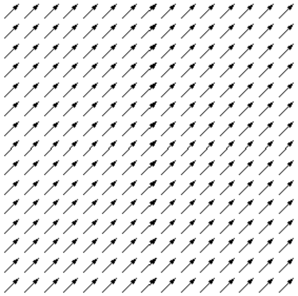
What 126 GeV Higgs mass means?
(5)

Scalars 2015, Warsaw, 3-7 Dec/2015

Naoyuki Haba (Shimane U, Japan)

波 場



Higgs (but still no BSM) discovery at LHC

$m_H = 125.09 \pm 0.32$ GeV, $m_{top} = 173.34 \pm 0.76$ GeV in the SM

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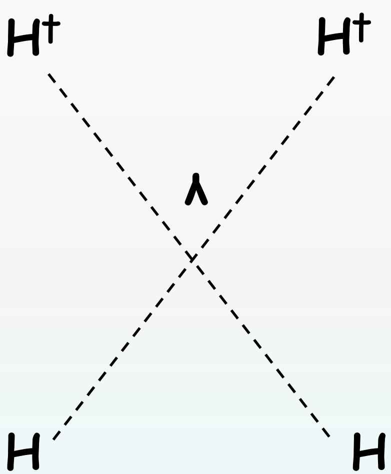
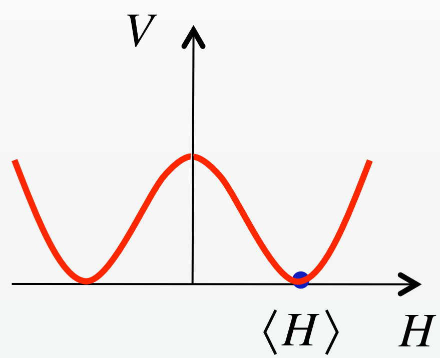


Higgs potential



$$V = \underbrace{\lambda}_{\parallel \, 0.131@M_Z}(|H|^2 - v)^2$$

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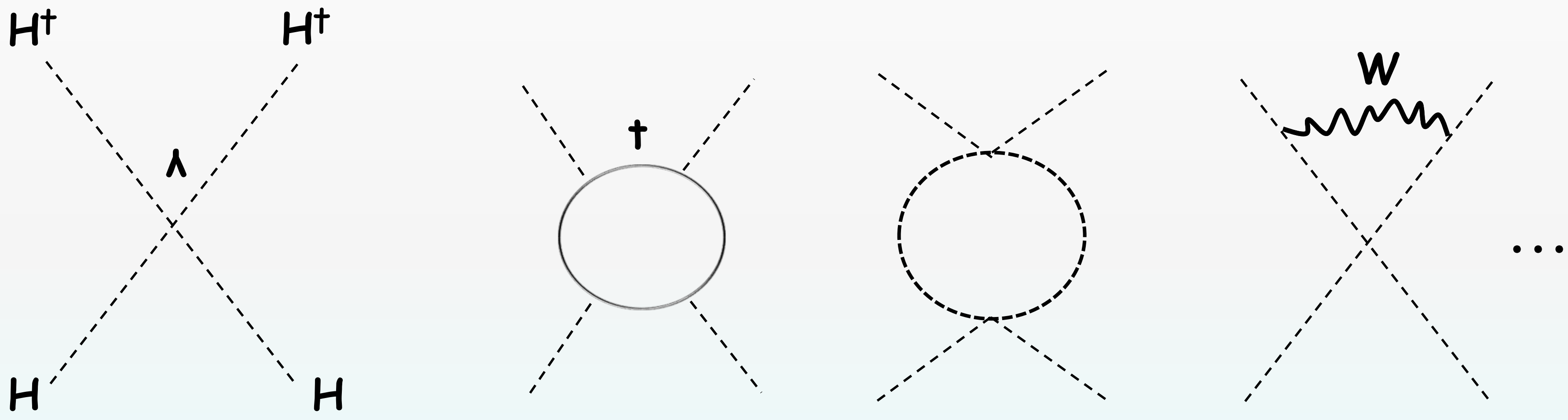
Quantum corrections



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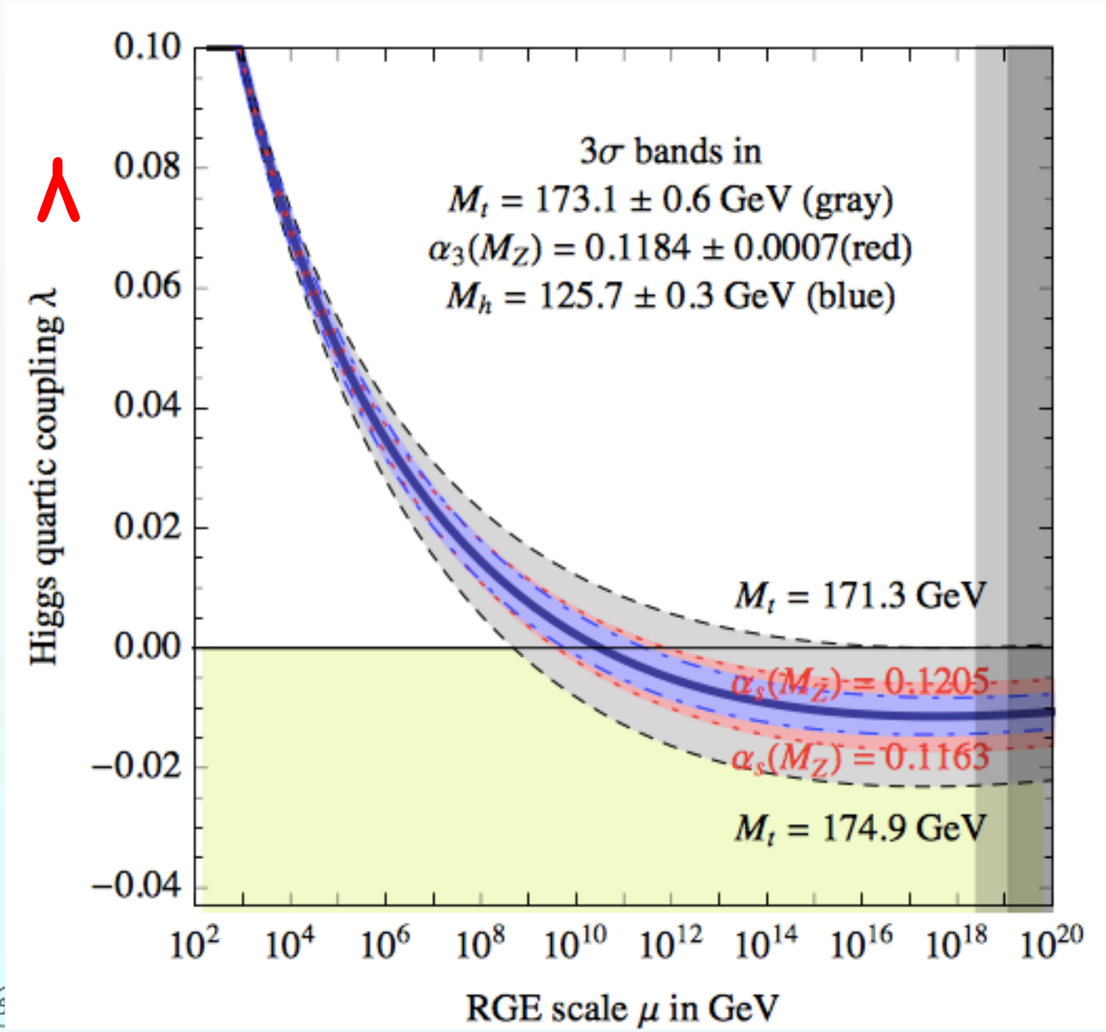

$$(4\pi)^2 \frac{d\lambda}{dt} = \underbrace{24\lambda^2 + 12\lambda y_t^2 - 6y_t^4 - 3\lambda(g'^2 + 3g^2) + \frac{3}{8}[2g^4 + (g'^2 + g^2)^2]}_{\beta_\lambda}$$

G.Degrassi, S.Di Vita, J.Elias-Miro, J.R.Espinosa, G.F.Giudice, G.Isidori and A.Strumia, JHEP1208 (2012) 098

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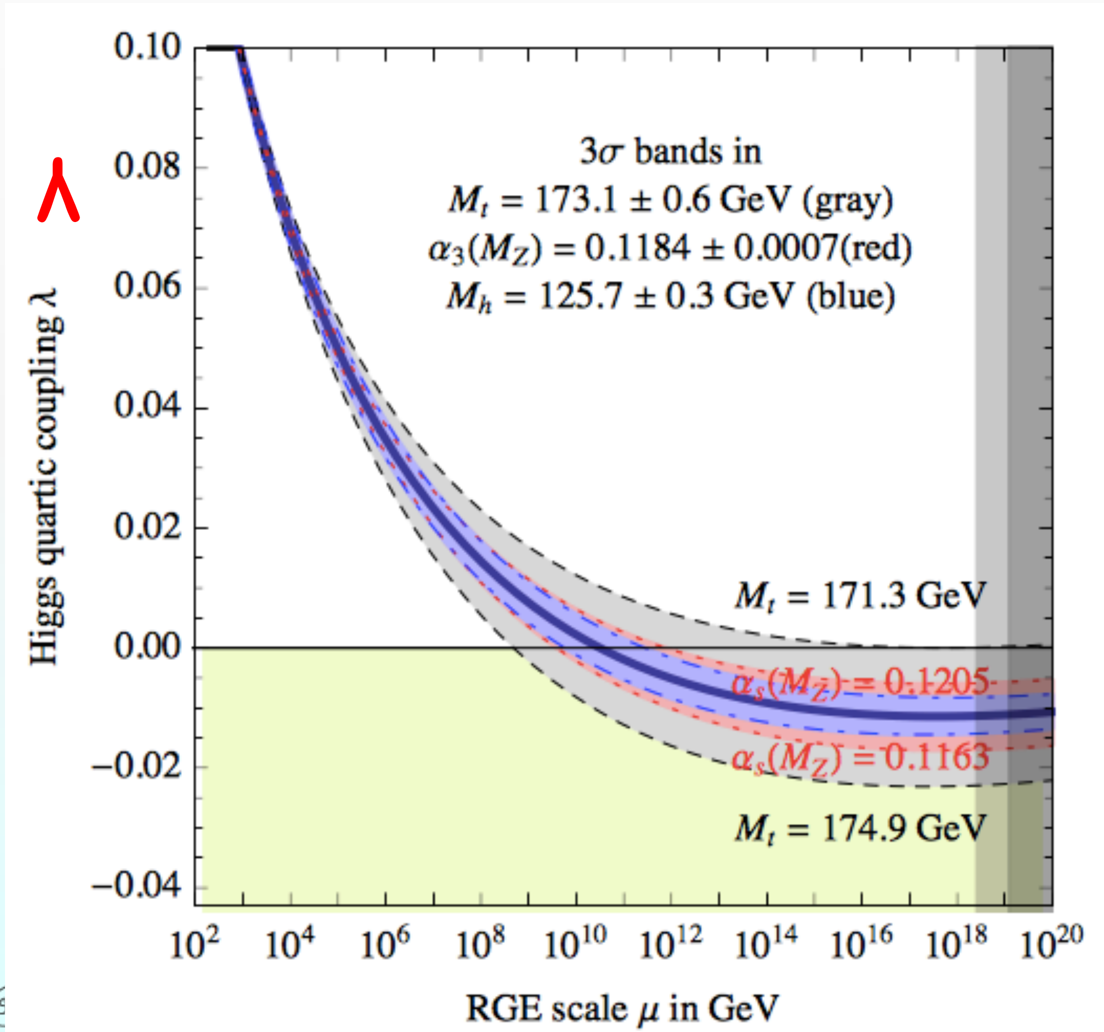

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↗ Higgs mass

↘ **top mass**

Higgs (but still no BSM) discovery at LHC

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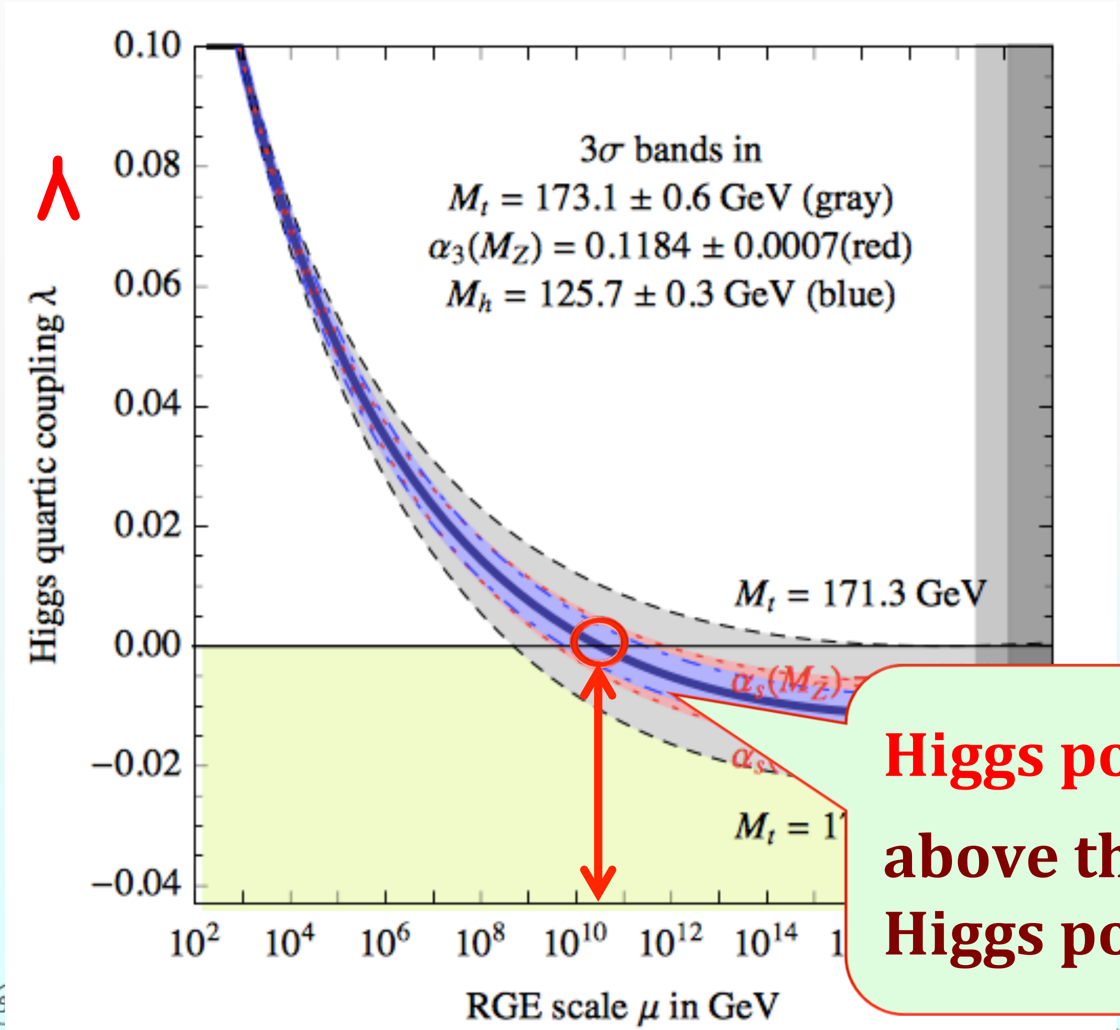

$$(4\pi)^2 \frac{d\lambda}{dt} = 24\lambda^2 + 12\lambda y_t^2 - 6y_t^4$$

$$-3\lambda(g'^2 + 3g^2) + \frac{3}{8}[2g^4 + (g'^2 + g^2)^2]$$

↗ Higgs mass

↘ top mass

Higgs pot. =0 at O(10^{10}) GeV

above the scale as M_{GUT}, M_P,

Higgs pot. is unbounded.

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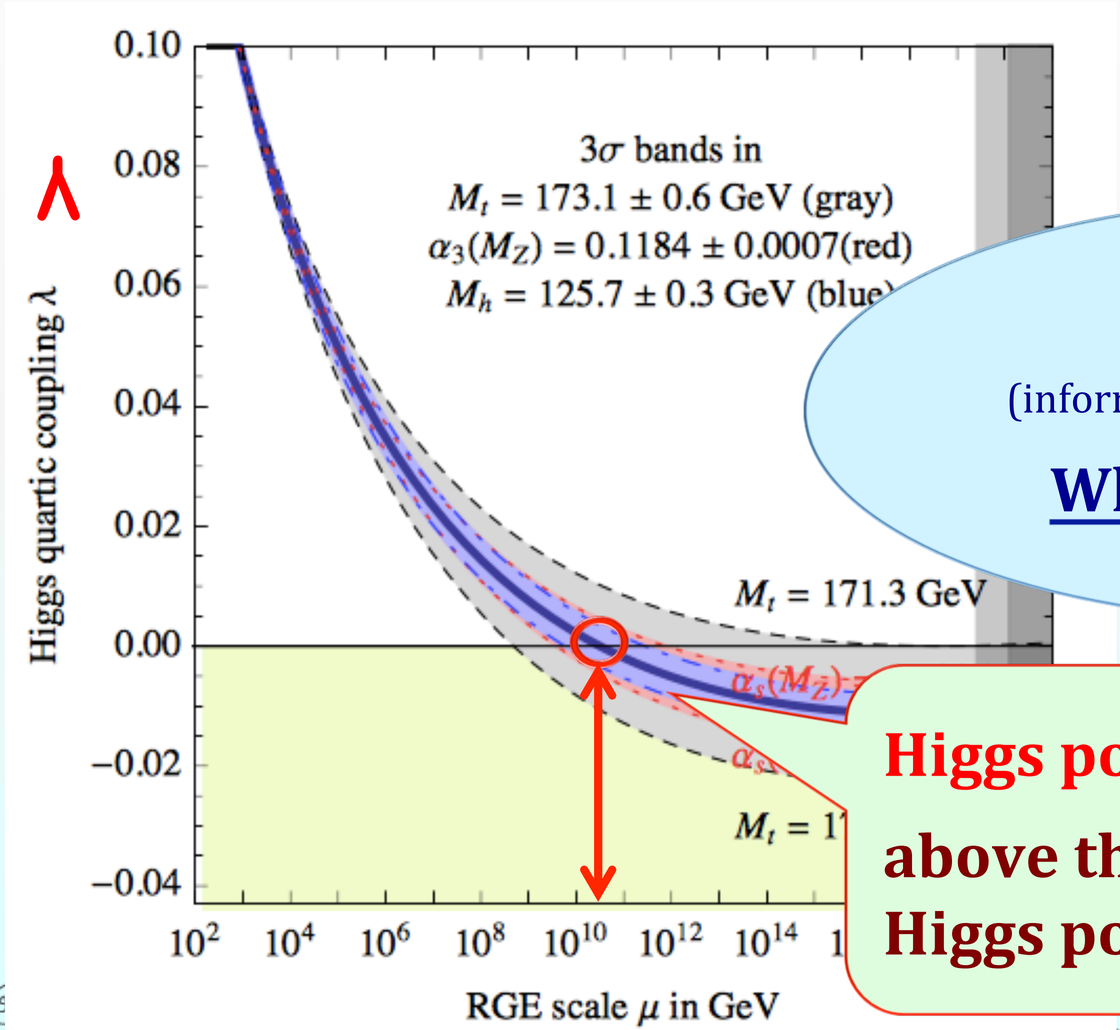


$$(4\pi)^2 \frac{d\lambda}{dt} = 24\lambda^2 + 12\lambda y_t^2 - 6y_t^4$$

Why not Mp?

