Bosonic seesaw mechanism in a classically scale invariant model

Yuya Yamaguchi

(Hokkaido U. and Shimane U.)

Collaborators

Naoyuki Haba (Shimane U.)

Hiroyuki Ishida (Shimane U.)

Nobuchika Okada (U. of Alabama)

Based on arXiv:1508.06828 (letter ver.), 1509.01923

Introduction

Gauge hierarchy problem can be avoided by

- – scale invariance in extended SM
- – dimensional transmutation not so far from EW scale

Towards the SM-like Higgs mass term

- – its value should be EW scale
- – its sign should be negative to break EW symmetry

We construct a model which
- avoids gauge hierarchy problem with scale invariance
- dynamically generates negative mass term of the Higgs
- explains active neutrino masses by type-I seesaw
- realizes vacuum stability ($\lambda_H > 0$) by scalar mixing

Model

We consider $U(1)_{B-L}$ gauge extended model with two Higgs doublet and one SM singlet scalars.

	$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L}$
Q^i	$(3,\ 2,\ 1/6)$	$1/3$
U^i	$(3,\ 1,\ 2/3)$	$1/3$
D^i	$(3,\ 1,\ -1/3)$	$1/3$
L^i	$(1,\ 2,\ -1/2)$	-1
E^i	$(1,\ 1,\ -1)$	-1
N^i	$(1,\ 1,\ 0)$	-1
H_1	$(1,\ 2,\ 1/2)$	0
H_2	$(1,\ 2,\ 1/2)$	4
Φ	$(1,\ 1,\ 0)$	2

different B-L charges

Only H_1 couples to the SM fields.

Bosonic seesaw mechanism

['02 X. Calmet], ['05 H.D. Kim], ['05 N. Haba, N. Kitazawa, N. Okada]

Potential

$$V = \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left(H_2^\dagger H_1\right)\left(H_1^\dagger H_2\right)$$
$$+\lambda_\Phi |\Phi|^4 + \lambda_{H_1\Phi} |H_1|^2 |\Phi|^2 + \lambda_{H_2\Phi} |H_2|^2 |\Phi|^2 + \left(\lambda_{\rm mix}\left(H_2^\dagger H_1\right)\Phi^2 + {\rm h.c.}\right)$$

After Φ obtains nonzero VEV (Coleman-Weinberg),

$$-\mathcal{L}_{\rm mass} = \frac{1}{2}\left(H_1^\dagger, H_2^\dagger\right)\begin{pmatrix} \lambda_{H_1\Phi} v_\Phi^2 & \lambda_{\rm mix} v_\Phi^2 \\ \lambda_{\rm mix} v_\Phi^2 & \lambda_{H_2\Phi} v_\Phi^2 \end{pmatrix}\begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$
$$\approx \frac{1}{2}\left(H_1'^\dagger, H_2'^\dagger\right)\begin{pmatrix} \lambda_{H_1\Phi} v_\Phi^2 - \frac{\lambda_{\rm mix}^2}{\lambda_{H_2\Phi}} v_\Phi^2 & 0 \\ 0 & \lambda_{H_2\Phi} v_\Phi^2 \end{pmatrix}\begin{pmatrix} H_1' \\ H_2' \end{pmatrix}$$

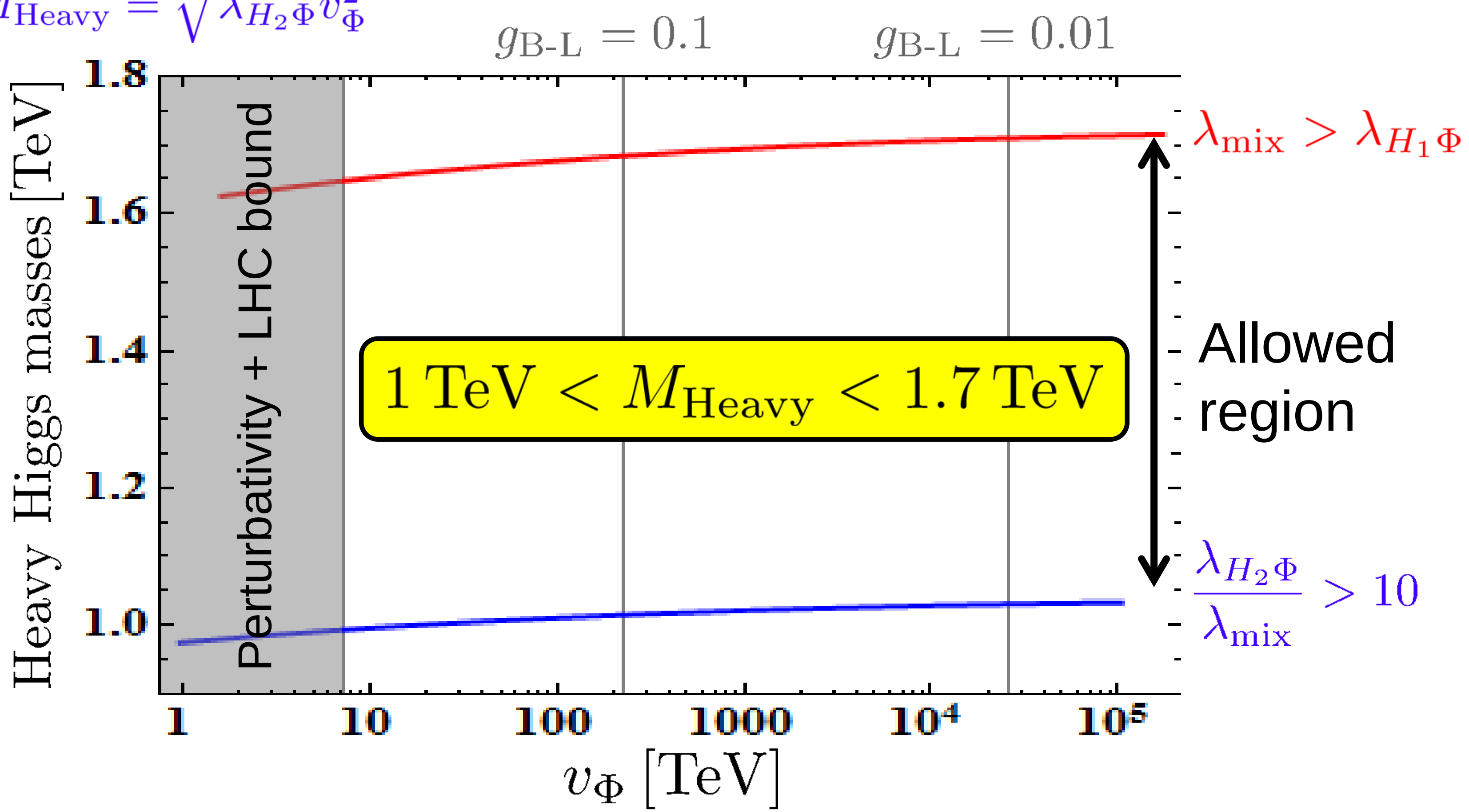
Bosonic seesaw

where we have assumed large hierarchy $\left(0 \le \lambda_{H_1\Phi} \ll \lambda_{\rm mix} \ll \lambda_{H_2\Phi}\right)$

Negative mass term dynamically generated: $m_h^2 \approx -\frac{\lambda_{\rm mix}^2}{2\lambda_{H_2\Phi}} v_\Phi^2$

