y)$	$(\mathbf{2}, 1/2)$	$(\mathbf{2}, 1/2)$	$(\mathbf{1}, 0)$
$U(1)_{B-L}$	0	0	2
Z_2	+	−	+

DM candidate Inert doublet

M2, C2

Yukawa interaction

$$-\mathcal{L}_Y = (y_\ell)_a \bar{L}_{La}\Phi e_{Ra} + (y_\eta)_a \bar{L}_{La}\eta^* N_{Ra} + \frac{1}{2}y_N\varphi\bar{N}_R^c N_R + \text{h.c.}$$

Potential

$$\mathcal{V} = \lambda_\Phi|\Phi|^4 + \lambda_\eta|\eta|^4 + \lambda_\varphi|\varphi|^4 + \lambda_{\Phi\eta}|\Phi|^2|\eta|^2 + \lambda'_{\Phi\eta}|\Phi^\dagger\eta|^2 + \lambda''_{\Phi\eta}[(\Phi^\dagger\eta)^2 + \text{c.c.}] + \lambda_{\Phi\varphi}|\Phi|^2|\varphi|^2 + \lambda_{\eta\varphi}|\eta|^2|\varphi|^2,$$

Assumptions

1. These couplings are zero at Planck scale for simplicity
2. There are no intermediate scale

C3

If B-L symmetry is broken, the SM Higgs doublet mass is generated through the mixing term in the scalar potential.

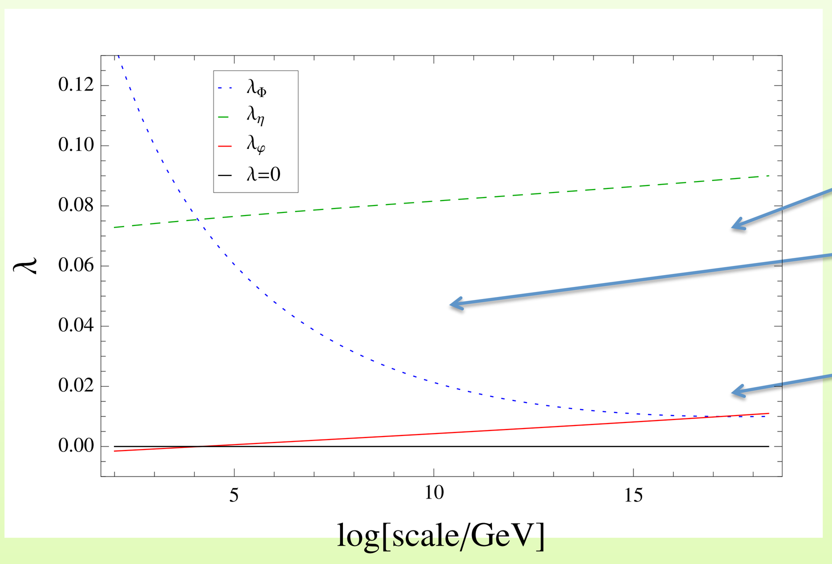
$$V \sim \lambda_\Phi\Phi^4 + \lambda_{\Phi\varphi}\Phi^2\varphi^2$$

Φ has VEV.

$$V \sim \lambda_\Phi\Phi^4 + \lambda_{\Phi\varphi}\Phi^2 v_{B-L}^2$$

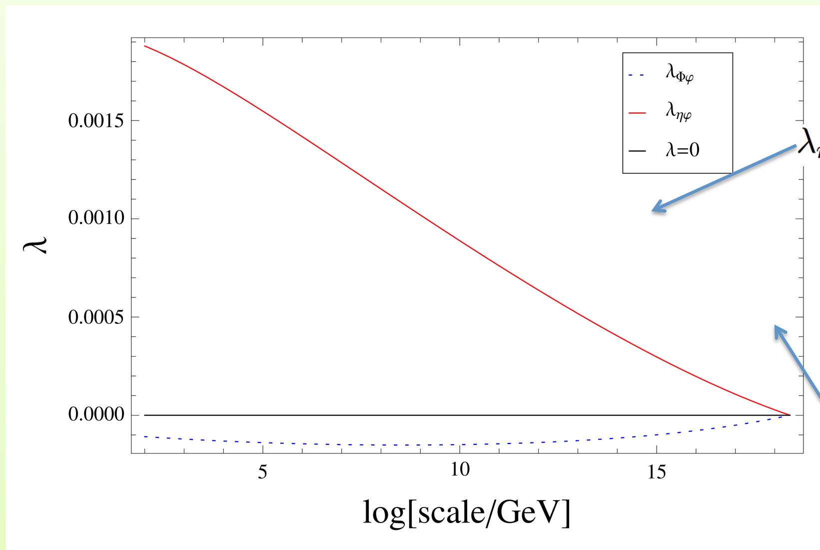
M3

$g_{B-L}=0.17$ $Y_N=0.2$
$\lambda''_{\Phi\eta}=10^{-9}$ $m_{z'}=3.7$ TeV



λ_η, λ_Φ } should be positive for stability

λ_φ: $\lambda_\Phi = -\frac{1}{4}\frac{d\lambda_\Phi}{dt} \sim -\frac{1}{64\pi^2}\left(96g'^4 - Y_N^4\right)$ $\Rightarrow \lambda_\Phi < 0$



$\lambda_{\eta\varphi}$: η mass term $\lambda_{\eta\varphi}v_{B-L}^2\eta^2$; η is inert doublet $\Rightarrow \lambda_{\eta\varphi} > 0$

$\lambda_{\Phi\varphi}$: Higgs mass term $\lambda_{\Phi\varphi}v_{B-L}^2\Phi^2$ $\Rightarrow \lambda_{\Phi\varphi} < 0$

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