(information of quantum gravity)

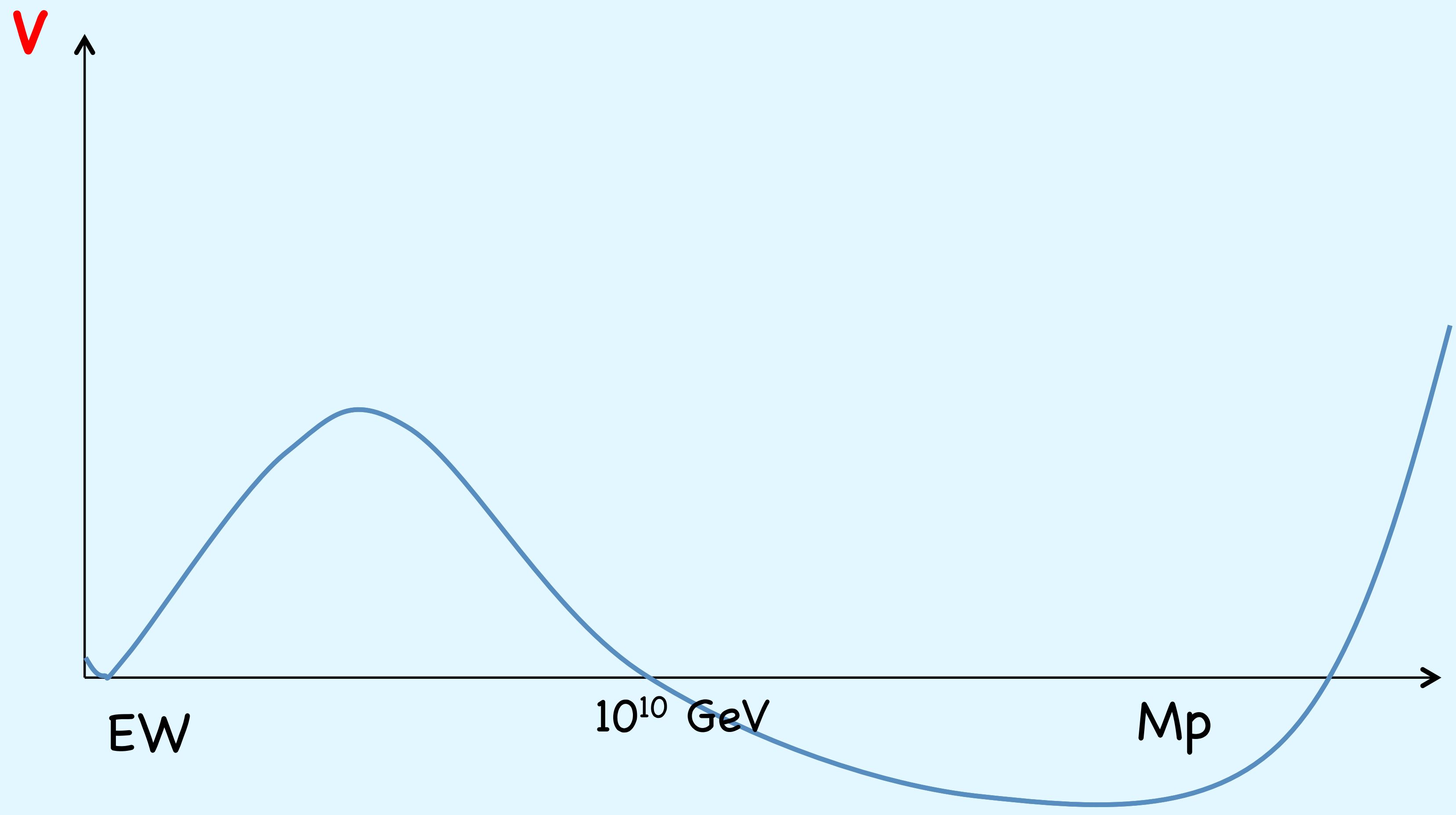
What is 10^{10} GeV?

Higgs pot. =0 at O(10^{10}) GeV

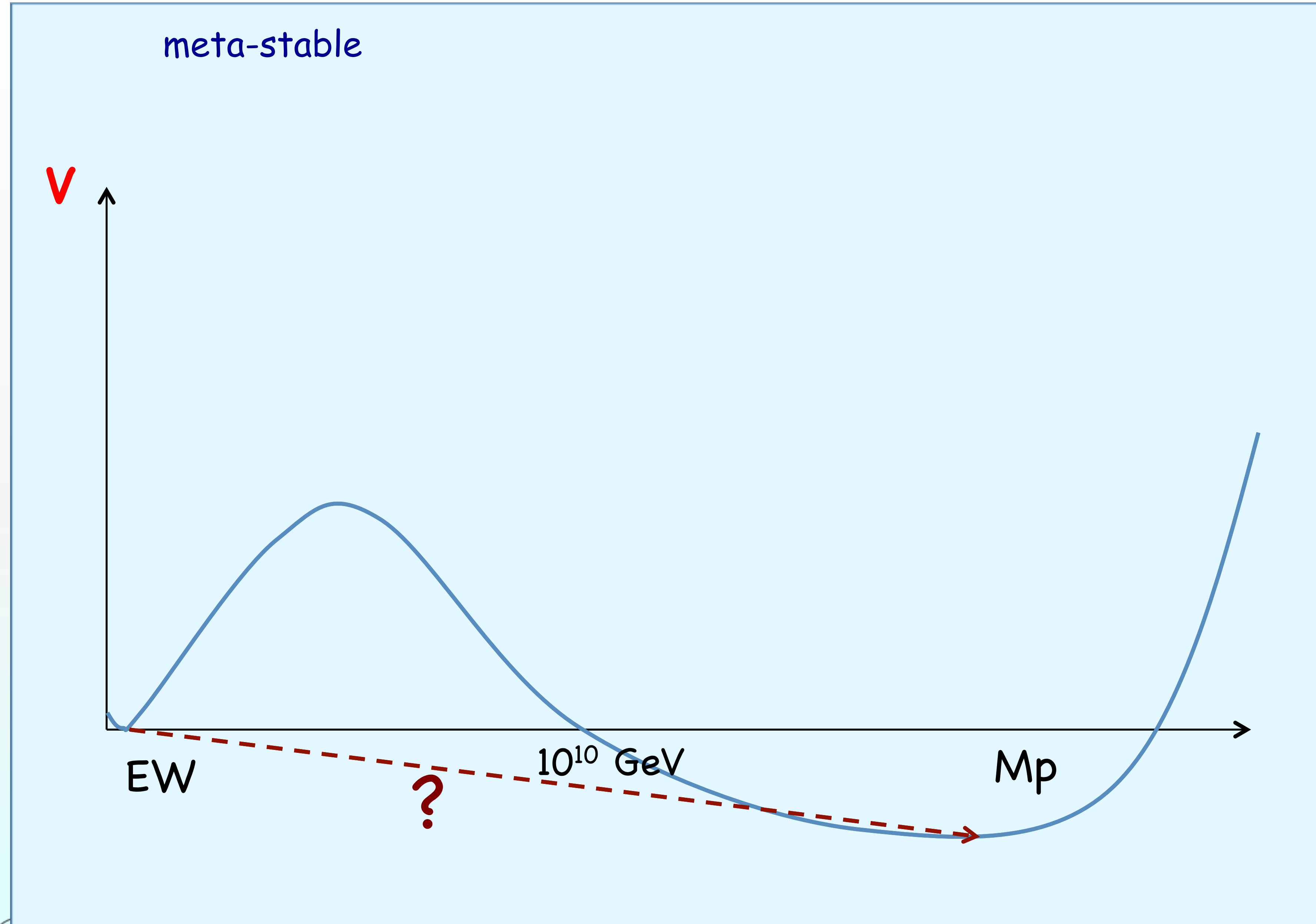
above the scale as M_{GUT}, M_P, Higgs pot. is unbounded.

SM Higgs potential

meta-stable



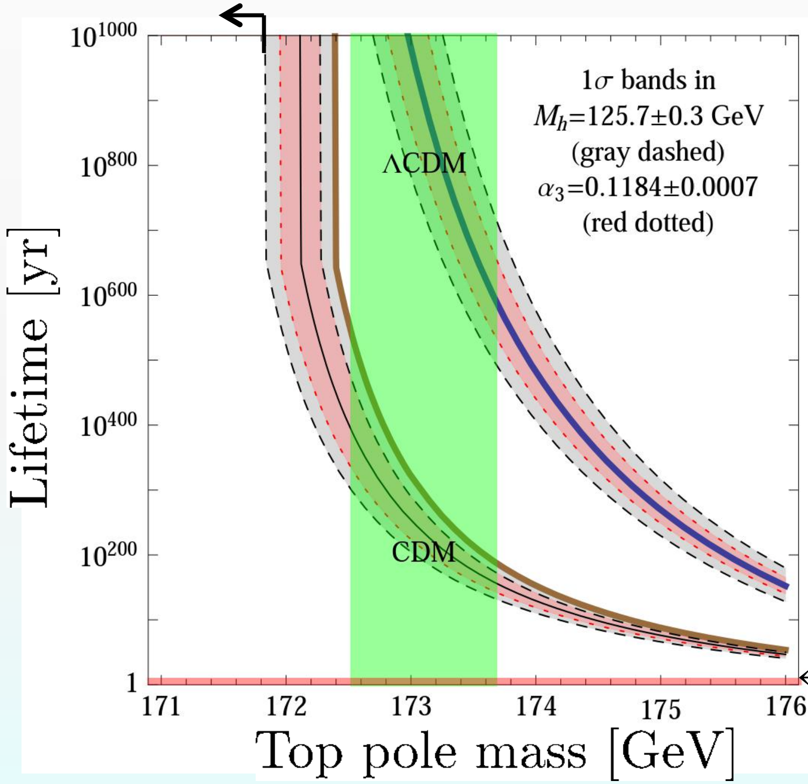
SM Higgs potential



SM Higgs potential seems meta-stable

lifetime is much longer than age of our Universe

$\lambda_H(\Lambda_B) > 0$ (Vacuum is stable)



Age of our Universe
(T_U = 13.8 Gyr)

[Buttazzo, et al., arXiv:1307.3536]

Lifetime

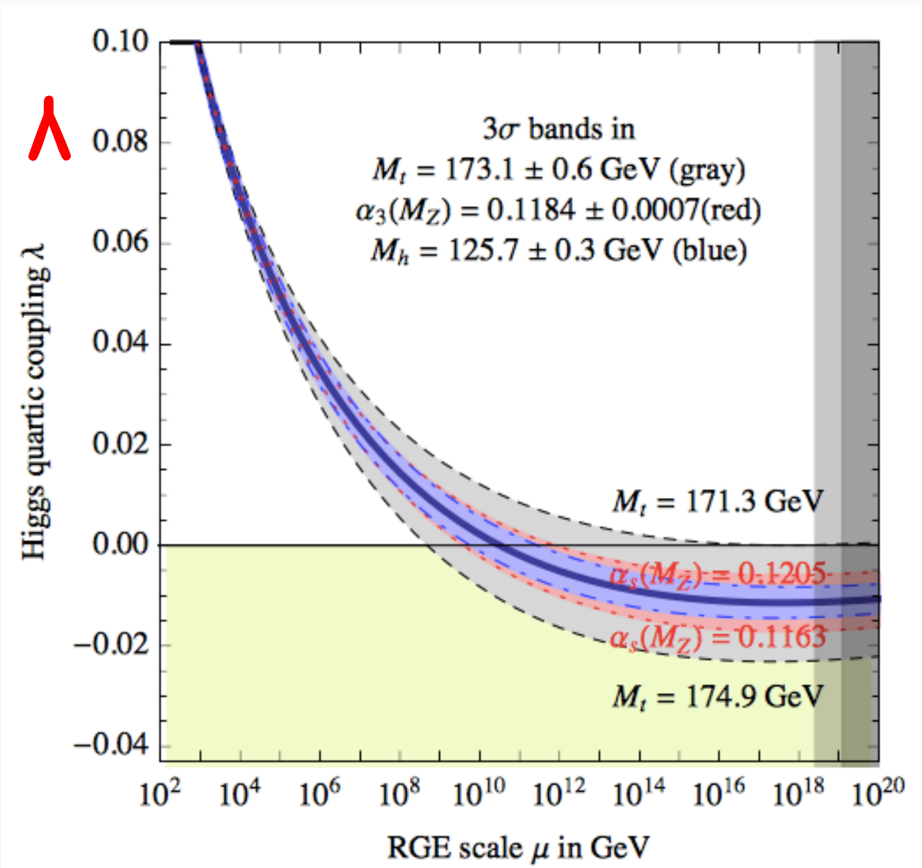
$$\tau = \begin{cases} \left(\frac{55}{3\pi}\right)^{1/4} \frac{e^{S(\Lambda_B)/4}}{\Lambda_B} \approx \frac{T_U}{p_0^{1/4}} & \text{for CDM} \\ \frac{3H^3 e^{S(\Lambda_B)}}{4\pi\Lambda_B^4} \approx \frac{0.02\, T_U}{p_0} & \text{for } \Lambda\text{CDM} \end{cases}$$

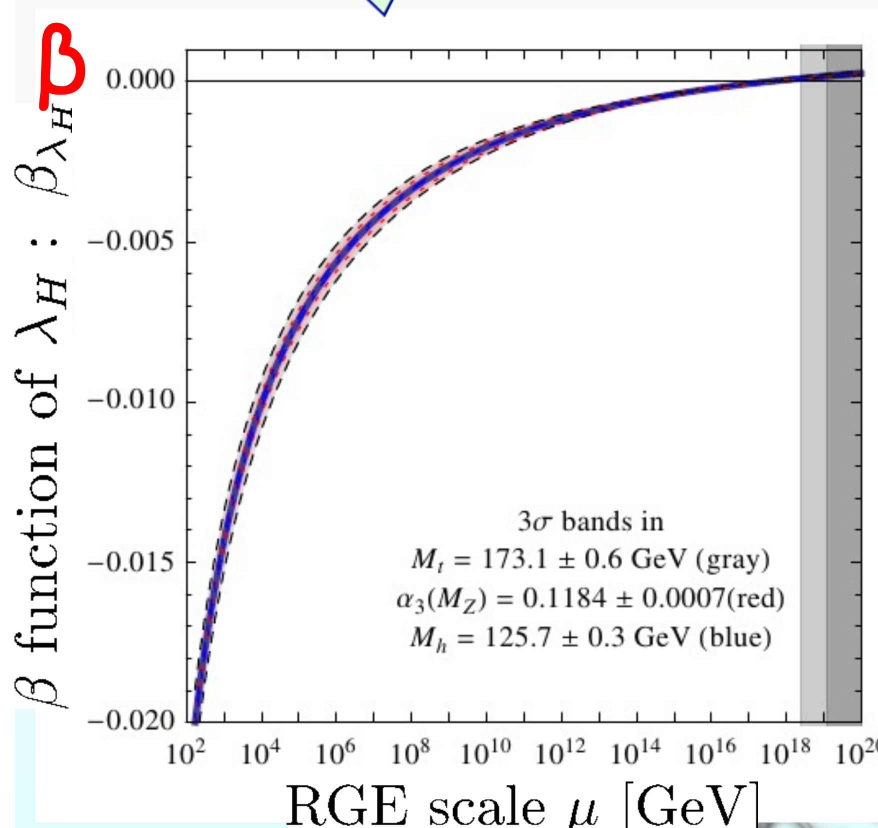
$$\begin{cases} \Lambda_B \text{ satisfys } \beta_{\lambda_H}(\Lambda_B) = 0 \\ S(\Lambda_B) = \frac{8\pi^2}{3|\lambda_H(\Lambda_B)|} \\ p_0 = 0.15 \frac{\Lambda_B^4}{H_0^4} e^{-S(\Lambda_B)} \end{cases}$$

Higgs (but still no D

How about slope of
the Higgs potential?

m_H = 125.09 ±0.32 GeV, m_{top} ... the SM





SM Higgs potential?

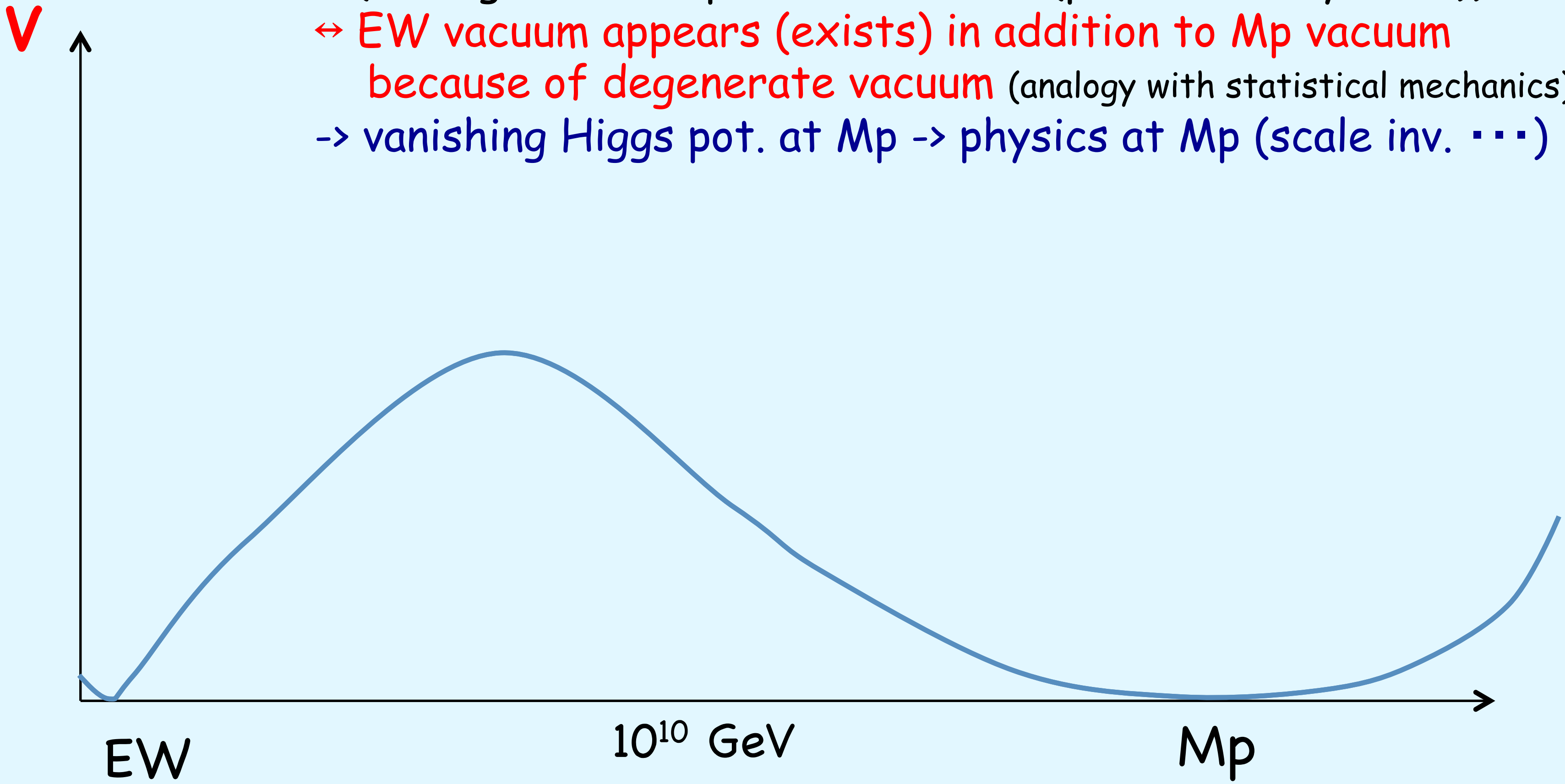
$\lambda=\beta=0$ at Mp (multiple point principle(MPP)) ['95 Froggatt, Nielsen]