Prediction of heavy Higgs mass

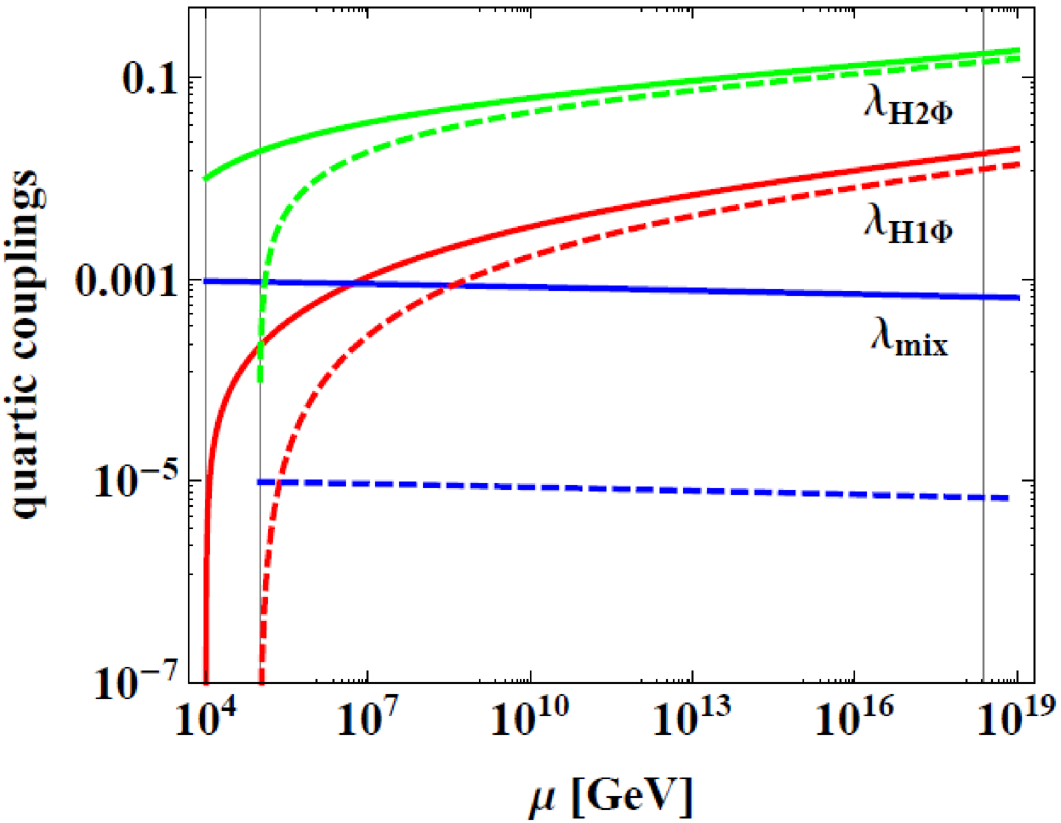
$M_{\text{Heavy}} = \sqrt{\lambda_{H_2\Phi} v_\Phi^2}$



Masses of heavy CP-even Higgs, CP-odd Higgs and charged Higgs

$$M_H^2 = M_A^2 = \underline{\lambda_{H_2\Phi} v_\Phi^2} + (\lambda_3 + \lambda_4)\, v_h^2 \qquad M_{H^\pm}^2 = \underline{\lambda_{H_2\Phi} v_\Phi^2} + \lambda_3 v_h^2$$

Running of quartic couplings



Solid: $v_\Phi = 10\,\mathrm{TeV}$

Dashed: $v_\Phi = 100\,\mathrm{TeV}$

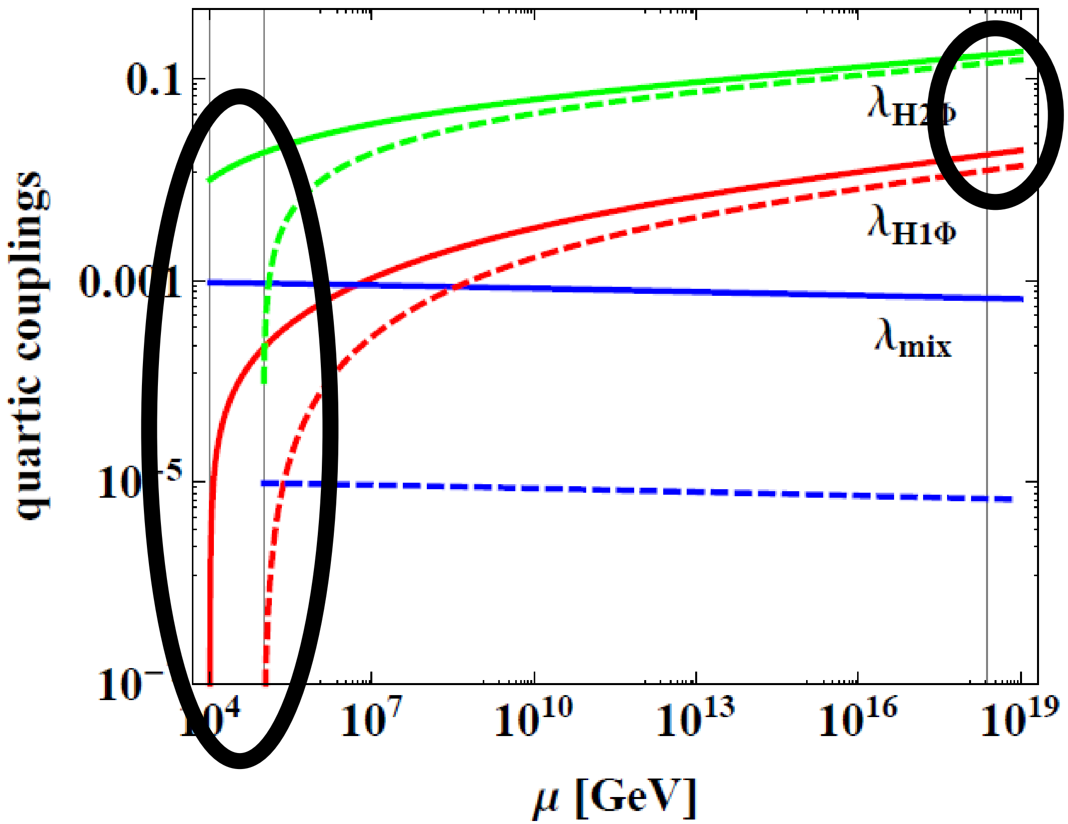
@ $\mu = v_\Phi$

$$\begin{cases} g_{\text{B-L}} = 0.17 \\ \lambda_{1,2} = \lambda_{SM} \\ \lambda_{3,4} = 0.17 \\ \lambda_\Phi = 10^{-3} \end{cases}$$

To realize the hierarchy ($0 \leq \lambda_{H_1\Phi} \ll \lambda_{mix} \ll \lambda_{H_2\Phi}$) at $\mu = v_\Phi$, we take

- $\lambda_{H_1\Phi} = 0,\ \lambda_{H_2\Phi} = 10^{-2}\ (10^{-4})$ for $v_\Phi = 10\,\mathrm{TeV}\ (100\,\mathrm{TeV})$
- λ_{mix} is determined to realize the 125GeV Higgs mass

Running of quartic couplings



Solid: $v_\Phi = 10\,\mathrm{TeV}$

Dashed: $v_\Phi = 100\,\mathrm{TeV}$

@ $\mu = v_\Phi$

$$\begin{cases} g_{\text{B-L}} = 0.17 \\ \lambda_{1,2} = \lambda_{SM} \\ \lambda_{3,4} = 0.17 \\ \lambda_\Phi = 10^{-3} \end{cases}$$

Large hierarchy becomes milder during renormalization evolution

= **No fine-tuning**

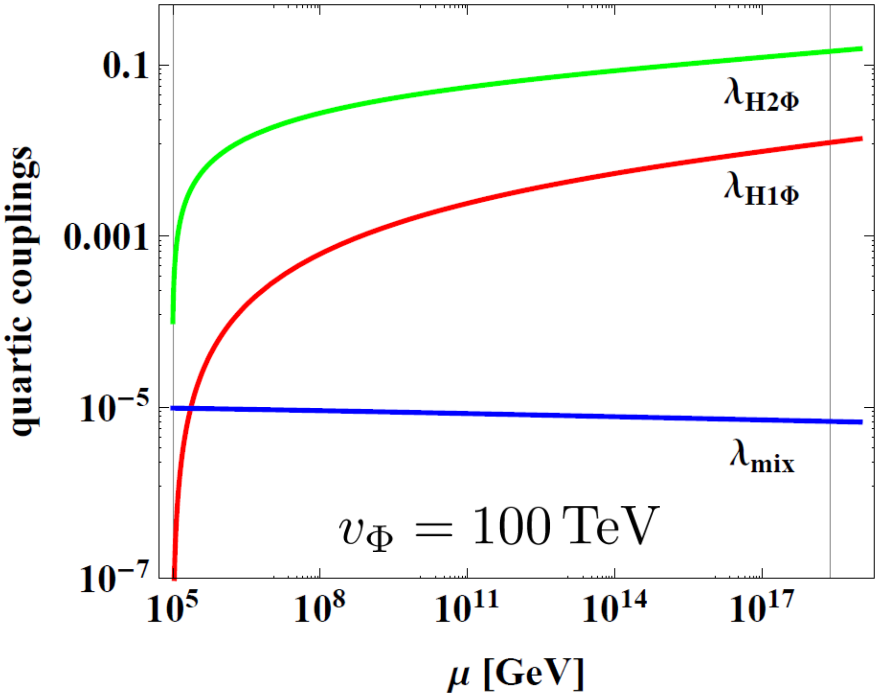
Running of quartic couplings

When we extend the model with vector-like fermions, hierarchy for $\lambda_{\rm mix}$ is also much milder than before.

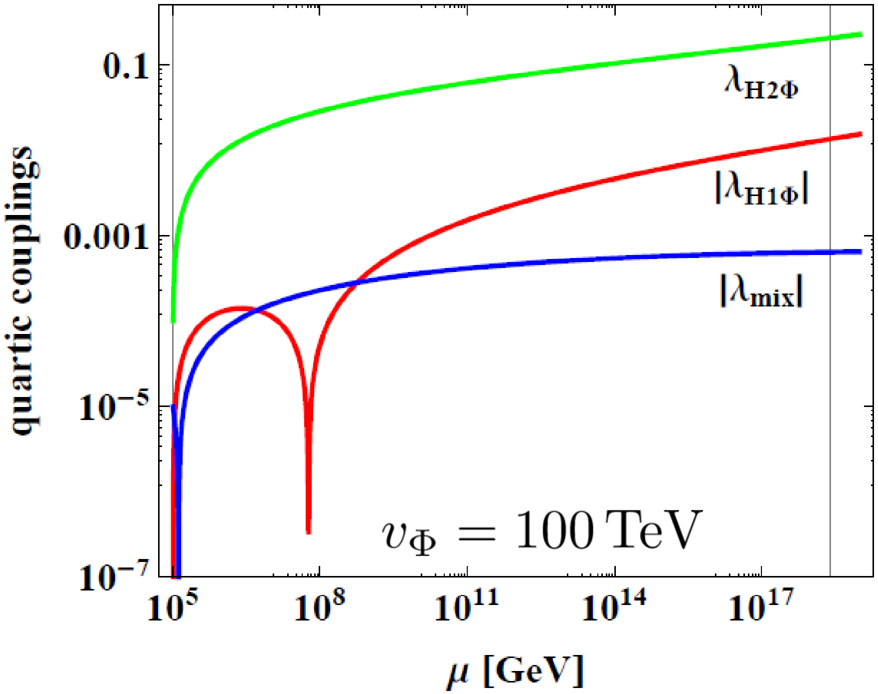
(For example)

	$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L}$
$S_{L,R}$	$(1,\ 1,\ 0)$	x
$S'_{L,R}$	$(1,\ 1,\ 0)$	$x-2$
$D_{L,R}$	$(1,\ 2,\ 1/2)$	x
$D'_{L,R}$	$(1,\ 2,\ 1/2)$	$x+2$

Before



After



Summary

- We have constructed a model which
  - avoids gauge hierarchy problem with scale invariance
  - dynamically generates negative mass term of Higgs doublet
  - explains active neutrino masses by type-I seesaw
  - realizes vacuum stability ($\lambda_H > 0$) by scalar mixing

- Negative mass term of Higgs doublet dynamically arises from "bosonic seesaw mechanism"

- Heavy Higgs masses are $1\,\mathrm{TeV} < M_{\mathrm{Heavy}} < 1.7\,\mathrm{TeV}$

* Bosonic seesaw can be used for a general THDM.
Particularly, it is a new possibility in scale invariant models.

Back up

Introduction

From the Bardeen's argument [1995, W. A. Bardeen]

"We have argued that <u>the Standard Model does not, by itself, have a fine tuning problem</u> due to the approximate scale invariance of the perturbative expansion."

- RGE of the Higgs mass parameter in the SM

$$\frac{dm_h^2}{d\ln\mu} = \frac{1}{16\pi^2} m_h^2 \left[12\lambda_H + 6y_t^4 - \frac{3}{2}g_1^2 - \frac{9}{2}g_2^2\right]$$

⇨ $m_h^2(\mu) \sim m_h^2(\Lambda)$ → Order of magnitude does not change

- RGE of the Higgs mass parameter in some extended SM

$$\frac{dm_h^2}{d\ln\mu} = \frac{1}{16\pi^2} m_h^2 \left[12\lambda_H + 6y_t^4 - \frac{3}{2}g_1^2 - \frac{9}{2}g_2^2\right] + \frac{1}{16\pi^2}\lambda M^2$$

⇨ $m_h^2(\mu) \sim m_h^2(\Lambda) - \lambda M^2 \ln\frac{\Lambda^2}{\mu^2}$ → Large contribution appears

CW mechanism

- Scalar potential

$$V = \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left(H_2^\dagger H_1\right)\left(H_1^\dagger H_2\right)$$
$$+\lambda_\Phi |\Phi|^4 + \lambda_{H_1\Phi} |H_1|^2 |\Phi|^2 + \lambda_{H_2\Phi} |H_2|^2 |\Phi|^2 + \left(\lambda_{\rm mix}\left(H_2^\dagger H_1\right)\Phi^2 + {\rm h.c.}\right)$$