Analogy with triple point of water

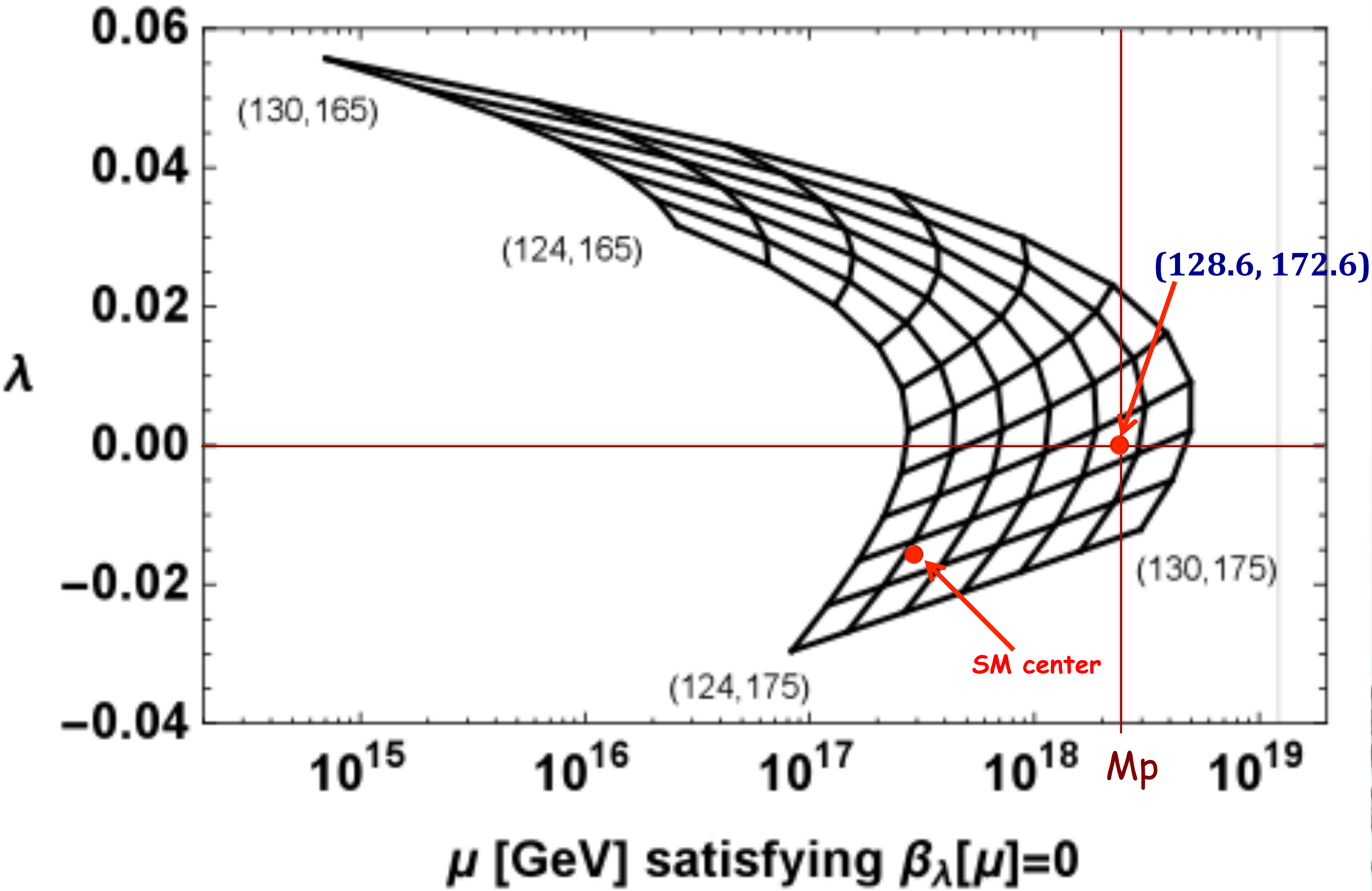
(strong 1st order phase transition (predictability E, P,.))

↔ EW vacuum appears (exists) in addition to Mp vacuum because of degenerate vacuum (analogy with statistical mechanics)

-> vanishing Higgs pot. at Mp -> physics at Mp (scale inv. ･･･)



Higgs mass & top mass dependence for λ, β



Higgs mass & top mass are uniquely determined by MPCP @ Mp

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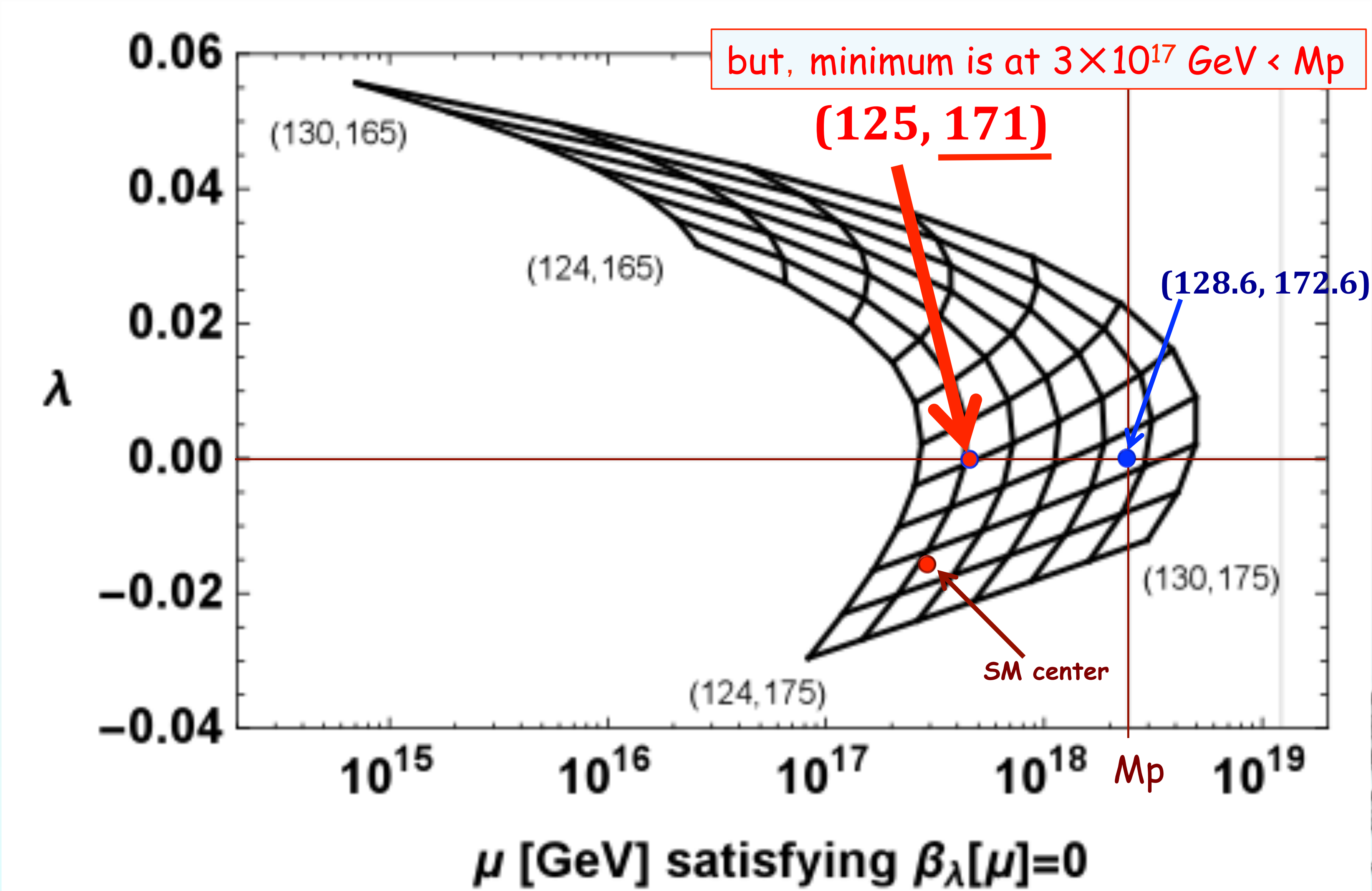

Higgs mass & top mass are uniquely determined by MPCP @ Mp

1. What is 10^{10} GeV? not Mp?

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2. BSM must exist.

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big mysteries remain in the SM, such as,

(A): What is origin of “Mexican hat” Higgs potential?
(B): Why $m_\nu \ll m_{q/l}$?
(C): What is dark matter?
(D): Why Q(p) = -Q(e)?
(E): Why our universe is 4D?
. . . . .

→ strongly suggest an existence of more fundamental physics beyond the SM (BSM).

1. What is 10^{10} GeV? not Mp?

2. BSM must exist.

3. **Naturalness**

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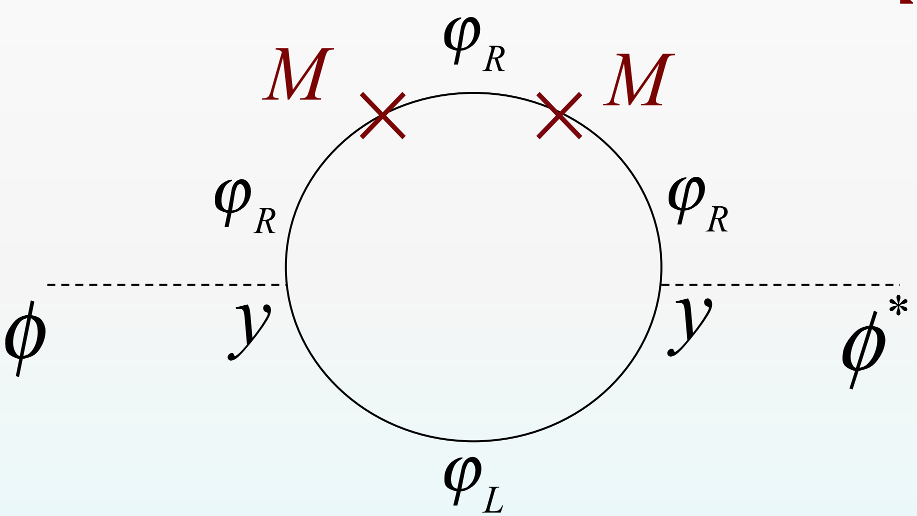
3. Naturalness



【Heavy particles which couples to Higgs】

$$\int \frac{d^4 p}{16\pi^2}\left(\frac{i}{\not p}\right)^4 M_R^2$$

$$\sim -\frac{y^2}{16\pi^2} M^2 \log \Lambda$$

1. What is 10^{10} GeV? not Mp?

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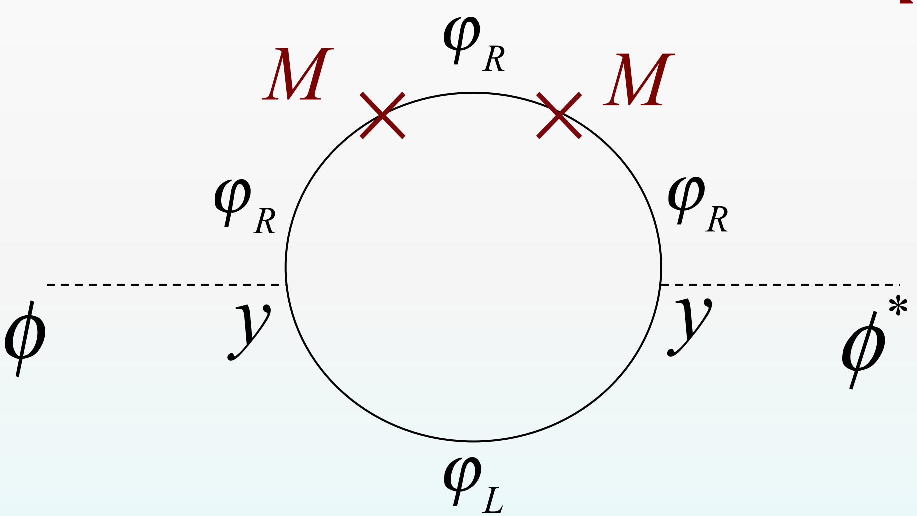

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$$\int \frac{d^4 p}{16\pi^2}\left(\frac{i}{p}\right)^4 M_R^2$$

$$\sim -\underline{\frac{y^2}{16\pi^2} M^2 \log \Lambda}$$

$$< (125\ GeV)^2$$

Physical quantity independent of renormalization scheme
（↔ **quadratic divergence**）

→ **Higgs mass inevitably receive this quantum correction that should be smaller than 125 GeV.**

1. What is 10^{10} GeV? not Mp?

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【Heavy particles which couples to Higgs】

M

$$M_h^2 = -2m_h^2 - \frac{y^2}{16\pi^2} M^2 \log\Lambda$$

Δm^2 ($<125^2\ \mathrm{GeV}^2$)

$$(125\,\mathrm{GeV})^2 = (\mathcal{O}(100)\,\mathrm{GeV})^2 + \left(\mathcal{O}(\sqrt{\lambda}M)\,\mathrm{GeV}\right)^2$$

Bardeen's argument for naturalness

['95 Bardeen]

☆ quadratic divergence does not physical,

– *care about only logarithmic divergence*

☆ running of m_h^2 is governed by RGE,

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

← no other mass scales

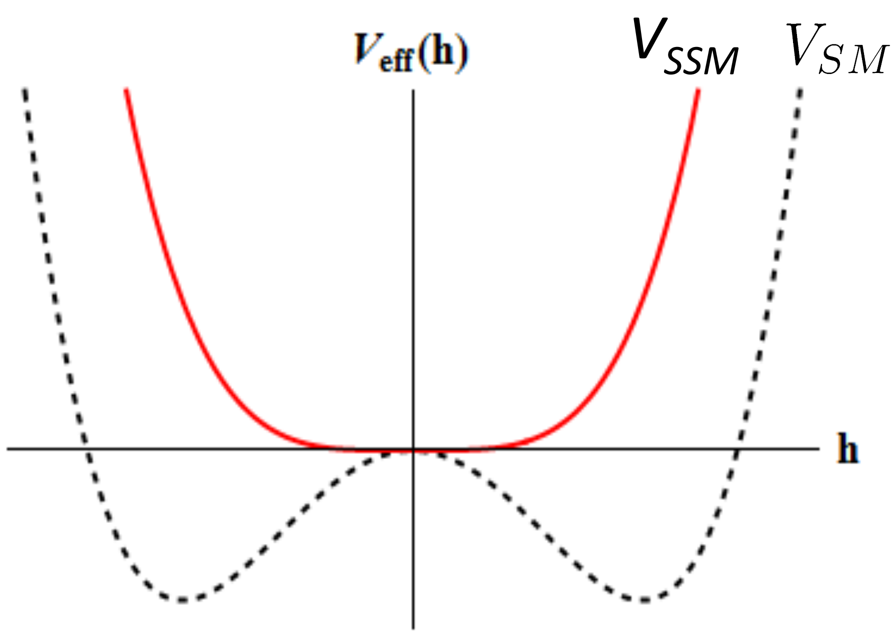
once m_h^2 vanishes (← classical scale inv. is imposed), it remains zero.

→ non-zero Higgs mass needs quantum effects of RGE + α

classical scale invariance symmetry

Field equation should be invariant for rescaling ($x \to Cx$)
→ There are no dimensionful parameters at classical level.

- In SM, only Higgs mass parameter m_h^2 is dimensionful



$$\begin{cases} V_{SM} = \frac{1}{4}\lambda_H h^4 + \frac{1}{2} m_h^2 h^2 \\ V_{SSM} = \frac{1}{4}\lambda_H h^4 \end{cases}$$

In SSM, EWSB cannot occur at classical level.

classical scale invariance symmetry

+α quantum effects can break classical scale inv.

- Coleman-Weinberg mechanism
- hidden strong dynamics (dimensional transmutation)

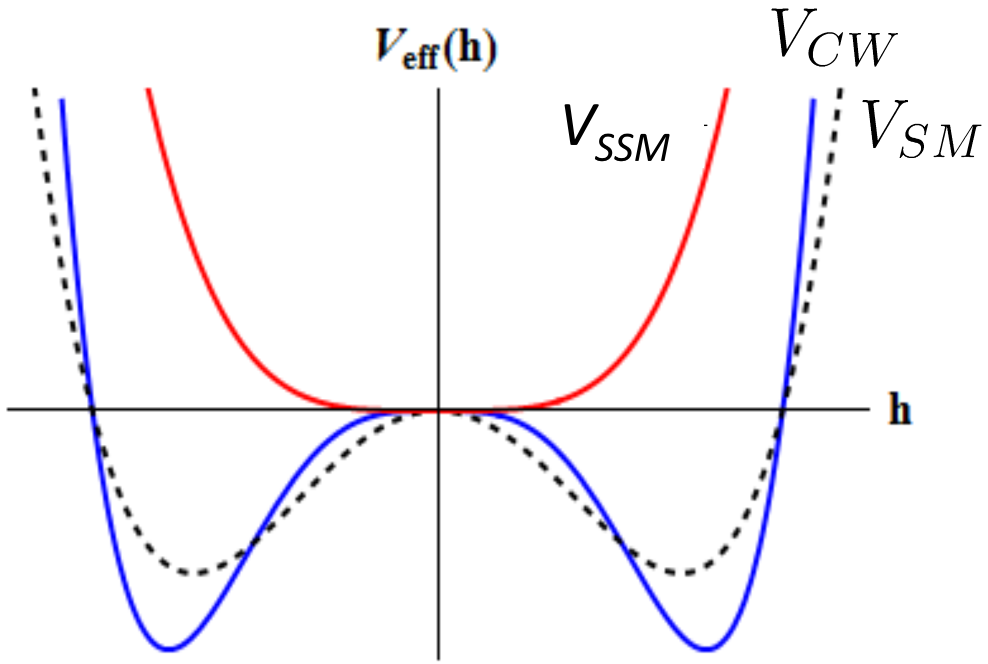
  ……

classical scale invariance symmetry

+α quantum effects can break classical scale inv. that leads EWSB

- Coleman-Weinberg ['73 Coleman, Weinberg]

$$V_{CW} = \frac{1}{4}\lambda_H h^4 + \sum_i \frac{h^4}{64\pi^2} n_i \alpha_i^2 \left[\ln\left(\frac{h^2}{Q^2}\right) - C_i\right]$$



n_i : d.o.f of particle i

α_i : coupling of Higgs with i

C_i : constant for i

Q : renormalization scale

classical scale invariance symmetry

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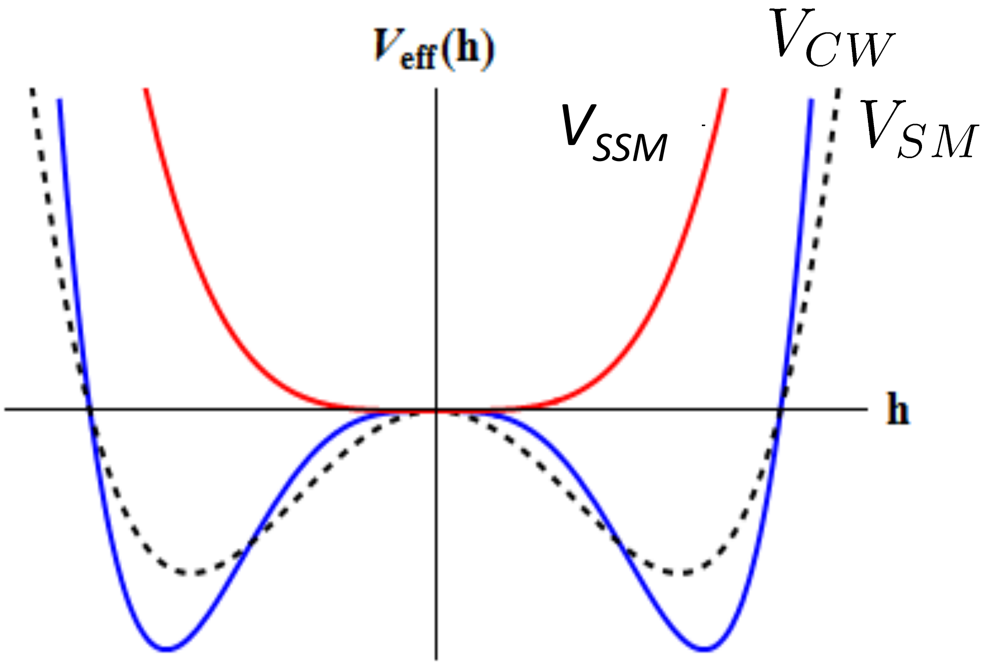

n_i : d.o.f of particle i

α_i : coupling of Higgs with i

C_i : constant for i

Q : renormalization scale

it requires tiny λ_H!