where there is no mass term due to scale invariance

- One-loop CW potential for the SM singlet scalar

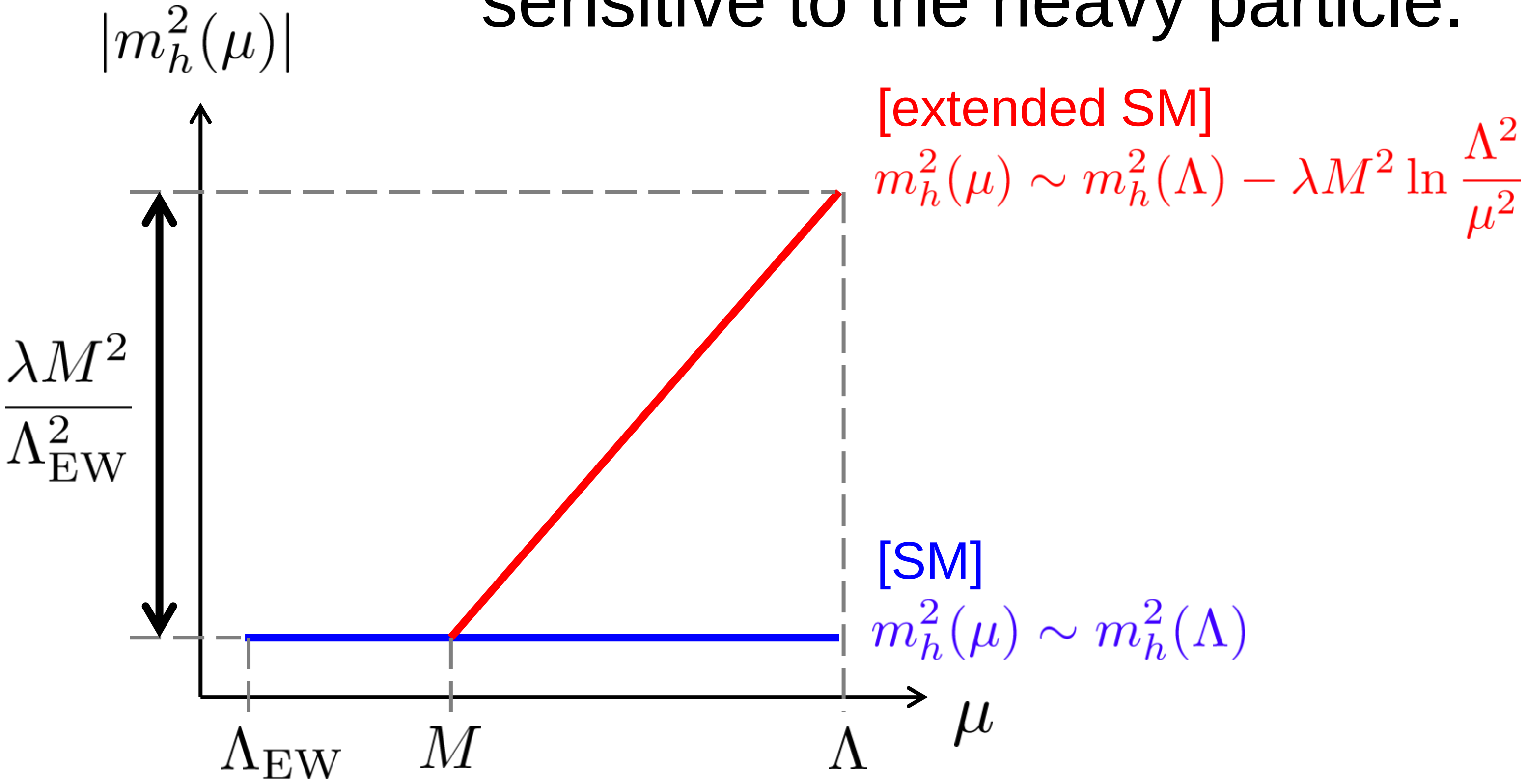
$$V_\Phi(\phi) = \frac{1}{4}\lambda_\Phi(v_\Phi)\phi^4 + \frac{1}{8}\beta_{\lambda_\Phi}(v_\Phi)\phi^4\left(\ln\frac{\phi^2}{v_\Phi^2} - \frac{25}{6}\right)$$

⇨ $$\lambda_\Phi(v_\Phi) \simeq \frac{11}{6\pi^2}\left[6 g_{\text{B-L}}^4(v_\Phi) - {\rm tr} Y_M^4(v_\Phi)\right]$$ (minimization condition)

Nonzero VEV causes $U(1)_{B-L}$ breaking.

Introduction

Renormalization condition at the UV scale is sensitive to the heavy particle.

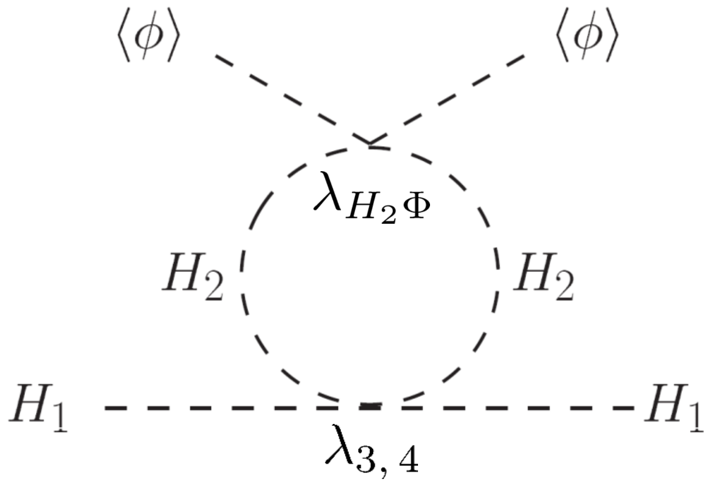


Gauge hierarchy problem arises when $M \gg \Lambda_{\rm EW}$

(Fine-tuning for $m_h^2(\Lambda)$)

Higgs mass correction

Higgs mass correction mainly come from



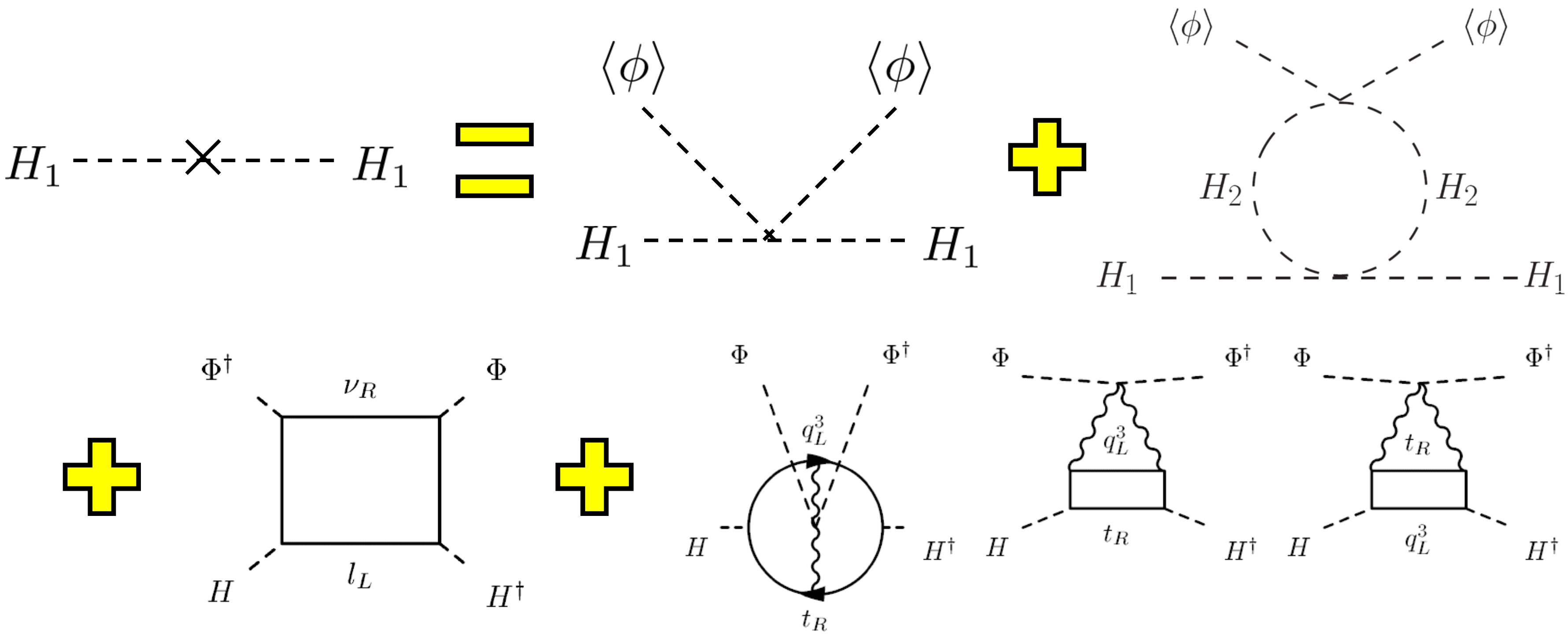
Then, the Higgs mass parameter is given by

$$m_h^2 \simeq -\frac{\lambda_{\rm mix}^2}{2\lambda_{H_2\Phi}} v_\Phi^2 - \frac{\lambda_{H_2\Phi}}{16\pi^2}\left(2\lambda_3 + \lambda_4\right) v_\Phi^2$$

Neutrino loop and $U(1)_{B-L}$ gauge boson loop also contribute, but we consider the case where they are enough small.

Higgs mass correction

Higgs mass correction mainly come from



Then, the Higgs mass parameter is given by

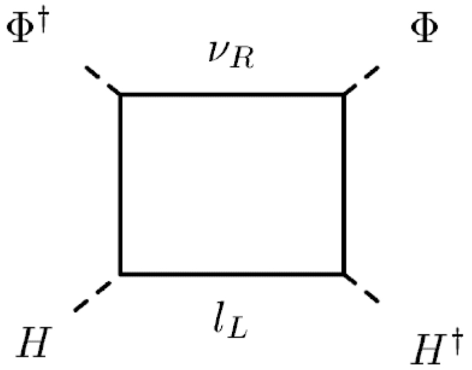
$$m_h^2 \simeq \frac{\lambda_{H_1\Phi}}{2} v_\Phi^2 - \frac{\lambda_{\text{mix}}^2}{2\lambda_{H_2\Phi}} v_\Phi^2 - \frac{\lambda_{H_2\Phi}}{16\pi^2}(2\lambda_3 + \lambda_4)\, v_\Phi^2 + \cdots$$

From bosonic seesaw

Higgs mass correction

Δm_h^2 should be lower than Higgs mass: $\Delta m_h^2 \lesssim (125\mathrm{GeV})^2$

- Neutrino (one-loop)



$$\Delta m_h^2 \sim \frac{Y_\nu^2 Y_M^2 v_\Phi^2}{16\pi^2} \sim \frac{m_\nu M_N^3}{16\pi^2 v_H^2}$$

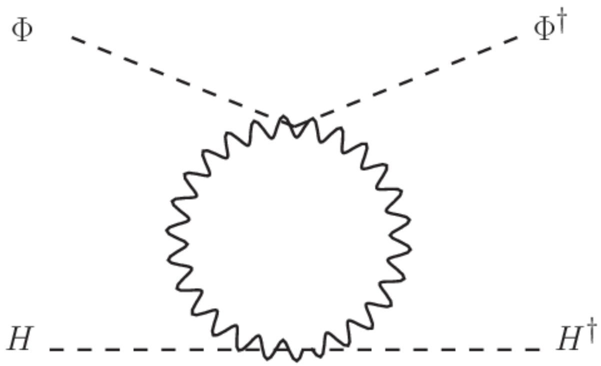
$$m_\nu \sim Y_\nu^2 v_H^2 / M_N \sim 0.1\mathrm{eV}$$

$\Rightarrow$ $M_N \lesssim 10^7 \mathrm{GeV}$ $\Rightarrow$ $v_\Phi \lesssim \left(\frac{0.1}{Y_N}\right) \times 10^8 \,\mathrm{GeV}$

Higgs mass correction

Δm_h^2 should be lower than Higgs mass: $\Delta m_h^2 \lesssim (125\mathrm{GeV})^2$

- U(1)' gauge (one-loop)



$$\Delta m_h^2 \sim \frac{x^2 g'^4 v_\Phi^2}{16\pi^2}$$

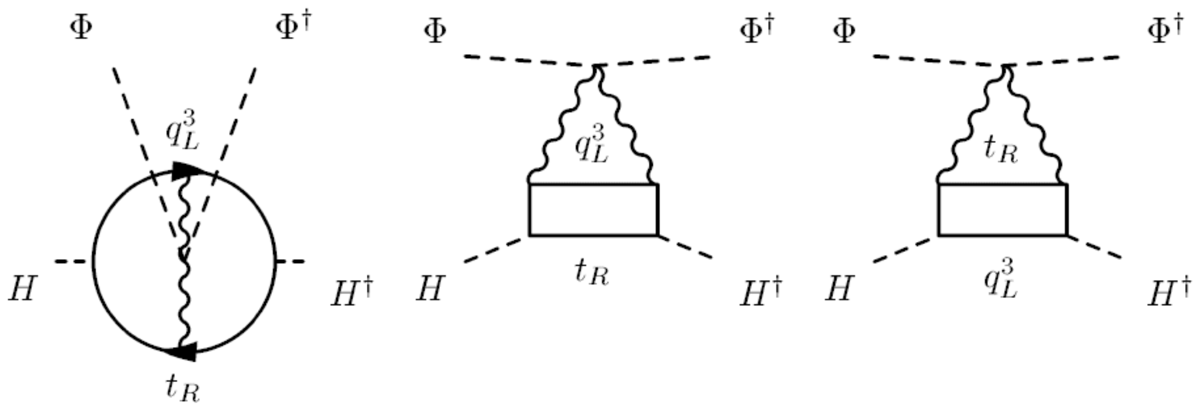
$$v_\Phi \lesssim \frac{1}{|x|}\left(\frac{0.1}{g'}\right)^2 \times 10^5\,\mathrm{GeV} \text{ for } x \neq 0$$

(x=0 corresponds to $U(1)_{B\text{-}L}$)

Higgs mass correction

Δm_h^2 should be lower than Higgs mass: $\Delta m_h^2 \lesssim (125\mathrm{GeV})^2$

- U(1)' gauge (two-loop with top Yukawa)



$$\Delta m_h^2 \sim \frac{y_t^2 g'^4 v_\Phi^2}{(16\pi^2)^2}$$

$$y_t \sim 1$$

$$\Rightarrow \quad v_\Phi \lesssim \left(\frac{0.1}{g'}\right)^2 \times 10^6\,\mathrm{GeV}$$

constraints on v_Φ

- Perturbativity up to the Planck scale: $g_{\text{B-L}} < 0.2$
- LHC bound on Z': $M_{Z'} > 2.9\,\text{TeV}\ \ (M_{Z'} = 2g_{\text{B-L}}v_\Phi)$

⇨ $v_\Phi > 7.25\,\text{TeV}$

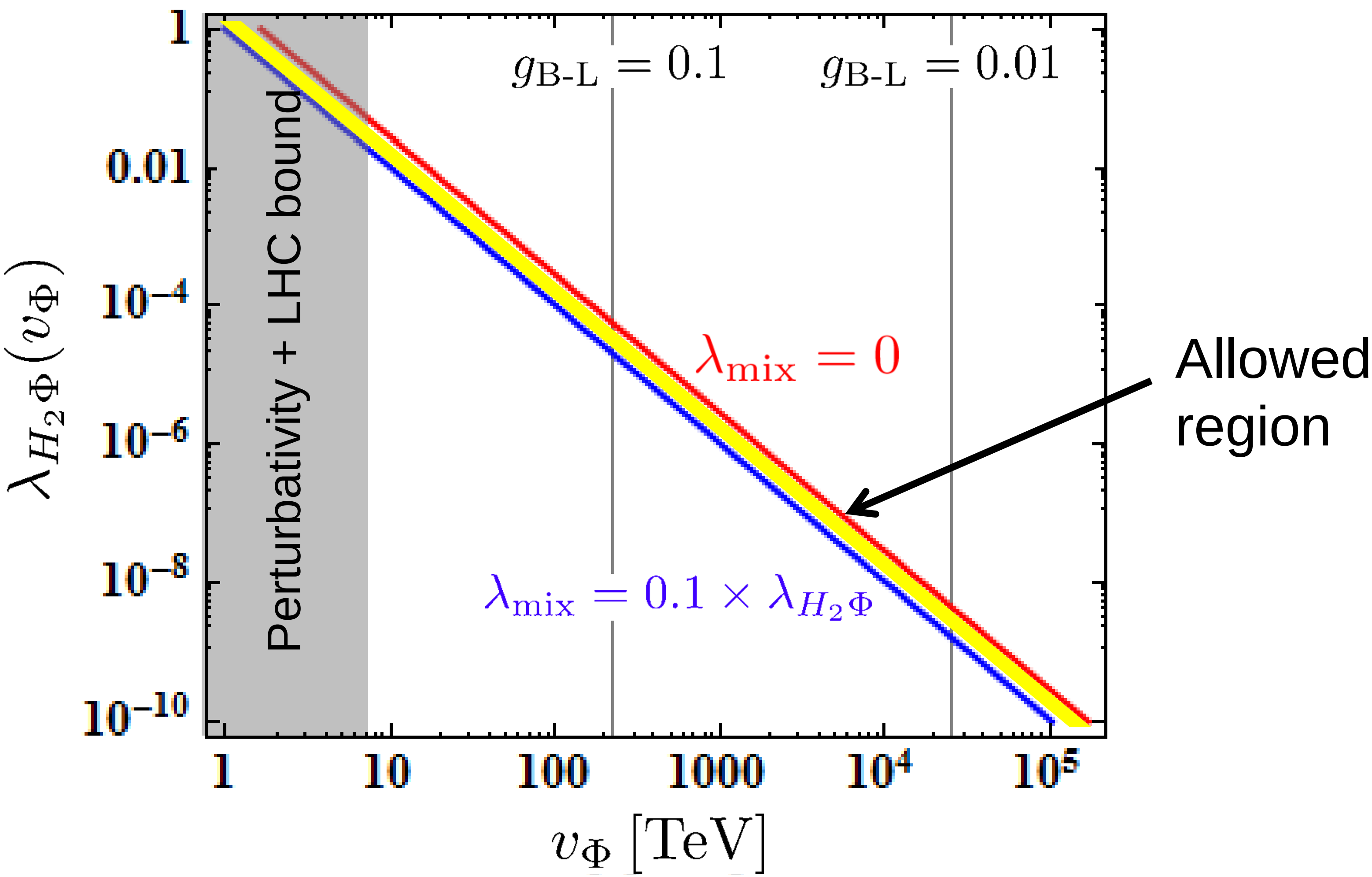
- Smallness of B-L gague contribution (assumption)