→125 GeV (λ_H~0.131) is too large to occur EWSB in the SM.

classical scale invariance symmetry

+α quantum effects can break classical scale inv. that leads EWSB

- hidden strong dynamics (dimensional transmutation)

$$V_{Hidden} = \frac{1}{4}\lambda_H h^4 - \frac{1}{2}\,\lambda_{mix}\,\langle S\rangle^2 h^2$$

⟨S⟩≠0 is triggered by condensation of hidden fermion pair.

['11 Hur, Jung, Ko, Lee]
['14 Holthausen, Kubo, Lim, Lindner]

Bardeen's argument for naturalness

['95 Bardeen]

☆ quadratic divergence does not physical,

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→ **non-zero Higgs mass needs quantum effects RGE + α**

(Coleman-Weinberg, strong effects, ・・・)

☆ **no heavy particles with intermediate energy scale masses**

$$M_h^2 = -2m_h^2 \underbrace{- \frac{y^2}{16\pi^2} M^2 \log\Lambda}$$

Δm^2 (<125² GeV²)

1. What is 10^{10} GeV? not Mp?

2. BSM must exist.

3. Naturalness

A: completely new physics at 10^{10} GeV

(GH, strong dynamics, composite)

B: Higgs potential is stable up to Mp

new particles effects which do not be contained in SM
(type-II seesaw, DM, GUT)

C: Higgs potential vanishes at Mp

(flatland, strong dynamics)

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☆ Gauge-Higgs Unification

Higgs=extra-dimensional component of higher-dimensional gauge field

$$A_M = A_\mu + \mathbf{A_5} \ \textbf{(scalar @ 4D)}$$

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above energy of 1/R (size of XD) , Higgs is absorbed into A_M.

→ Higgs potential vanishes at 10^{10} GeV ↔ 1/R = 10^{10} GeV !?

$H \sim A_5$

R

5D

$m_H \sim 1/16\pi^2 \times (1/R)$

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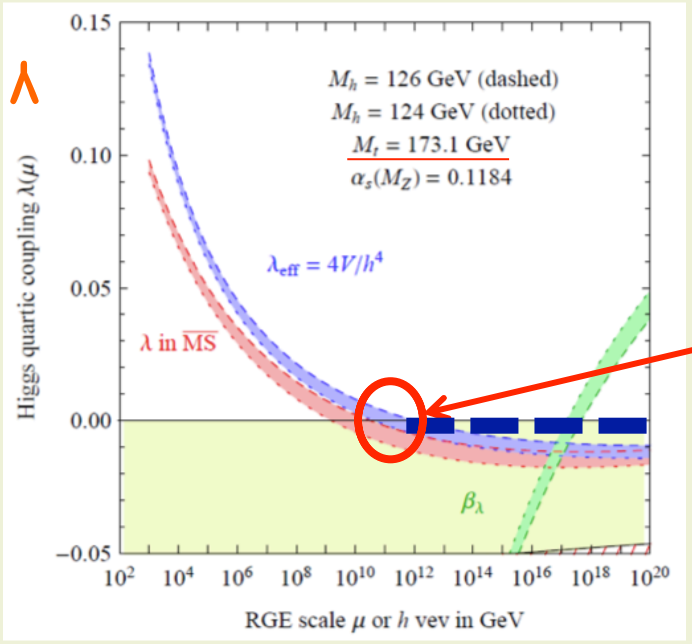

For this meta-stability, GHU says

1/R~10^{10} GeV!

N. Okada, Q. Shafi, et al

B: Higgs potential is stable up to Mp

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Possibly, effects of yet-to-be-discovered particles !?

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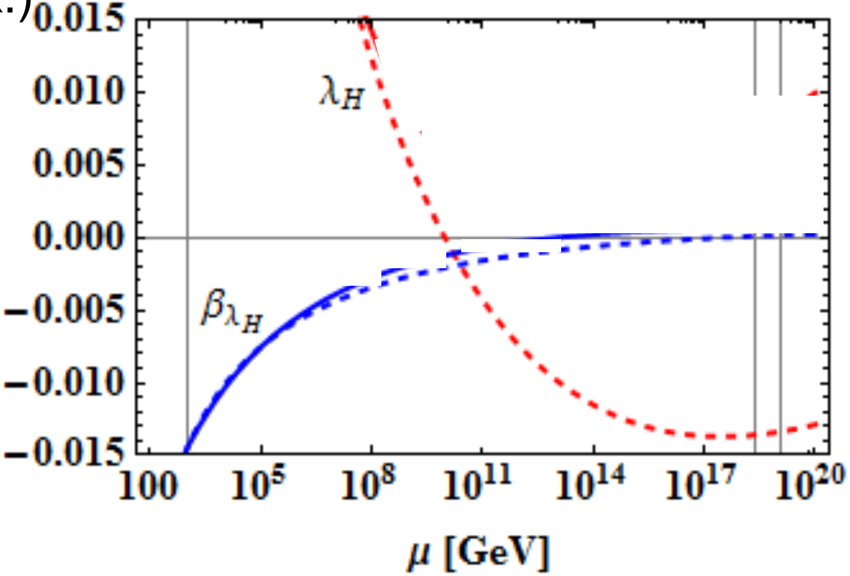
Possibly, effects of yet-to-be-discovered particles !?

→ β_λ of SM,

$$\beta_{\lambda_H} = \frac{1}{(4\pi)^2}\left[\lambda_H\left(24\lambda_H + 12y_t^2 - 3g_Y^2 - 9g_2^2\right) - 6y_t^4 + \frac{3}{8}g_Y^4 + \frac{9}{8}g_2^4 + \frac{3}{4}g_Y^2 g_2^2\right]$$

ex.)



B: Higgs potential is stable up to Mp

Possibly, effects of yet-to-be-discovered particles !?

→ β_λ becomes larger than SM, **+ ◎**

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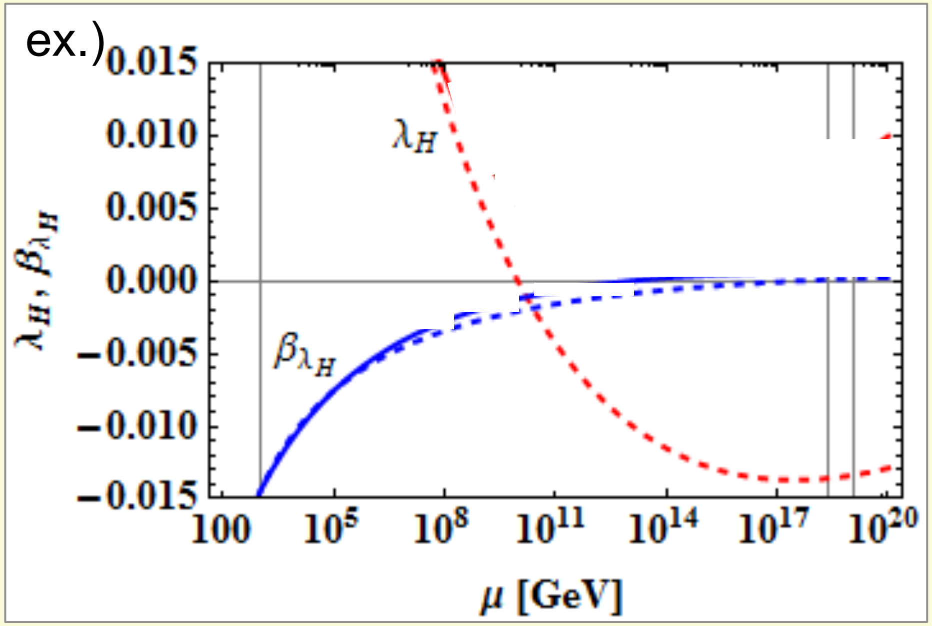

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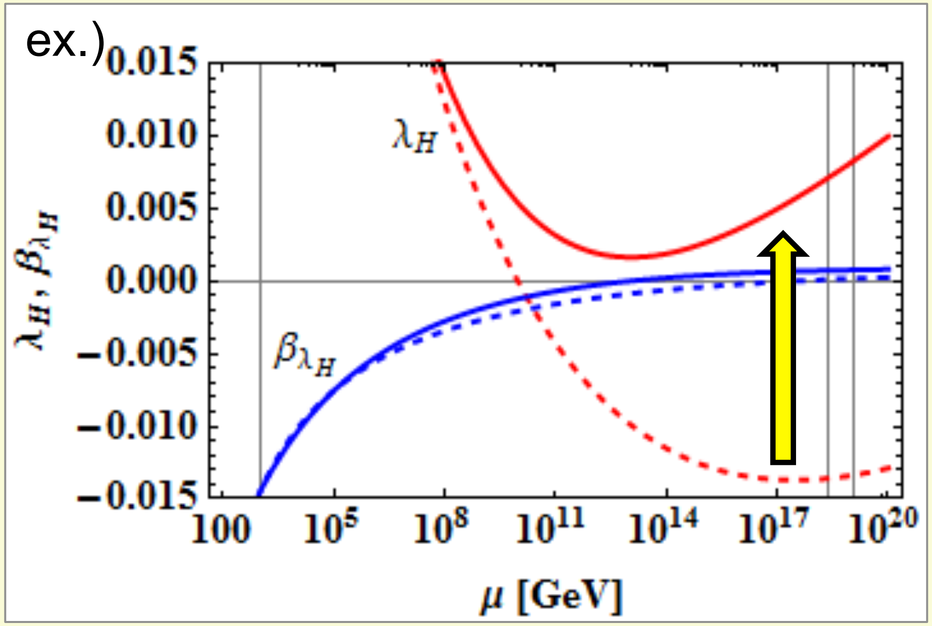
→ λ > 0 at any energy scale.



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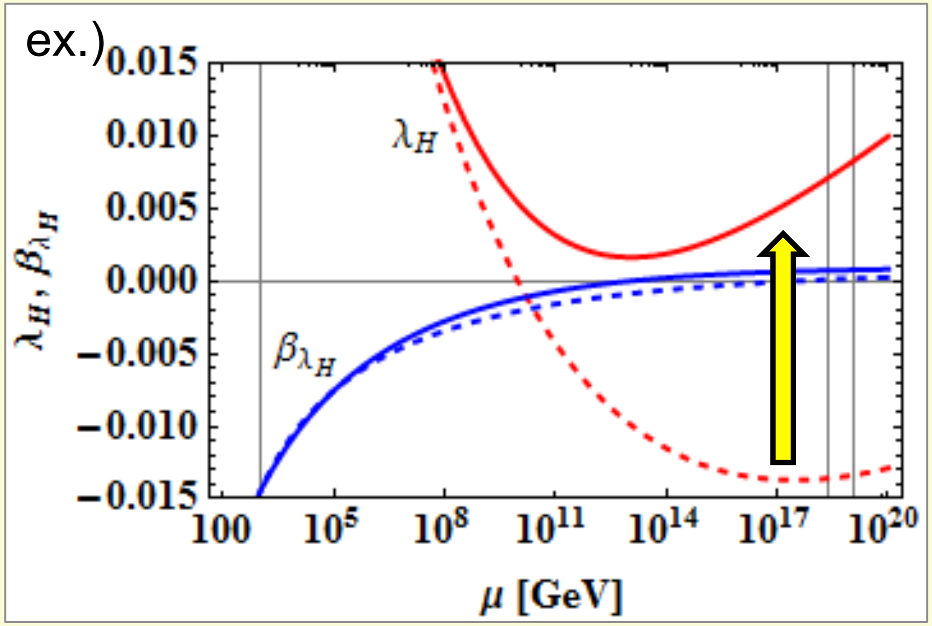
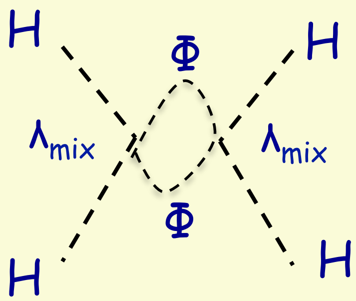
→ $\lambda > 0$ at any energy scale.



[example]

- **new scalar** with coupling

$\lambda_{mix} H^2 \Phi^2 \rightarrow \beta \sim + \lambda_{mix}^2$



B: Higgs potential is stable up to Mp

Possibly, effects of yet-to-be-discovered particles !?

→ β_λ becomes larger than SM, **+ g'^{4}**

$$\beta_{\lambda_H} = \frac{1}{(4\pi)^2}\left[\lambda_H\left(24\lambda_H + 12y_t^2 - 3g_Y^2 - 9g_2^2\right) - 6y_t^4 + \frac{3}{8}g_Y^4 + \frac{9}{8}g_2^4 + \frac{3}{4}g_Y^2 g_2^2\right]$$

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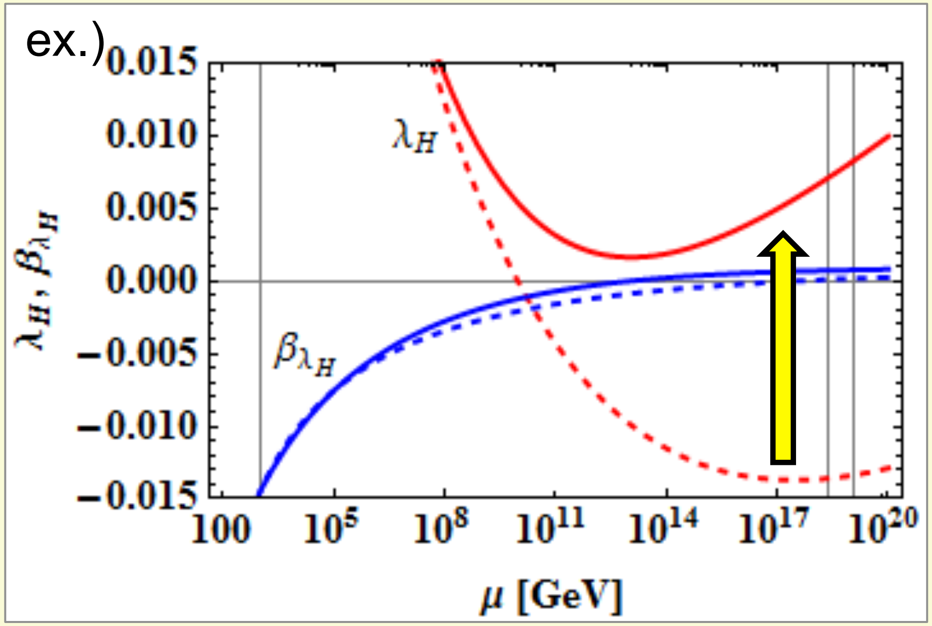

[example]

- **new scalar** with coupling

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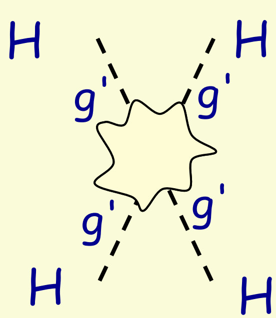
- **new gauge** which couples with H



→ β∼**+ g'^{4}**

B: Higgs potential is stable up to Mp

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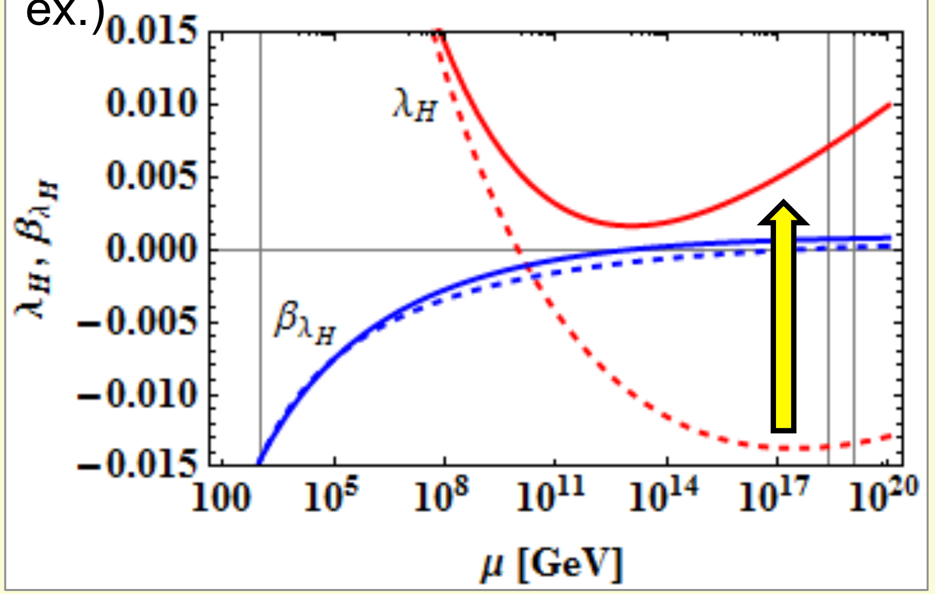
$$\beta_{\lambda_H} = \frac{1}{(4\pi)^2}\left[\lambda_H\left(24\lambda_H + 12y_t^2 - 3g_Y^2 - 9g_2^2\right) - \overset{\text{smaller}}{6y_t^4} + \overbrace{\frac{3}{8}g_Y^4 + \frac{9}{8}g_2^4 + \frac{3}{4}g_Y^2g_2^2}^{\text{larger}}\right]$$

→ $\lambda > 0$ at any energy scale.

ex.)