$$\delta m_h^2 \sim \frac{y_t^2 g_{\text{B-L}}^4}{(16\pi)^2} v_\Phi^2 < (10\,\text{GeV})^2$$

⇨ $v_\Phi < \dfrac{160\pi}{y_t g_{\text{B-L}}^2}\,\text{GeV}$

$$\sim 100\,\text{TeV}\ \text{for}\ g_{\text{B-L}} = 0.1$$

Relation between v_Φ and $\lambda_{H_2\Phi}$



To work the bosonic seesaw, $\lambda_{H_2\Phi} v_\Phi^2$ is almost fixed.

Vacuum stability

The EW vacuum becomes stable by the mixing between H_1 and H_2

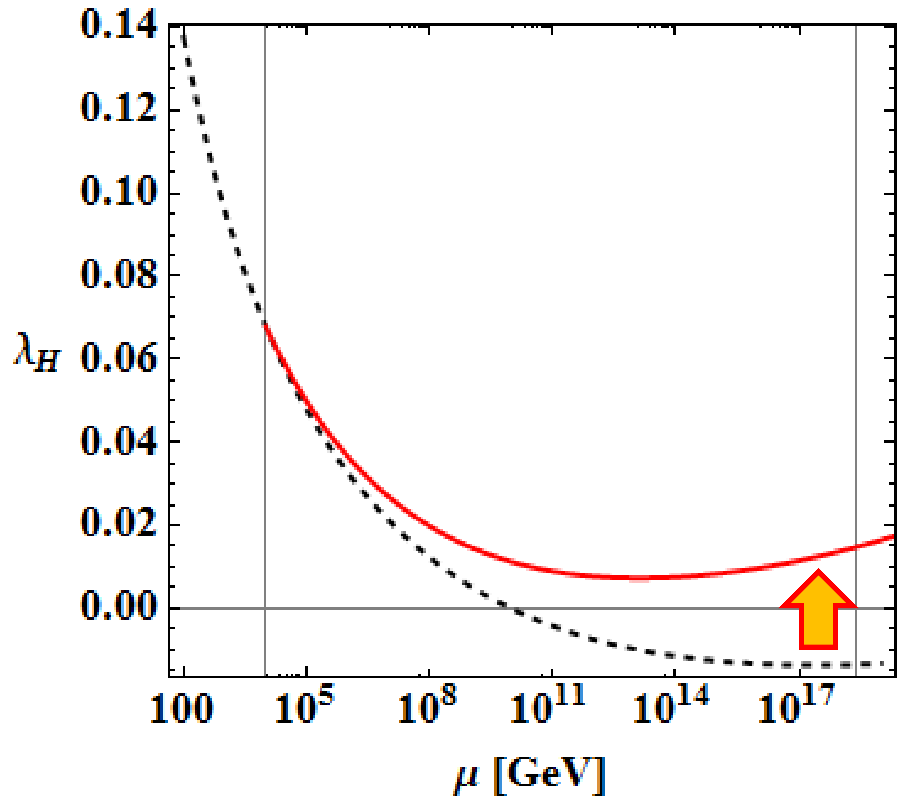
- The vacuum stability

$$\lambda_{3,4} \geq 0.15$$

- Perturbativity

$$\lambda_{3,4} \leq 0.48$$

$$0.15 \leq \lambda_{3,4} \leq 0.48$$



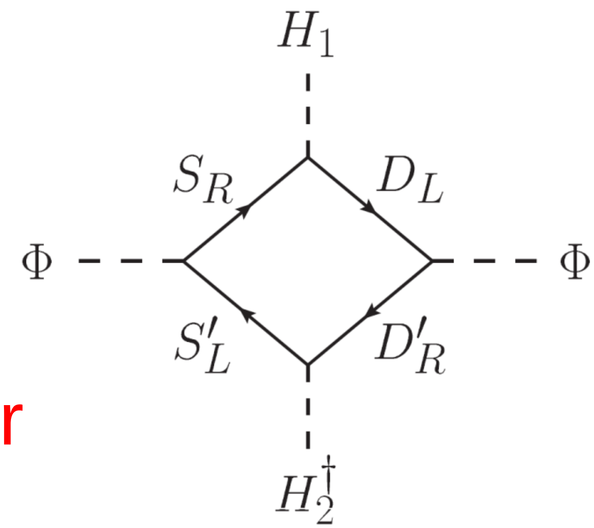
Further extension

- Toward more complete model

	$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L}$
$S_{L,R}$	$(1,\ 1,\ 0)$	x
$S'_{L,R}$	$(1,\ 1,\ 0)$	$x-2$
$D_{L,R}$	$(1,\ 2,\ 1/2)$	x
$D'_{L,R}$	$(1,\ 2,\ 1/2)$	$x+2$

Extra loop contributions appear in the running of $\lambda_{\rm mix}$

Hierarchy becomes much milder



Constraint on new parameters

- Extra Yukawa terms

$$-\mathcal{L} = Y_{SS}\overline{S_L}\Phi S'_R + Y_{SD}\overline{S'_R}H_2^\dagger D'_L + Y_{DD}\overline{D'_L}\Phi D_R + Y_{DS}\overline{D_R}H_1 S_L$$
$$+Y'_{SS}\overline{S_R}\Phi S'_L + Y'_{SD}\overline{S'_L}H_2^\dagger D'_R + Y'_{DD}\overline{D'_R}\Phi D_L + Y'_{DS}\overline{D_L}H_1 S_R + \mathrm{h.c.}$$

- Minimization condition

$$\lambda_\Phi \simeq \frac{11}{6\pi^2}\left(6g_{\text{B-L}}^4 - \mathrm{tr}Y_M^4 - \frac{1}{8}\left(Y_{SS}^4 + Y_{SS}'^4 + 2Y_{DD}^4 + 2Y_{DD}'^4\right)\right)$$