[example]

- **new scalar** with coupling

  $\lambda_{mix} H^2 \Phi^2 \;\rightarrow \beta \sim + \lambda_{mix}^2$

- **new gauge** which couples with H

  $\rightarrow \beta \sim + g'^4$

- **new particles with SM charges → larger gauge couplings**

  → β becomes larger via larger $+g^4$ (+ smaller y_t via y_t RGE)

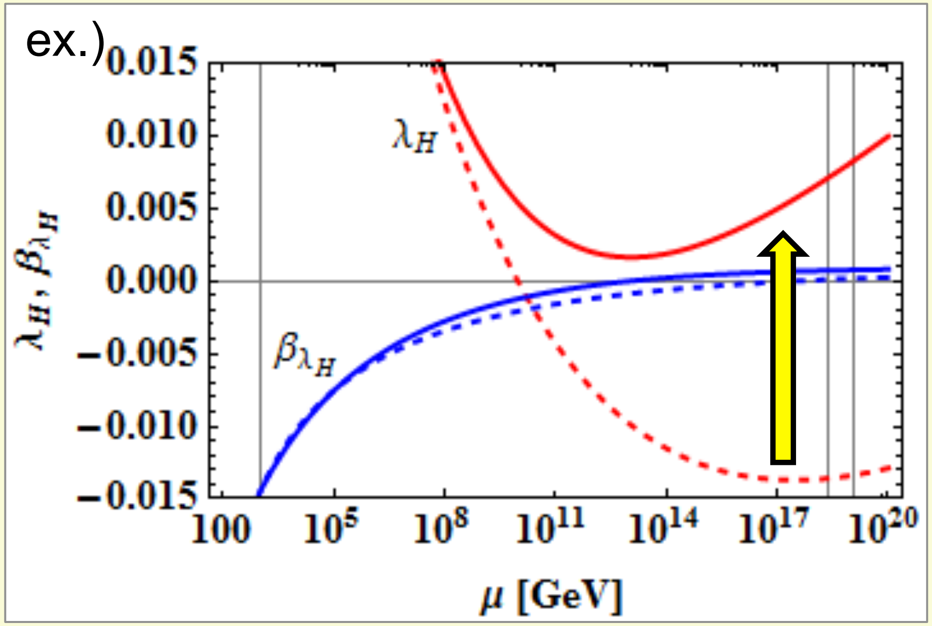
B: Higgs potential is stable up to Mp

Possibly, effects of yet-to-be-discovered particles !?

→ β_λ becomes larger than SM,

$$\beta_{\lambda_H} = \frac{1}{(4\pi)^2}\left[\lambda_H\left(24\lambda_H + 12y_t^2 - 3g_Y^2 - 9g_2^2\right) - \overset{\text{smaller}}{6y_t^4} + \overbrace{\frac{3}{8}g_Y^4 + \frac{9}{8}g_2^4 + \frac{3}{4}g_Y^2 g_2^2}^{\text{larger}}\right]$$

→ $\lambda > 0$ at any energy scale.



[example]

- **new scalar** with coupling

  $\lambda_{mix} H^2 \Phi^2 \rightarrow \beta \sim + \lambda_{mix}^2$

- **new gauge** which couples with H

  $\rightarrow \beta \sim + g'^4$

- **new particles with SM charges → larger gauge couplings**

  → β becomes larger via larger $+g^4$ (+ smaller y_t via y_t RGE)

B: Higgs potential is stable up to Mp

(ex) GUT @ Mp model

NH, Ishida, Takahashi, Yamaguchi
arXiv:1412.8230

- **naturalness → no intermediate scales such as GUT** (Bardeen)

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(ex) GUT @ Mp model

- **naturalness → no intermediate scales such as GUT** (Bardeen)
  - **→ GCU is also realized at Mp**
  - → extra SM charged vector-like fields realize GCU at Mp

Extra fermions	(b'_1, b'_2, b'_3)	α_{GUT}^{-1}
$W \times 1\ (0.5) \oplus U\overline{U} \times 1\ (1) \oplus Q\overline{Q} \times 2\ (10) \oplus D\overline{D} \times 4\ (10)$	$(\frac{12}{5}, \frac{16}{3}, 6)$	19.1
$E\overline{E} \times 2\ (0.5) \oplus Q\overline{Q} \times 2\ (2) \oplus Q\overline{Q} \times 2\ (10) \oplus D\overline{D} \times 4\ (10)$	$(\frac{46}{15}, 6, \frac{20}{3})$	14.9
$L\overline{L} \times 1\ (0.5) \oplus E\overline{E} \times 1\ (0.5) \oplus Q\overline{Q} \times 1\ (1) \oplus U\overline{U} \times 1\ (1) \oplus Q\overline{Q} \times 2\ (10) \oplus D\overline{D} \times 4\ (10)$	$(\frac{56}{15}, \frac{20}{3}, \frac{22}{3})$	11.1
$E\overline{E} \times 1\ (0.5) \oplus W \times 1\ (0.5) \oplus U\overline{U} \times 2\ (4) \oplus Q\overline{Q} \times 3\ (10) \oplus D\overline{D} \times 4\ (10)$	$(\frac{22}{5}, \frac{22}{3}, 8)$	7.95

m_H=125.09±0.32 GeV, m_{top}=173.34±0.76 GeV in the SM

$$(4\pi)^2\frac{d\lambda}{dt}=\underline{24\lambda^2}+12\lambda y_t^2\,\underline{-6y_t^4}-3\lambda(g'^2+3g^2)+\frac{3}{8}[2g^4+(g'^2+g^2)^2]$$

⇒ λ lift !

extra SM charged fields → **gauge becomes strong**

$m_H = 125.09{\scriptstyle \pm 0.32}$ GeV, $m_{top} = 173.34{\scriptstyle \pm 0.76}$ GeV in the SM

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gauge → large ⇒ Yt → small

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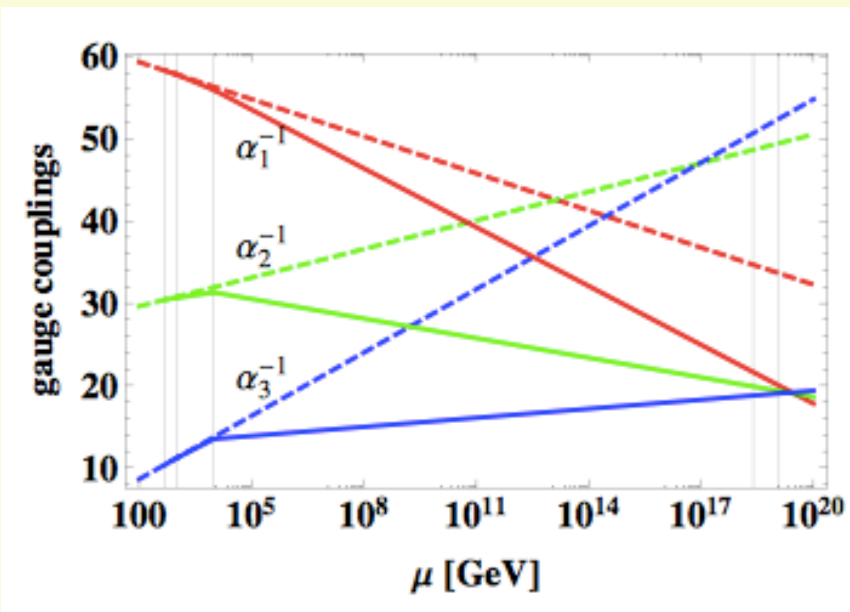
  - → GCU is also realized at Mp
  - → vector-like fields cause not only GCU but also stable Higgs pot. up to Mp

gauge → large



→ vacuum becomes stable

B: Higgs potential is stable up to Mp

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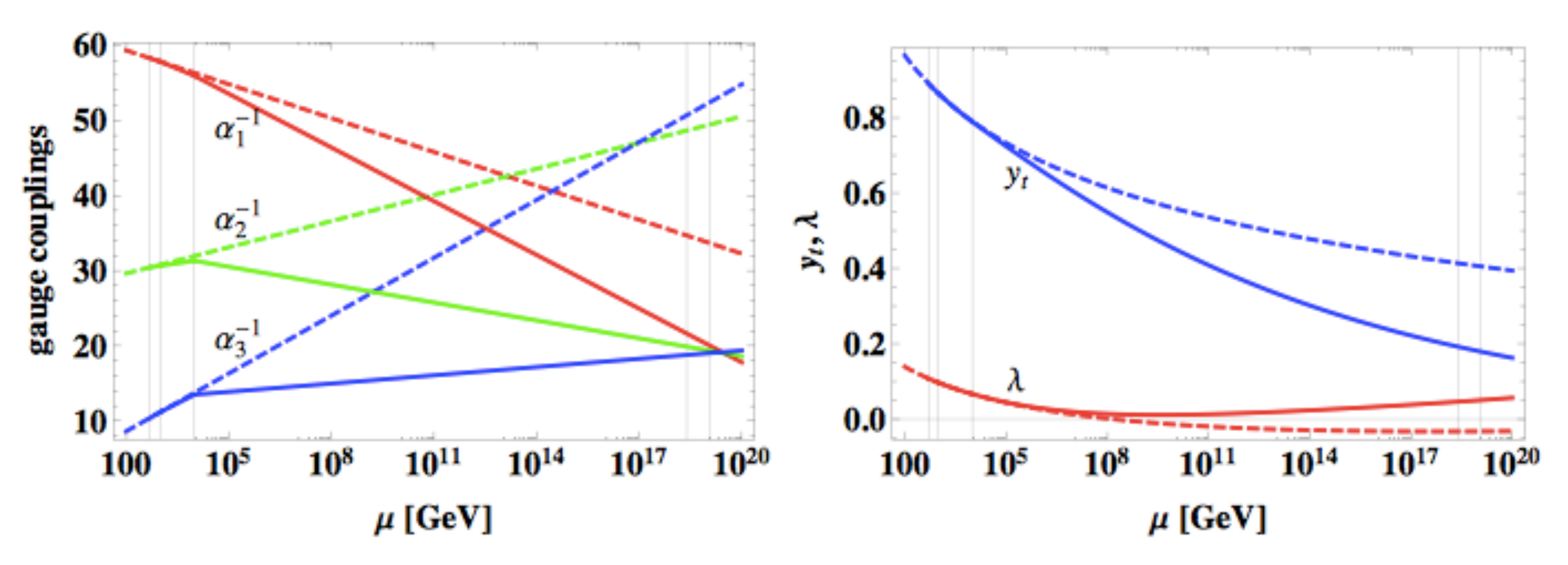
gauge → large (→ Yt → small) ⇒ λ is lifted !



→ vacuum becomes stable

C: Higgs potential vanishes at Mp

(ex) SM + U(1)' model (flatland scenario)

To realize EWSB with m_h=125 GeV, consider U(1)' extension of SSM.

['09 Iso, Okada, Orikasa], etc.

	$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$	$U(1)'$
Q	$(3,\ 2,\ 1/6)$	$(x+1)/3$
U^c	$(\overline{3},\ 1,\ -2/3)$	$(-4x-1)/3$
D^c	$(\overline{3},\ 1,\ 1/3)$	$(2x-1)/3$
L	$(1,\ 2,\ -1/2)$	$-x-1$
E^c	$(1,\ 1,\ 1)$	$2x+1$
N^c	$(1,\ 1,\ 0)$	1
H	$(1,\ 2,\ 1/2)$	x
Φ	$(1,\ 1,\ 0)$	2

SM singlet scalar

$$\begin{cases} x = 0 : U(1)_{B-L} \\ x = -1 : U(1)_R \\ x = -2/5 : U(1)_\chi \end{cases}$$

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SM singlet scalar

- scalar potential:

no dimensionful parameters (scale inv.)

$$V = \lambda_H |H|^4 + \lambda_\Phi |\Phi|^4 + \lambda_{mix} |H|^2 |\Phi|^2$$

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- right-handed neutrino:

$$\mathcal{L}_N = -Y_N^{\alpha i} \overline{L_\alpha} H N_i - Y_M^{ij} \Phi \overline{N_i^c} N_j + (h.c.)$$

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$$\mathcal{L}_N = -Y_N^{\alpha i} \overline{L_\alpha} H N_i - M_R \overline{N_i^c} N_j + (h.c.)$$

dimensionful parameters m_H, M_R ← generated by ⟨Φ⟩ through CW mech.

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m_H=125.09$\pm$0.32 GeV, m_{top}=173.34$\pm$0.76 GeV in the SM

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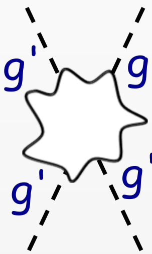
new Higgs Φ has new gauge's charge $\rightarrow$ $\beta_\lambda \sim +g'^4$

$\Rightarrow$ λ lift !



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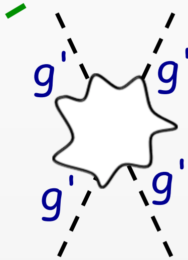
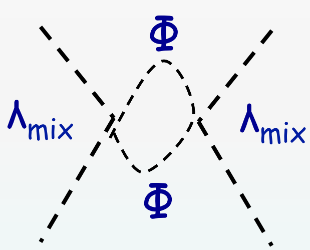
⇒ λ lift !





→ $\beta_\lambda \sim +\lambda_{mix}^2$ ⇒ λ lift !

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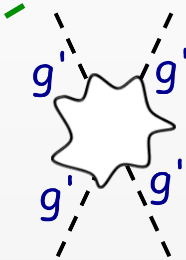

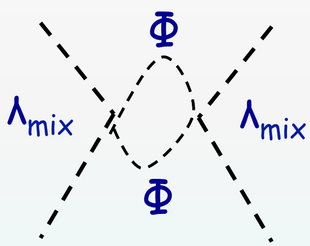

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⇒ λ lift !

(ex) SM + U(1)' model (flatland scenario)

$$V = \lambda_H |H|^4 + \lambda_{mix} |\phi|^2 |H|^2 + \lambda_\phi |\phi|^4$$

- SM + U(1)' gauge

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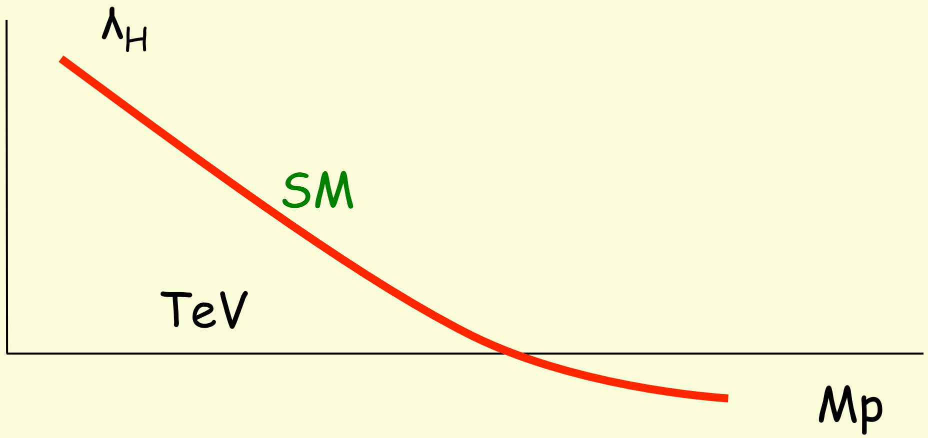

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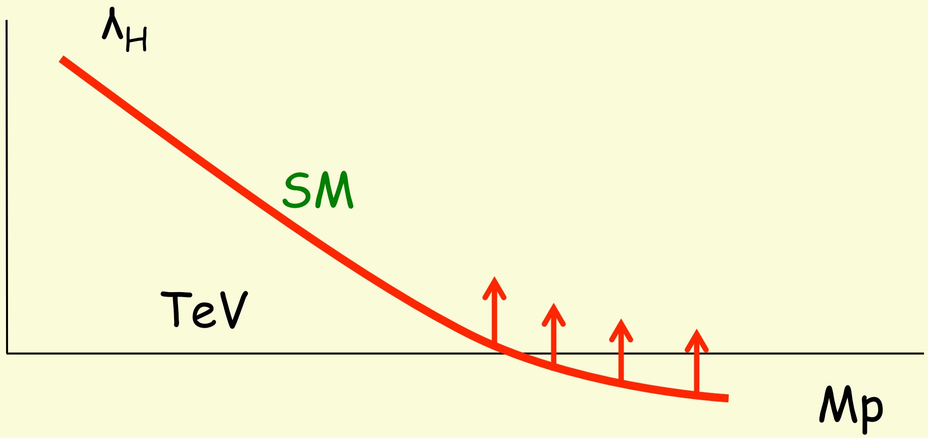
→ results



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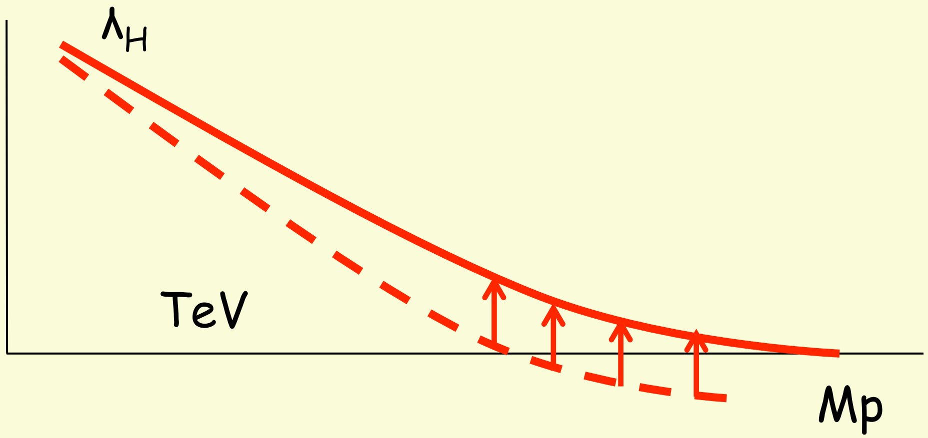

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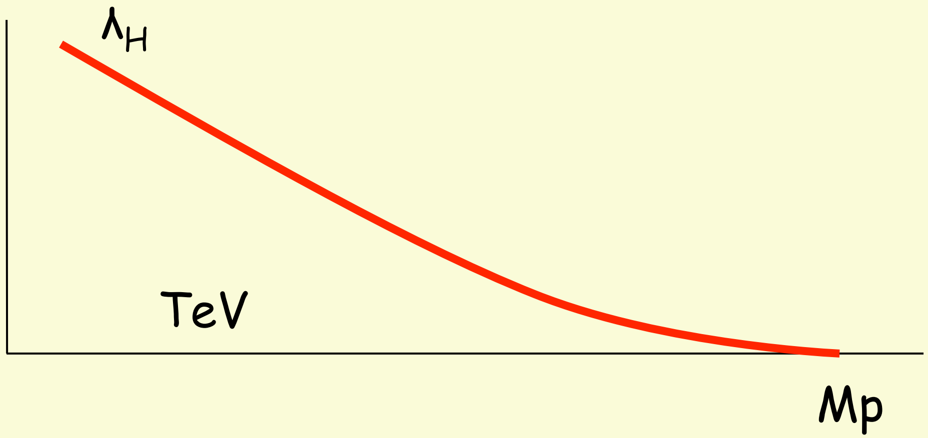