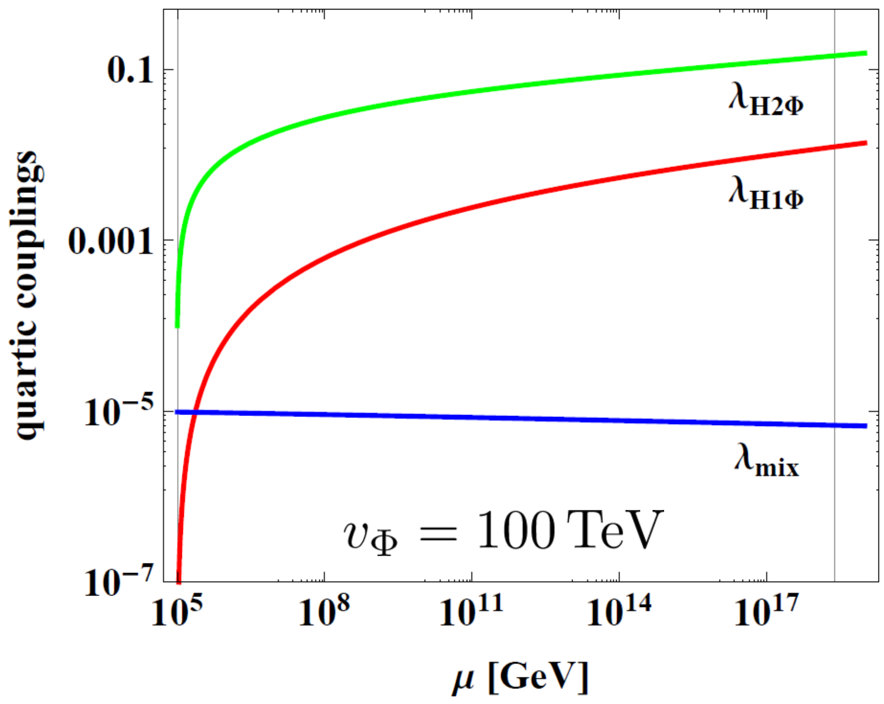
$\lambda_\Phi > 0$ and $g_{\text{B-L}} < 0.2$

$$Y_{SS}^4 + Y_{SS}'^4 + 2Y_{DD}^4 + 2Y_{DD}'^4 \lesssim 3 \times (0.4)^4$$

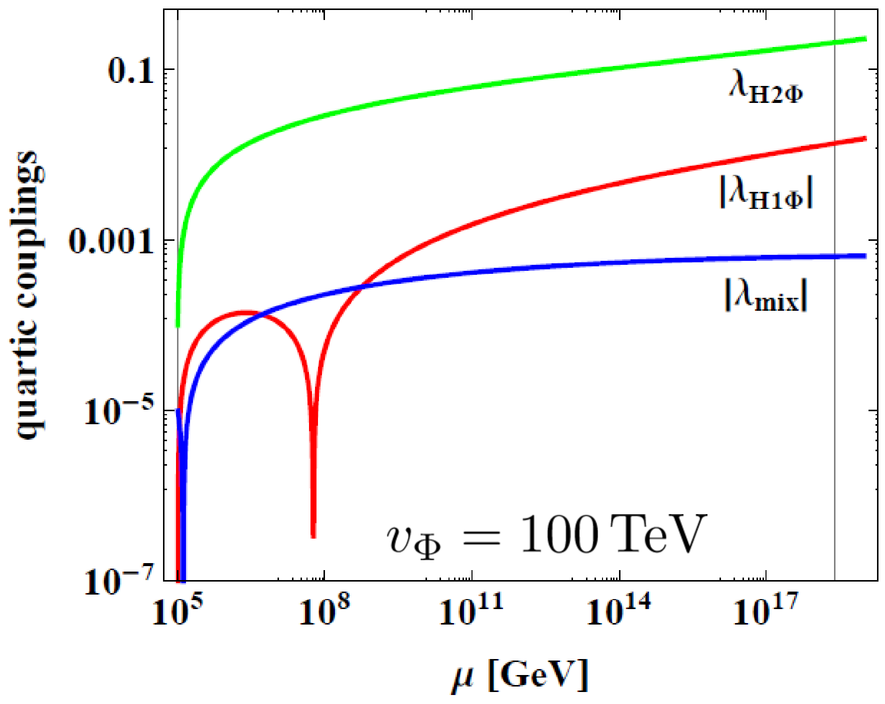
We take all Ys are 0.2 and Y's are 0.1 @ v_Φ

Running of quartic couplings

Before

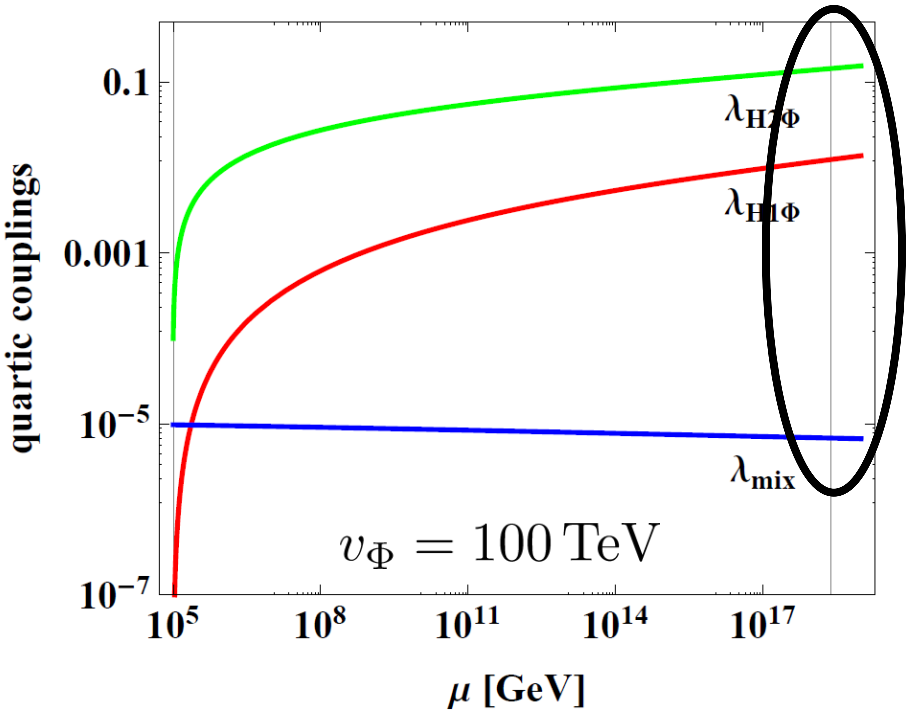


After

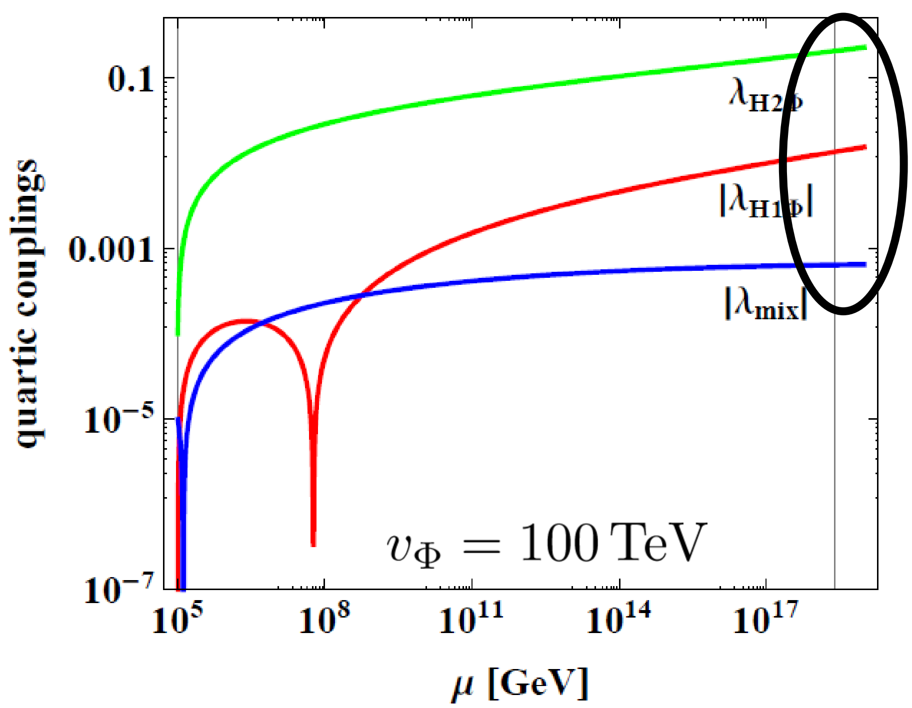


Running of quartic couplings

Before



After



Hierarchy for λ_{mix} becomes much milder than before.