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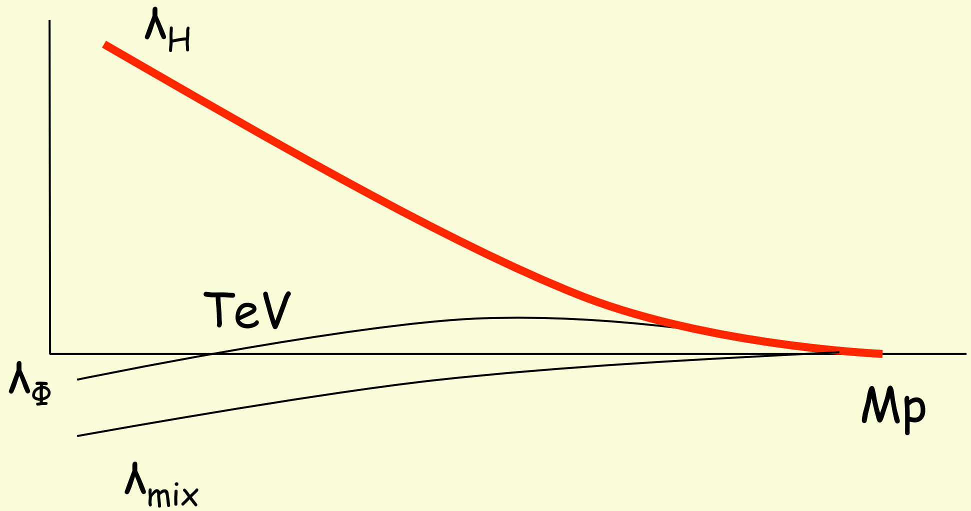

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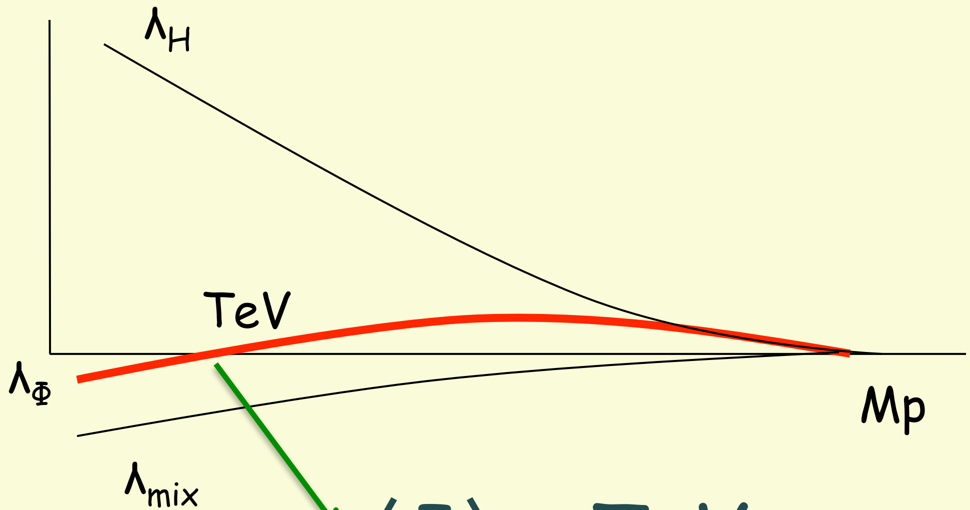
→ results



$\langle \Phi \rangle \sim \mathrm{TeV}$

CW mech.

①

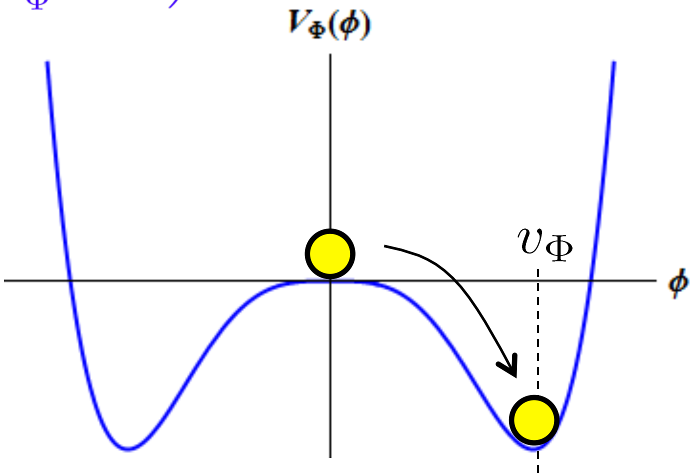
① CW potential for singlet scalar ($\langle\Phi\rangle \neq 0$)

$$V_\Phi(\phi) = \frac{1}{4}\lambda_\Phi \phi^4 + \frac{\phi^4}{64\pi^2}\left(10\lambda_\Phi^2 + 48g'^4 - 8\,\mathrm{tr}Y_M^4\right)\left(\ln\frac{\phi^2}{v_\Phi^2} - \frac{25}{6}\right)$$

→ $\langle\Phi\rangle \neq 0$ VEV

→ U(1)' is broken
(new particles become massive)

$$M_\phi = \sqrt{\frac{6}{11}\lambda_\Phi} v_\Phi,\ M_{Z'} = 2g' v_\Phi,\ M_N = \sqrt{2} Y_M v_\Phi$$



(ex) SM + U(1)' model (flatland scenario)

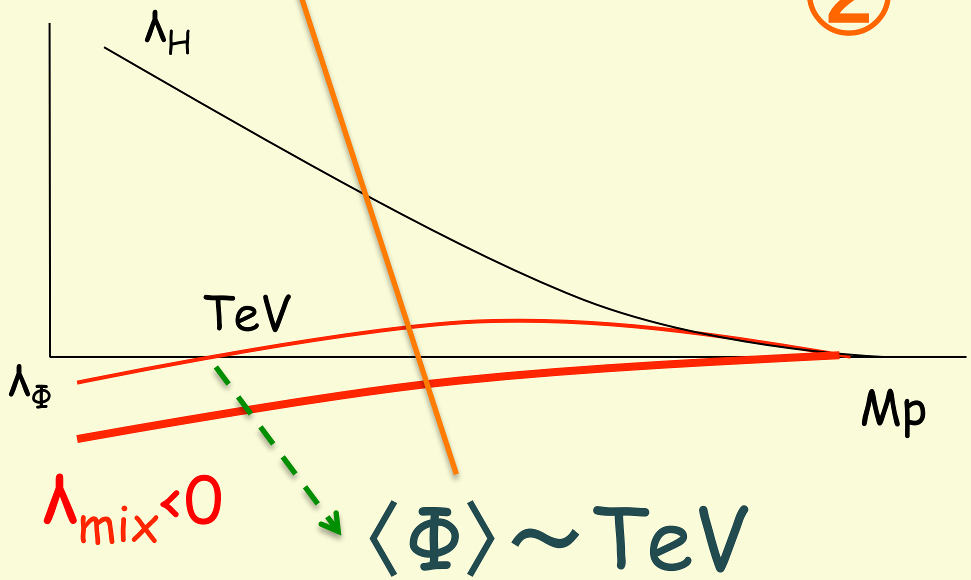
$$V = \lambda_H |H|^4 + \underline{\lambda_{mix}} |\phi|^2 |H|^2 + \lambda_\phi |\phi|^4$$

$= -m^2$ (origin of the Mexican hat (EWSB))

②

・SM + U(1)' gauge

→ results



① CW potential for singlet scalar (⟨Φ⟩≠0)

$$V_\Phi(\phi) = \frac{1}{4}\lambda_\Phi \phi^4 + \frac{\phi^4}{64\pi^2}\left(10\lambda_\Phi^2 + 48 g'^4 - 8\,\mathrm{tr} Y_M^4\right)\left(\ln\frac{\phi^2}{v_\Phi^2} - \frac{25}{6}\right)$$

→ ⟨Φ⟩≠ 0 VEV

→ U(1)' is broken
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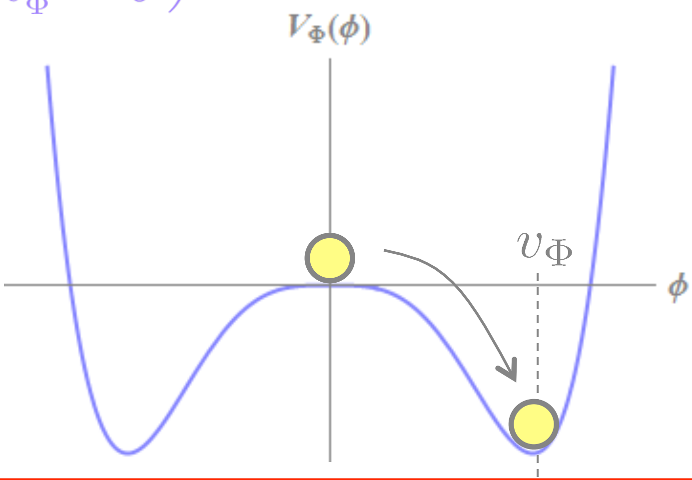
$$M_\phi = \sqrt{\frac{6}{11}\lambda_\Phi} v_\Phi, \;\; M_{Z'} = 2g' v_\Phi, \;\; M_N = \sqrt{2} Y_M v_\Phi$$

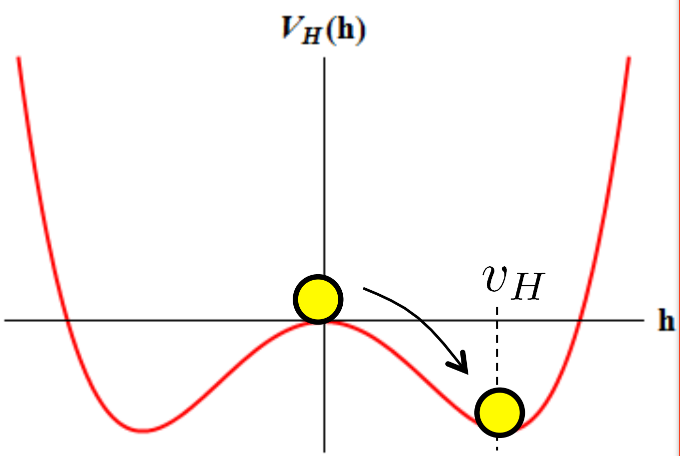


② Higgs potential after U(1)' breaking(⟨H⟩≠0)

$$V_H = \frac{1}{4}\lambda_H h^4 + \frac{1}{2} m_h^2 h^2, \quad m_h^2 \equiv \frac{1}{2}\lambda_{mix} v_\Phi^2 < 0$$

→ ⟨h⟩≠ 0 VEV

→ EWSB
(SM particles become massive)



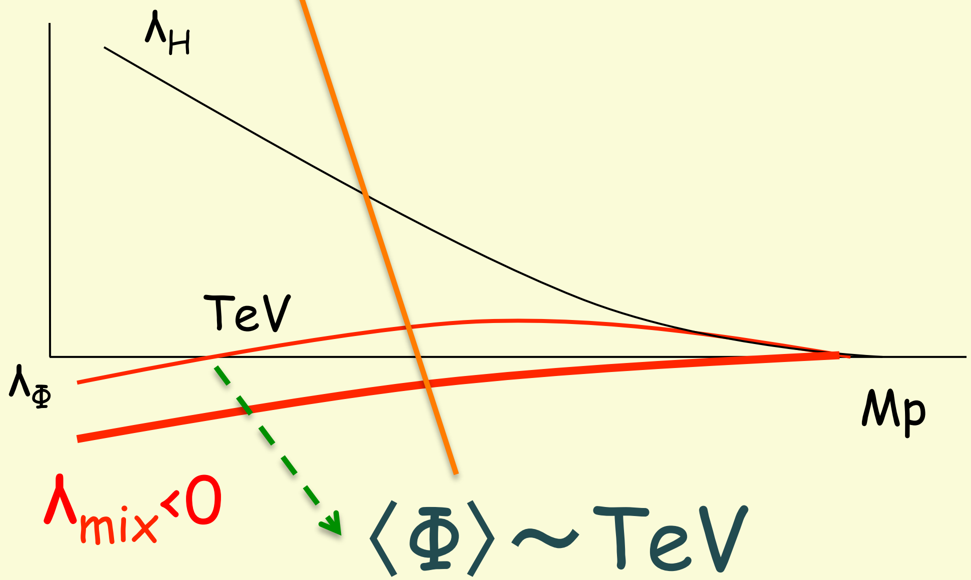
(ex) SM + U(1)' model (flatland scenario)

$$V = \lambda_H |H|^4 + \underbrace{\lambda_{mix} |\phi|^2}_{=-m^2} |H|^2 + \lambda_\phi |\phi|^4$$

(origin of the wine-bottle (EWB)

- SM + U(1)' gauge

→ results



- $L \sim \langle\Phi\rangle \nu_R{}^2$ → not large Majorana mass of ν_R (Mayoron -> longitudinal comp.)

→ low energy scale seesaw, (resonant) leptogenesis,
(phenomenology can be around TeV)

(ex) SM + U(1)' model (flatland scenario)

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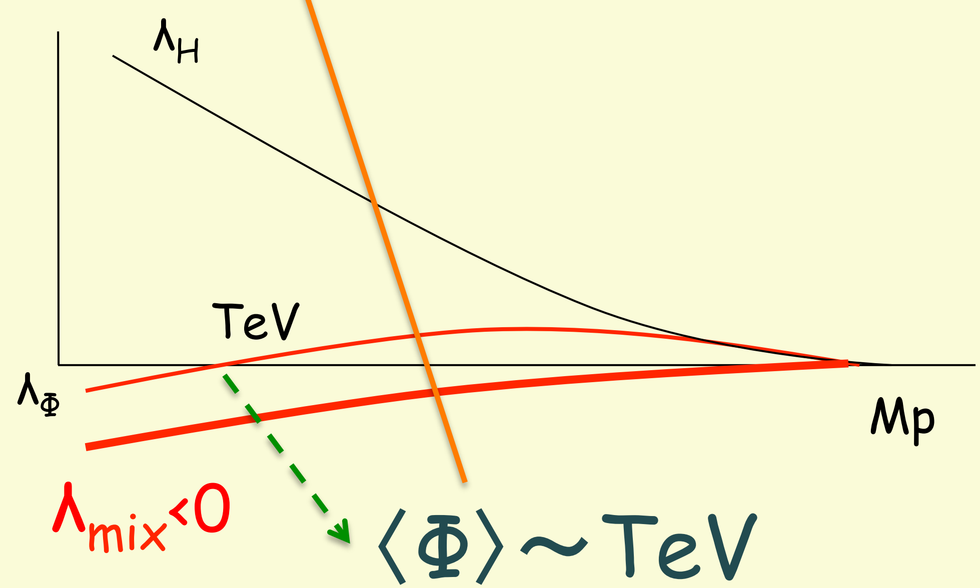
$= -m^2$ (origin of the wine-bottle (EWB)

- SM + U(1)' gauge

→ results



Does this scenario really works?
(from view point of vacuum stability)

NH and Y. Yamaguchi, PTEP 2015, no. 9, 093B05 (2015)

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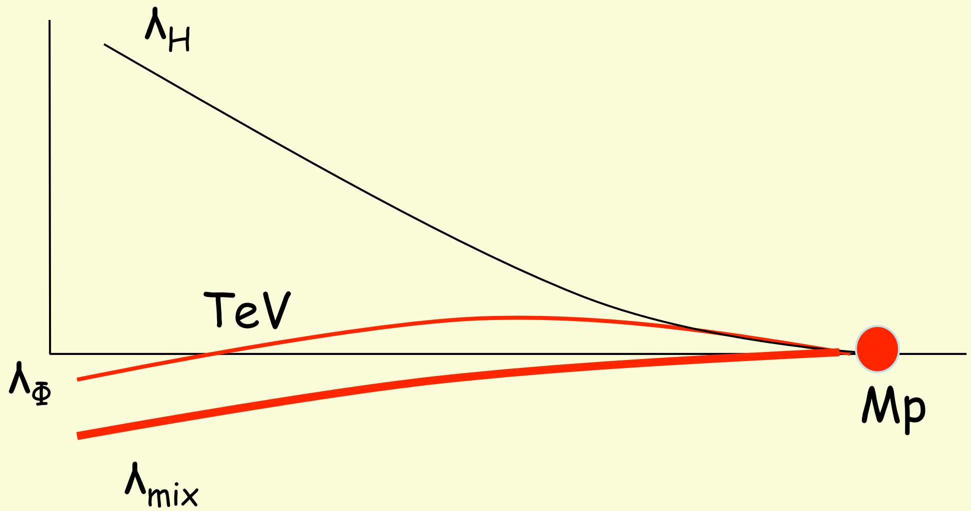

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vacuum stability of flatland scenario

- vacuum stability conditions:

$$
\begin{aligned}
V &= \lambda_H |H|^4 + \lambda_\Phi |\Phi|^4 + \lambda_{mix} |H|^2 |\Phi|^2 \\
&= \frac{1}{4} \left[\lambda_H h^4 + \lambda_\Phi \phi^4 + \lambda_{mix} h^2 \phi^2 \right] \\
&= \frac{1}{4} \left[\left(\sqrt{\lambda_H} h^2 - \sqrt{\lambda_\Phi} \phi^2 \right)^2 + \left(2\sqrt{\lambda_H \lambda_\Phi} + \lambda_{mix} \right) h^2 \phi^2 \right] > 0
\end{aligned}
$$

$\lambda_H > 0$ $\lambda_\Phi > 0$ $|\lambda_{mix}|^2 < 4\lambda_H \lambda_\Phi$

- check these three conditions
- experimental bounds (such as constraints on $M_{Z'}$)

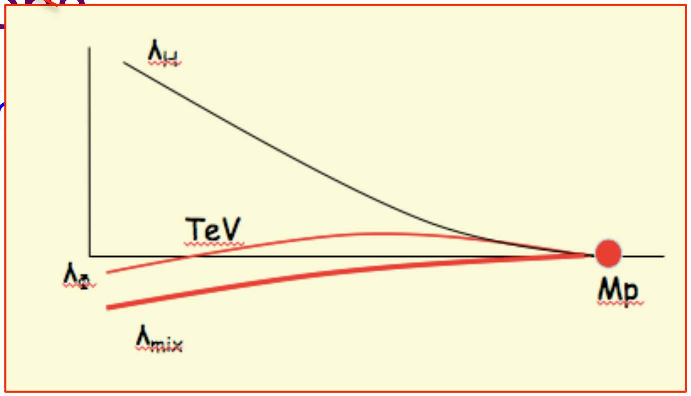
vacuum stability of flatland scenario

- vacuum stability conditions:

$$\begin{aligned} V &= \lambda_H |H|^4 + \lambda_\Phi |\Phi|^4 + \lambda_{mix} |H|^2 |\Phi|^2 \\ &= \frac{1}{4}\left[\lambda_H h^4 + \lambda_\Phi \phi^4 + \lambda_{mix} h^2 \phi^2\right] \\ &= \frac{1}{4}\left[\left(\sqrt{\lambda_H} h^2 - \sqrt{\lambda_\Phi}\phi^2\right)^2 + \left(2\sqrt{\lambda_H \lambda_\Phi} + \lambda_{mix}\right) h^2 \phi^2\right] > 0 \end{aligned}$$

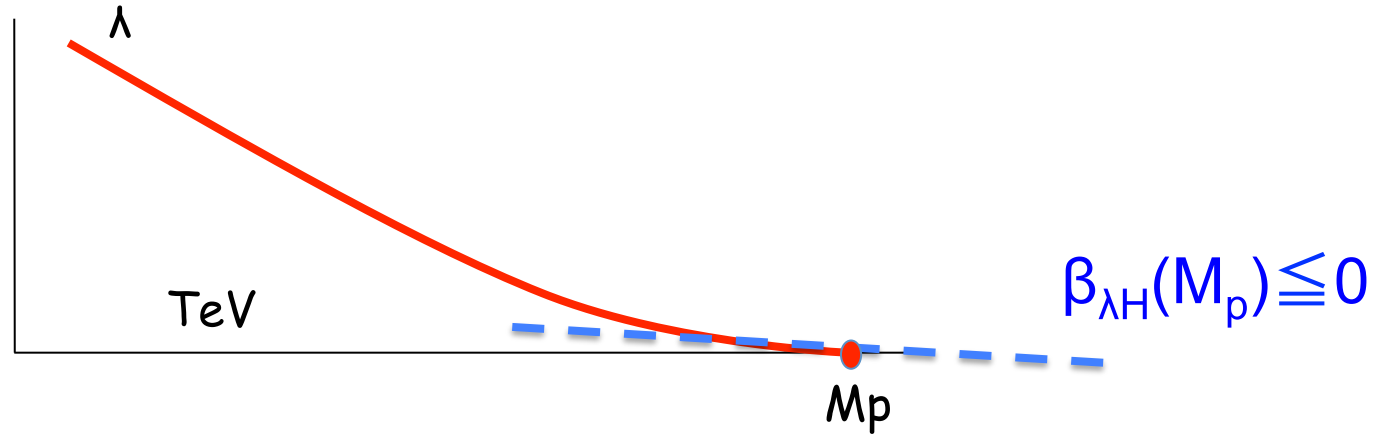
$$\lambda_H > 0 \qquad \lambda_\Phi > 0 \qquad |\lambda_{mix}|^2 < 4\lambda_H \lambda_\Phi$$

- check these three conditio
- experimental bounds (such



λ_H direction's stability

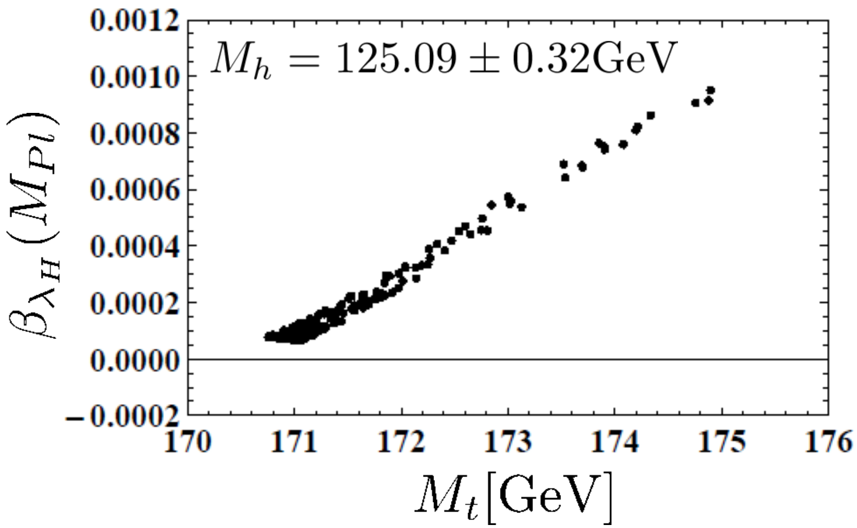
- vacuum stability of H direction: $\lambda_H \geqq 0 \Rightarrow \beta_{\lambda H} \leqq 0$

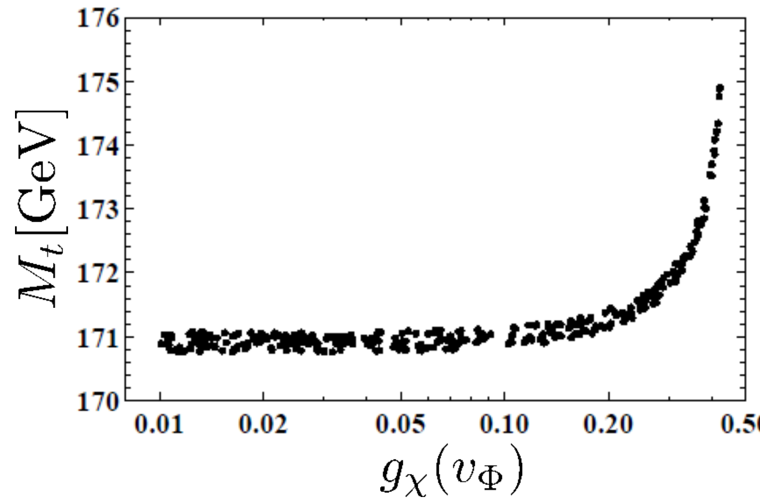


λ_H direction's stability

- vacuum stability of H direction: $\lambda_H \geqq 0 \Rightarrow \beta_{\lambda H} \leqq 0$

$$\beta_{\lambda_H}(M_{Pl}) = \frac{1}{(4\pi)^2}\left[-6y_t^4 + \frac{3}{8}\left\{2g_2^4 + \left(g_2^2 + g_Y^2 + \frac{16}{25}g_\chi^2\right)^2\right\}\right]$$





There are no region of $\beta_{\lambda H}(M_p) \leqq 0$.

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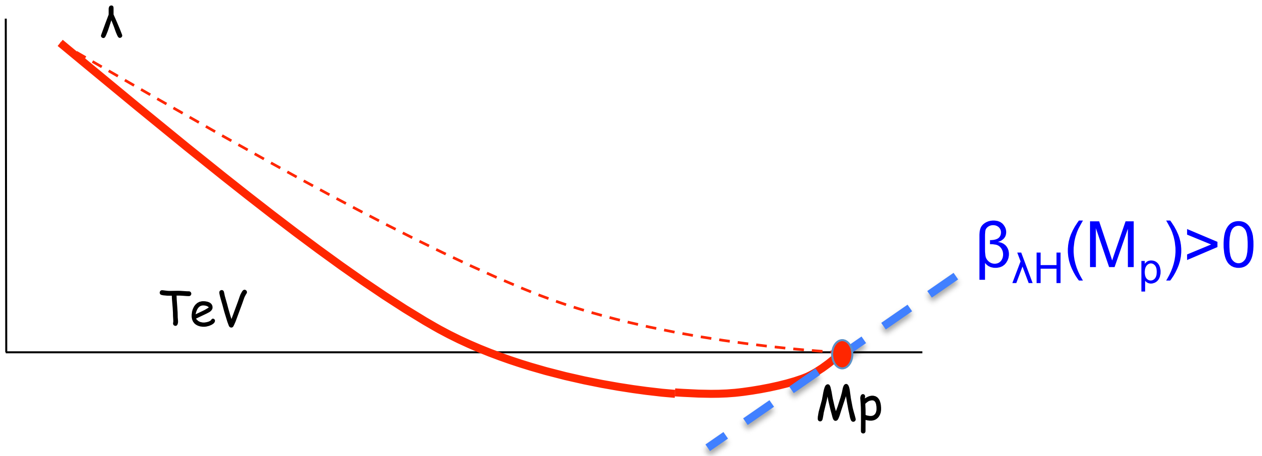

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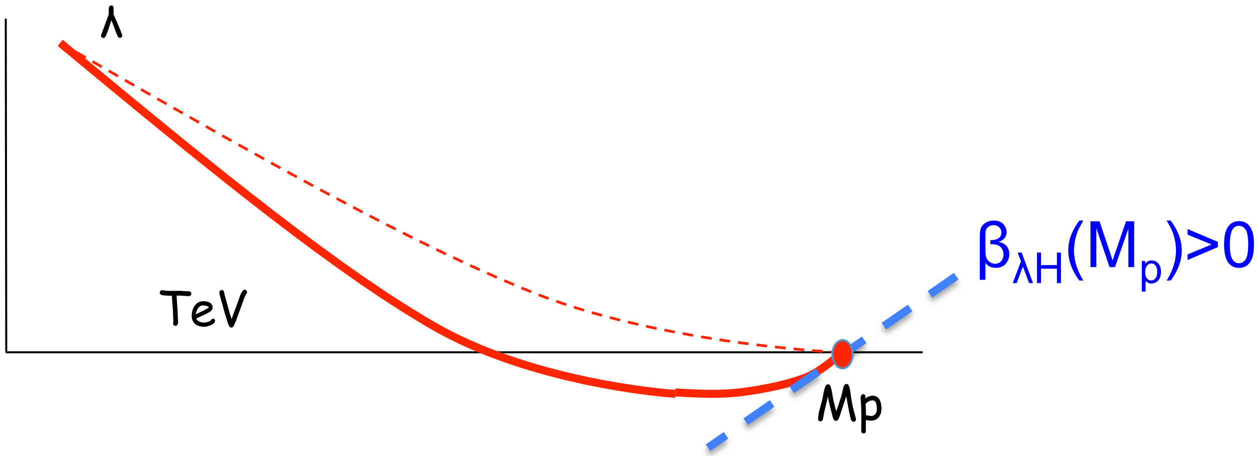


There are no region of $\beta_{\lambda H}(M_p) \leqq 0$.

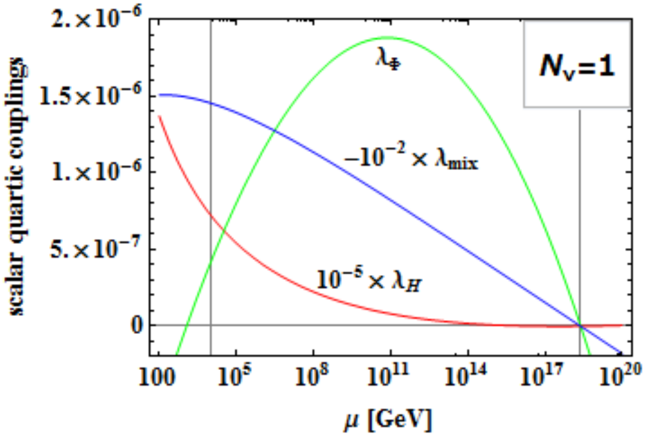
→ $\lambda_H \geqq 0$ cannot be realized in flatland scenario.

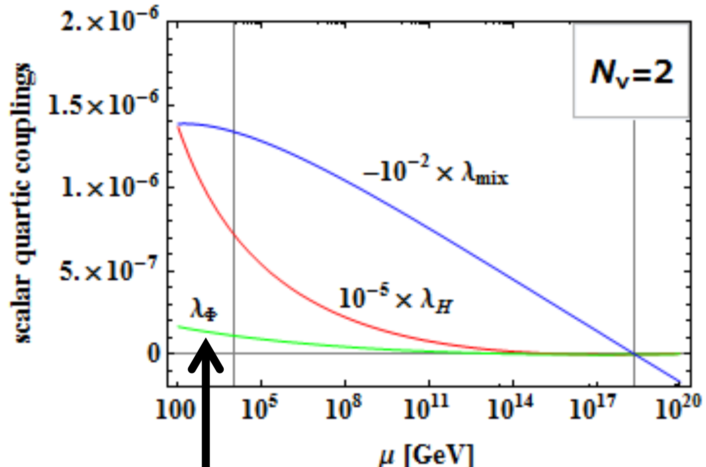
vacuum is meta-stable as in the SM (for H-direction).

runnings of λ_H, λ_{mix}, λ_Φ

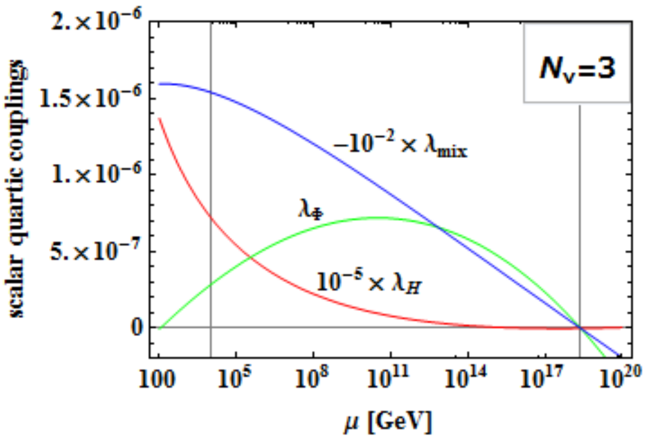
N_ν=1~3, $(\mathrm{tr}Y_M = N_\nu y_M)$

$$\mathcal{L}_N = -Y_N^{\alpha i}\overline{L_\alpha}HN_i - \underline{Y_M^{ij}}\Phi\overline{N_i^c}N_j + (h.c.)$$





λ_Φ is monotonically decreasing because of $\beta_{\lambda\Phi}\sim 0$ in this case.



runnings of λ_H, λ_{mix}, λ_Φ

N_ν=1~3, $(\mathrm{tr}Y_M = N_\nu y_M)$

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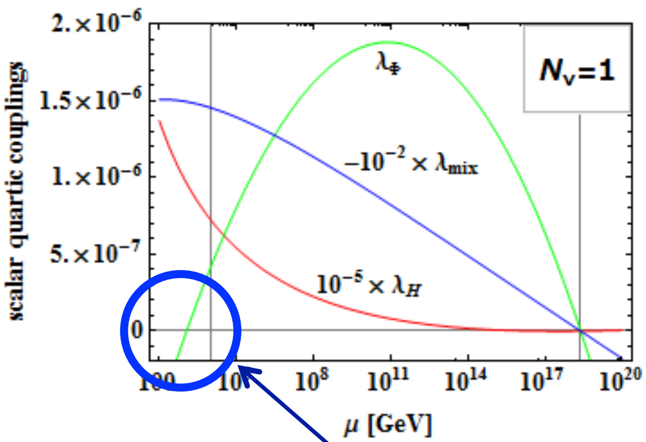
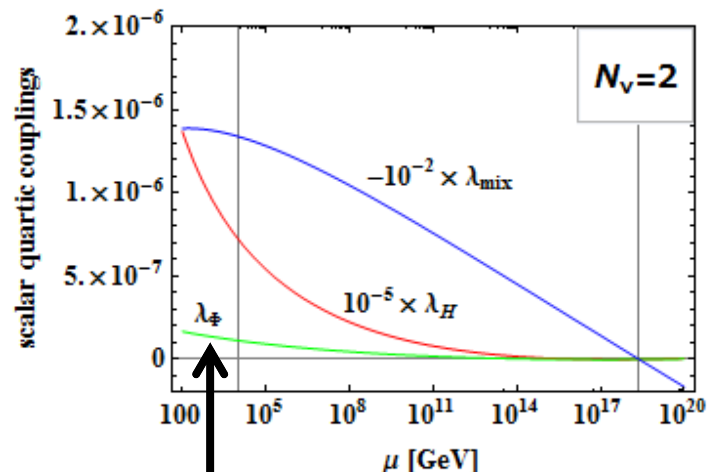
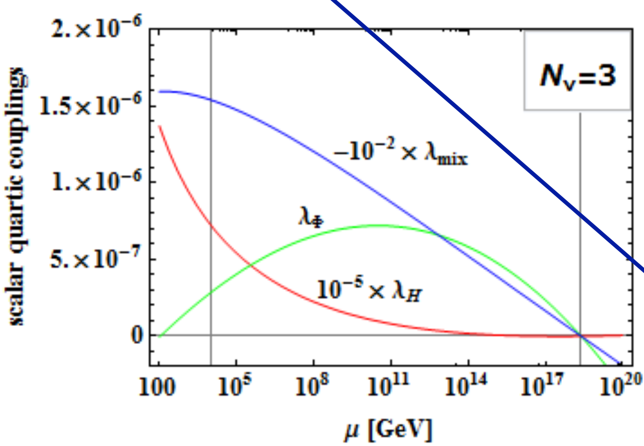






λ_Φ is monotonically decreasing because of $\beta_{\lambda\Phi}$~0 in this case.

λ_Φ seems to become negative!

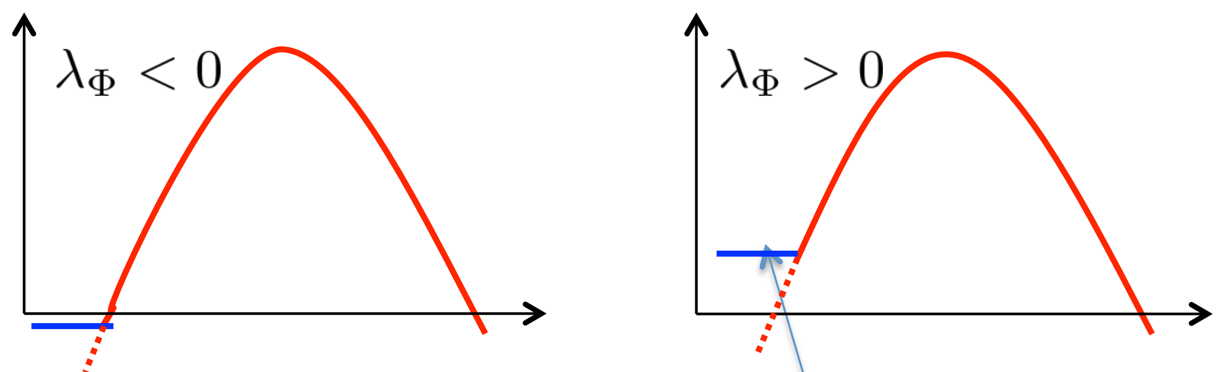
λ_Φ : direction's stability

Below ⟨Φ⟩, Z' and ν_R (N) are massive. → Z' and N decouple,

$$\rightarrow \quad \beta_{\lambda_\Phi}(\mu < M_{Z'}, M_N) = \frac{1}{(4\pi^2)}\left[20\lambda_\Phi^2 + 2\lambda_{mix}^2\right] \simeq 0$$

$$\Rightarrow \quad \lambda_\Phi(\mu < M_{Z'}, M_N) \simeq \lambda_\Phi(M_{Z'}) \simeq \lambda_\Phi(M_N) > 0$$

N_ν=1



- N_ν=1: strongly constrained as $g_X(\sim y_M)>0.055$ **→ upper bound of $M_{Z'}$**