⇔ There is no fine-tuning at the Planck scale.

Beta functions

Gauge couplings

$$\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}7, \qquad \beta_{g_2} = \frac{g_2^3}{16\pi^2}(-3), \qquad \beta_{g_3} = \frac{g_3^3}{16\pi^2}(-7)$$

$$\beta_{g_{B-L}} = \frac{g_{B-L}}{16\pi^2}\left(7g_{\rm mix}^2 + 8g_{\rm mix}g_{B-L} + \frac{68}{3}g_{B-L}^2\right)$$

$$\beta_{g_{\rm mix}} = \frac{1}{16\pi^2}\left[g_{\rm mix}\left(14g_Y^2 + 7g_{\rm mix}^2 + 8g_{\rm mix}g_{B-L} + \frac{68}{3}g_{B-L}^2\right) + 8g_{B-L}g_Y^2\right]$$

Yukawa couplings

$$\beta_{y_t} = \frac{y_t}{16\pi^2}\left(-8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{12}(g_Y^2 + g_{\rm mix}^2) - \frac{5}{3}g_{\rm mix}g_{B-L} - \frac{2}{3}g_{B-L}^2 + \frac{9}{2}y_t^2\right)$$

$$\beta_{Y_M} = \frac{Y_M}{16\pi^2}\left(-6g_{B-L}^2 + 4Y_M^2 + 2{\rm tr}Y_M^2\right)$$

Beta functions

Quartic couplings

$$\beta_{\lambda_1} = \frac{1}{16\pi^2}\Big[\frac{3}{8}\left(2g_2^4+(g_2^2+g_Y^2+g_{\rm mix}^2)^2\right)-6y_t^4+\lambda_1\left(-9g_2^2-3(g_Y^2+g_{\rm mix}^2)+12y_t^2\right)$$
$$+24\lambda_1^2+2\lambda_3^2+2\lambda_3\lambda_4+\lambda_4^2+\lambda_{H1\Phi}^2\Big]$$

$$\beta_{\lambda_2} = \frac{1}{16\pi^2}\Big[\frac{3}{8}\left(2g_2^4+(g_2^2+g_Y^2+g_{\rm mix}^2)^2\right)+48g_{B-L}^2(g_2^2+g_Y^2)-12g_{\rm mix}g_{B-L}(g_2^2+g_Y^2+g_{\rm mix}^2)$$
$$+144g_{\rm mix}^2g_{B-L}^2-768g_{\rm mix}g_{B-L}^3+1536g_{B-L}^4-6y_t^4+\lambda_2\left(-9g_2^2-3(g_Y^2+g_{\rm mix}^2)\right.$$
$$\left.+48g_{\rm mix}g_{B-L}-192g_{B-L}^2+12y_t^2\right)+24\lambda_2^2+2\lambda_3^2+2\lambda_3\lambda_4+\lambda_4^2+\lambda_{H2\Phi}^2\Big]$$

$$\beta_{\lambda_3} = \frac{1}{16\pi^2}\Big[\frac{3}{4}(2g_2^4+(-g_2^2+g_Y^2+g_{\rm mix}^2)^2)+48g_{\rm mix}^2g_{B-L}^2-12g_{\rm mix}g_{B-L}(-g_2^2+g_{\rm mix}^2+g_Y^2)$$
$$+\lambda_3(-9g_2^2-3(g_Y^2+g_{\rm mix}^2)+24g_{\rm mix}g_{B-L}-96g_{B-L}^2+6y_t^2+12\lambda_1+12\lambda_2)+4\lambda_3^2$$
$$+4\lambda_1\lambda_4+4\lambda_2\lambda_4+2\lambda_4^2+2\lambda_{H1\Phi}\lambda_{H2\Phi}\Big]$$

$$\beta_{\lambda_4} = \frac{1}{16\pi^2}\Big[3g_2^2(g_Y^2+g_{\rm mix}^2)-24g_2^2g_{\rm mix}g_{B-L}+\lambda_4(-9g_2^2-3(g_Y^2+g_{\rm mix}^2)+24g_{\rm mix}g_{B-L}$$
$$-96g_{B-L}^2+6y_t^2+4\lambda_1+4\lambda_2+8\lambda_3)+4\lambda_4^2+4\lambda_{\rm mix}^2\Big]$$

Beta functions

Quartic couplings

$$\beta_{\lambda_\Phi} = \frac{1}{16\pi^2}\left(96 g_{B-L}^4 - 16\mathrm{tr}Y_M^4 + \lambda_\Phi(-48 g_{B-L}^2 + 8\mathrm{tr}Y_M^2) + 20\lambda_\Phi^2 + 2\lambda_{H1\Phi}^2 + 2\lambda_{H2\Phi}^2 + 4\lambda_{\mathrm{mix}}^2\right)$$

$$\beta_{\lambda_{H1\Phi}} = \frac{1}{16\pi^2}\left[\lambda_{H1\Phi}\left(-\frac{9}{2}g_2^2 - \frac{3}{2}(g_Y^2 + g_{\mathrm{mix}}^2) - 24 g_{B-L}^2 + 4\mathrm{tr}Y_M^2 + 6y_t^2 + 12\lambda_1 + 8\lambda_\Phi\right)\right.$$
$$\left. + 4\lambda_{H1\Phi}^2 + 4\lambda_3\lambda_{H2\Phi} + 2\lambda_4\lambda_{H2\Phi} + 8\lambda_{\mathrm{mix}}^2 + 12 g_{\mathrm{mix}}^2 g_{B-L}^2\right]$$

$$\beta_{\lambda_{H2\Phi}} = \frac{1}{16\pi^2}\left[\lambda_{H2\Phi}\left(-\frac{9}{2}g_2^2 - \frac{3}{2}(g_Y^2 + g_{\mathrm{mix}}^2) + 24 g_{\mathrm{mix}} g_{B-L} - 120 g_{B-L}^2 + 4\mathrm{tr}Y_M^2 + 12\lambda_2 + 8\lambda_\Phi\right)\right.$$
$$\left. + 4\lambda_{H2\Phi}^2 + 4\lambda_3\lambda_{H1\Phi} + 2\lambda_4\lambda_{H1\Phi} + 8\lambda_{\mathrm{mix}}^2 + 12 g_{\mathrm{mix}}^2 g_{B-L}^2 - 192 g_{\mathrm{mix}} g_{B-L}^3 + 768 g_{B-L}^4\right]$$

$$\beta_{\lambda_{\mathrm{mix}}} = \frac{\lambda_{\mathrm{mix}}}{16\pi^2}\left[-\frac{9}{2}g_2^2 - \frac{3}{2}(g_Y^2 + g_{\mathrm{mix}}^2) + 12 g_{\mathrm{mix}} g_{B-L} - 72 g_{B-L}^2 + 4\mathrm{tr}Y_M^2 + 3y_t^2 + 2\lambda_3 + 4\lambda_4\right.$$
$$\left. + 4\lambda_{H1\Phi} + 4\lambda_{H2\Phi} + 4\lambda_\Phi\right]$$