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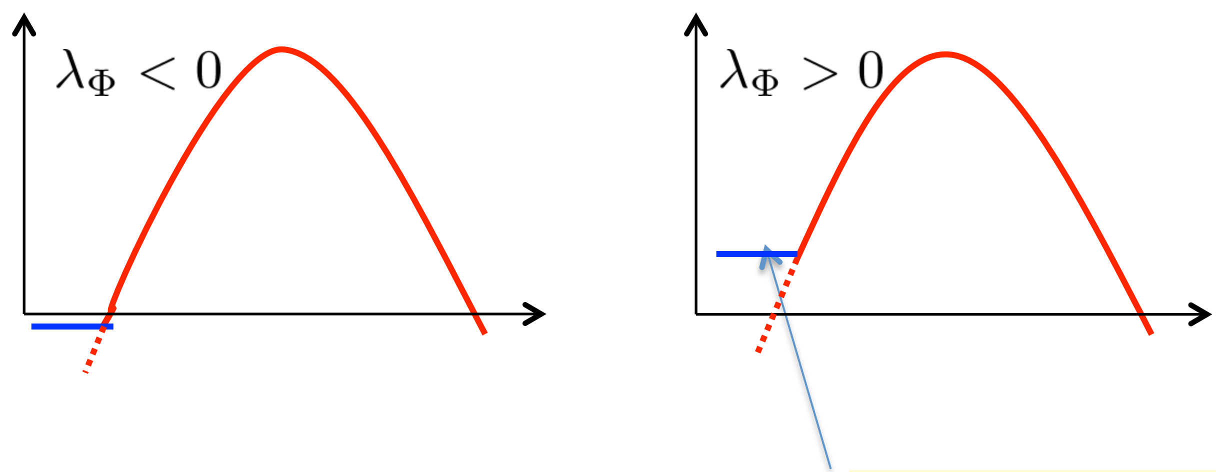


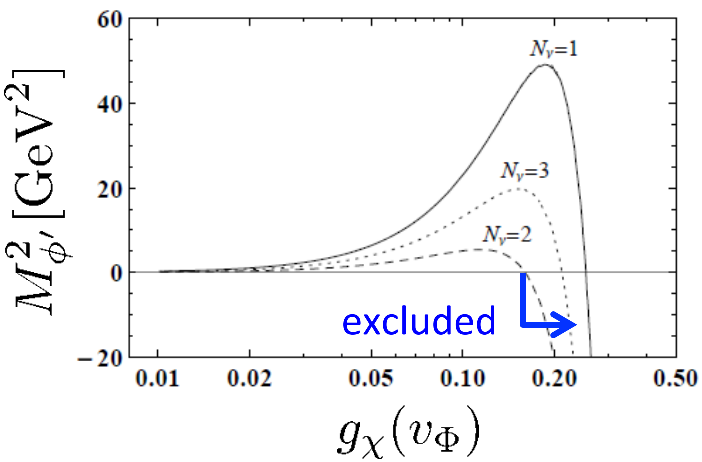
- N_ν=1: strongly constrained as $g_\chi(\sim y_M)>0.055$ **→ upper bound of $M_{Z'}$**
- N_ν=2: not constrained ($\lambda_\Phi>0$ is always satisfied)
- N_ν=3: almost not constrained ($\lambda_\Phi>0$ even for $g_\chi\sim0.01$)

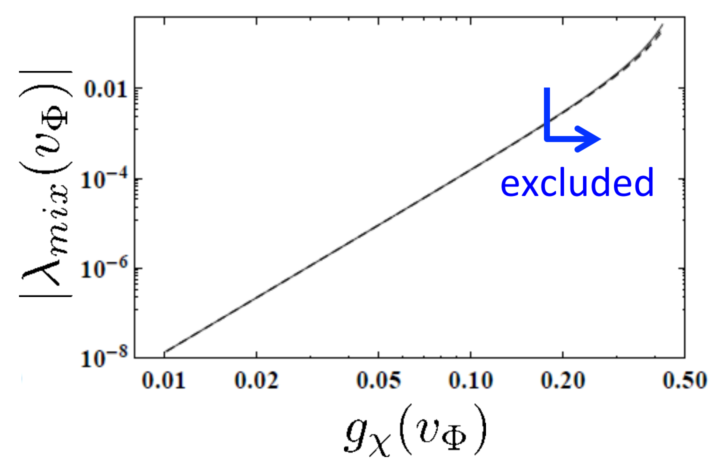
λ_{mix} : direction's stability

☆local min. condition, (scalar mass)^2 >0, restricts λ_{mix}.

$|\lambda_{mix}|^2 < 4\, \lambda_H\, \lambda_\Phi$ is almost always satisfied if λ_H >0. but, it cannot be realized as mentioned above.

$$\begin{array}{ccc} & H & \Phi \\ \mathcal{M}^2 = & \multicolumn{2}{c}{\begin{pmatrix} M_h^2 & \frac{1}{2}\lambda_{mix} v_H v_\Phi \\ \frac{1}{2}\lambda_{mix} v_H v_\Phi & M_\phi^2 \end{pmatrix}} \end{array} \Rightarrow M_{\phi'}^2 \approx M_\phi^2 - \frac{\lambda_{mix}^2 v_H^2 v_\Phi^2}{4\left(M_h^2 - M_\phi^2\right)}$$





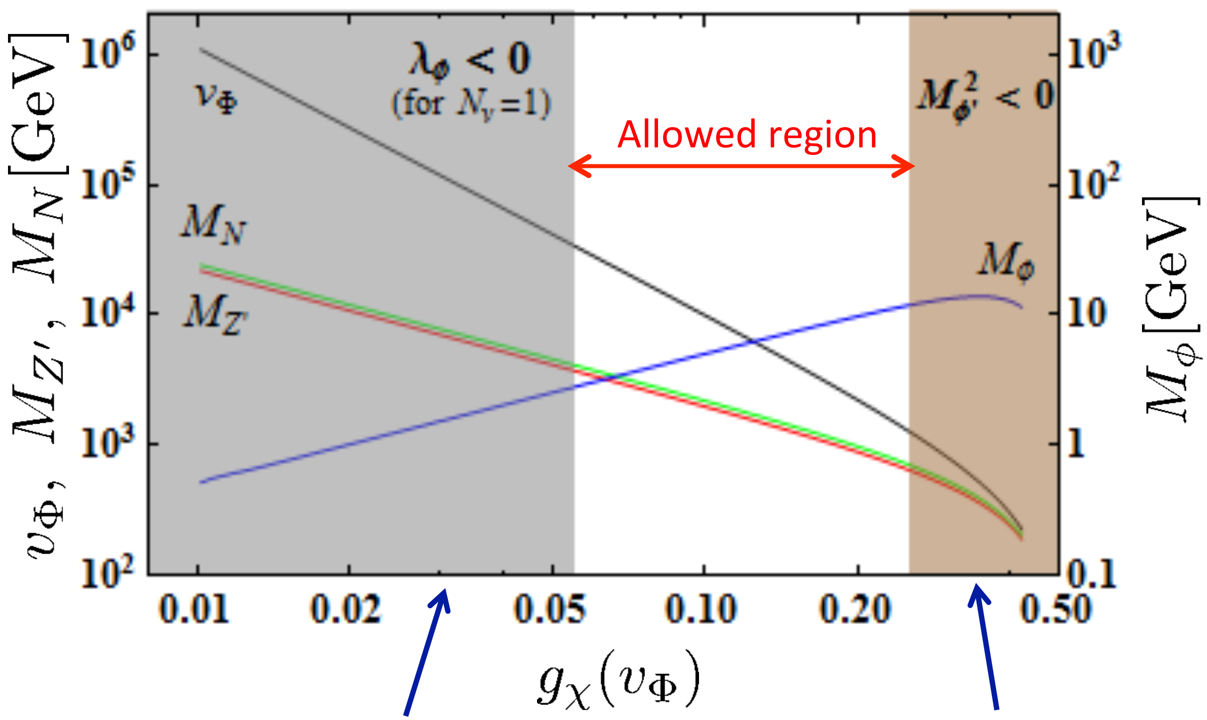
g_χ>0.2 is excluded.

larger g_χ ~ larger λ_{mix} (shown as right figure.)

→ lower bound of $M_{Z'}$

allowed parameter regions from vacuum stability

For N_ν=1:



excluded by λ_Φ>0 condition

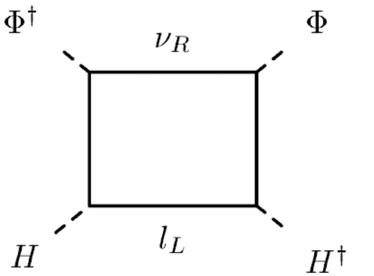
excluded by local minimum condition

	$N_\nu = 1$	$N_\nu = 2$	$N_\nu = 3$
g_χ	$0.055 \lesssim g_\chi \lesssim 0.25$	$g_\chi \lesssim 0.16$	$g_\chi \lesssim 0.23$
v_Φ	$1.3\,\text{TeV} \lesssim v_\Phi \lesssim 3.3 \times 10^5\,\text{GeV}$	$3.8\,\text{TeV} \lesssim v_\Phi$	$2.0\,\text{TeV} \lesssim v_\Phi$
M_ϕ	$2.8\,\text{GeV} \lesssim M_\phi \lesssim 12\,\text{GeV}$	$M_\phi \lesssim 4.2\,\text{GeV}$	$M_\phi \lesssim 7.7\,\text{GeV}$
$M_{Z'}$	$650\,\text{GeV} \lesssim M_{Z'} \lesssim 3.7\,\text{TeV}$	$1.2\,\text{TeV} \lesssim M_{Z'}$	$860\,\text{GeV} \lesssim M_{Z'}$
M_N	$720\,\text{GeV} \lesssim M_N \lesssim 4.1\,\text{TeV}$	$1.1\,\text{TeV} \lesssim M_N$	$720\,\text{GeV} \lesssim M_N$

naturalness in SM + U(1)' model

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

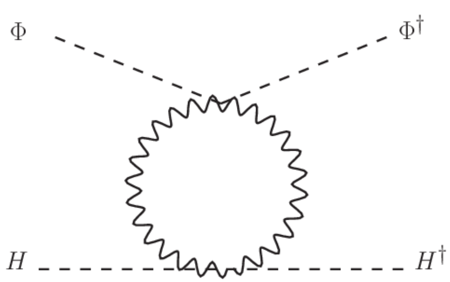
- Neutrino Yukawa contribution (one-loop)



$$\Delta m_h^2 \sim \frac{Y_\nu^2 Y_M^2 v_\Phi^2}{16\pi^2} \sim \frac{m_\nu M_N^3}{16\pi^2 v_H^2} \qquad m_\nu \sim Y_\nu^2 v_H^2/M_N \sim 0.1\mathrm{eV}$$

$$\Rightarrow M_N \lesssim 10^7\mathrm{GeV} \Rightarrow v_\Phi \lesssim (10^7/Y_N)\ \mathrm{GeV}$$

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

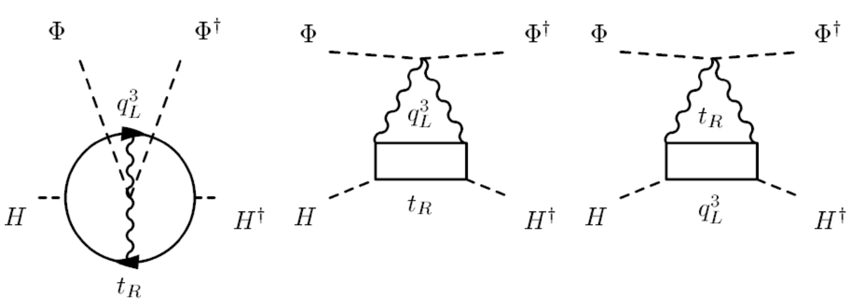


$$\Delta m_h^2 \sim \frac{(xg')^2(2g')^2 v_\Phi^2}{16\pi^2} = 4x^2\alpha_{g'}^2 v_\Phi^2 \qquad \alpha_{g'} \equiv g'^2/(4\pi)$$

$$\Rightarrow v_\Phi \lesssim \frac{1}{|x|}\left(\frac{0.01}{\alpha_{g'}}\right) \times 10^4\ \mathrm{GeV}\ \text{ for } x \neq 0$$

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

- U(1)' gauge contributions (two-loop including top loop)



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

$$\Rightarrow v_\Phi \lesssim (0.01/\alpha_{g'}) \times 10^6\ \mathrm{GeV}$$

naturalness in SM + U(1)’ model

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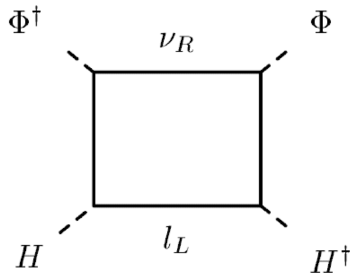

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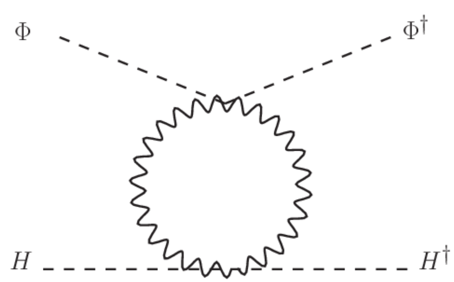

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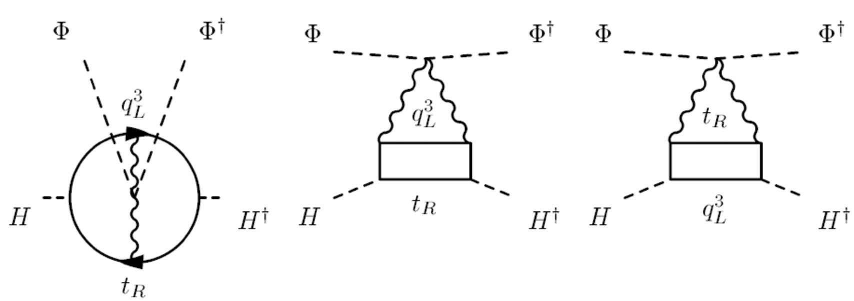
→upper bound of $M_{Z'}$< O(10) TeV

- U(1)’ gauge contributions (two-loop including top loop)



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

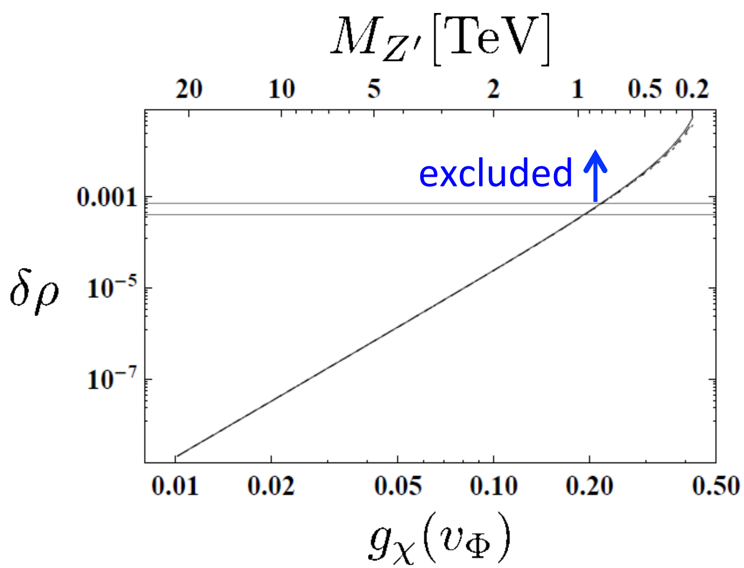
$$\Rightarrow v_\Phi \lesssim (0.01/\alpha_{g'}) \times 10^6\ \mathrm{GeV}$$

constraint from ρ –parameter

ρ-parameter derivates from U(1) mixing (Z-Z') (we set g_{mix}=0 @Mp)

$$\delta\rho \equiv \rho_0 - 1 \approx \frac{v_H^2}{4\left[\left(M_{Z'}^2 + \frac{1}{4}\left(g_{mix} - \frac{4}{5}g_\chi\right)^2 v_H^2\right) - M_Z^2\right]}\left(g_{mix} - \frac{4}{5}g_\chi\right)^2$$

$$M_Z = \frac{1}{2}\sqrt{g_Y^2 + g_2^2}\, v_H, \quad M_{Z'} = 2g_\chi v_\Phi, \quad \delta M^2 = \frac{1}{4}\sqrt{g_Y^2 + g_2^2}\left(g_{mix} - \frac{4}{5}g_\chi\right) v_H^2$$



$$\rho_0 = 1.0004^{+0.0003}_{-0.0004}$$

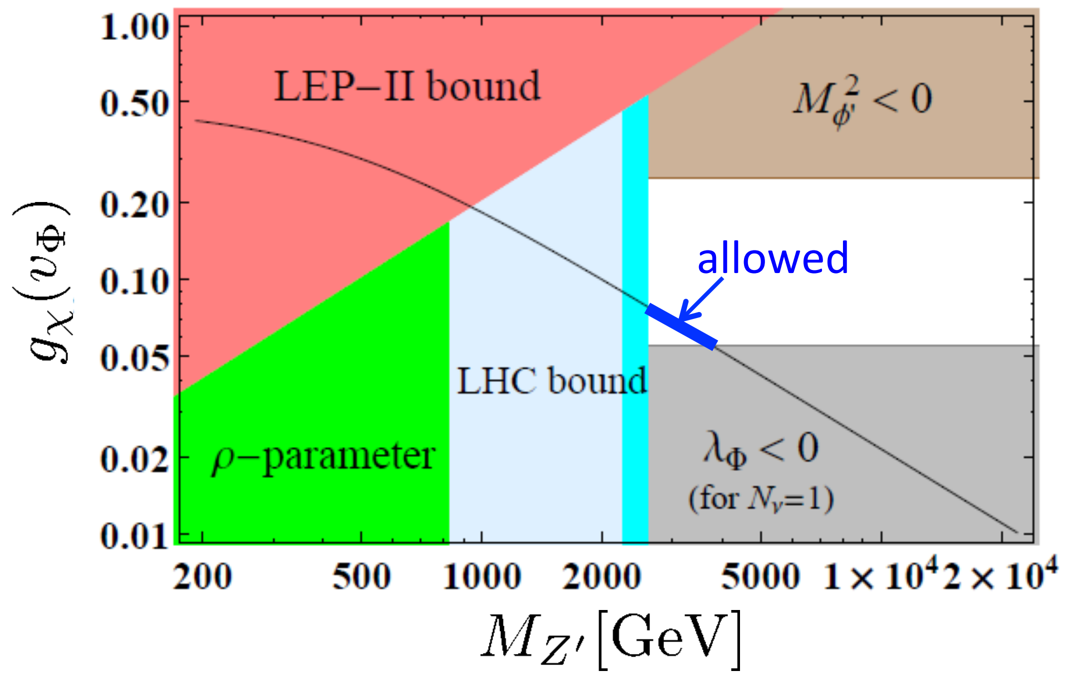
[1σ bounds in PDG2012]

$\rightarrow$ $M_{Z'}$ > 820 GeV

Z' mass bounds by collider

From direct Z' production experiments by ATLAS (CMS).

$$M_{Z'} > 2.24\ (2.59)\ \mathrm{TeV}$$



LEP-II bound

$$M_{Z'}/g_\chi \geq 4.8\,\mathrm{TeV}$$

constraint on Z' mass:

2.24 (2.59) TeV < M_Z' < O(10) TeV ← naturalness

< 3.7 TeV (N_ν =1 case) ← vacuum stability

summary

125 GeV Higgs mass with current top mass may suggests

Higgs pot. =0 at $O(10^{10})$ GeV

→ above the scale as M_{GUT}, M_P, Higgs pot. is unbounded.

What is 10^{10} GeV? not Mp?

BSM must exist

Naturalness

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BSM must exist (exstraD)

Naturalness (?)

A: completely new physics at 10^{10} GeV

(GH)

125 GeV Higgs mass with current top mass may suggests

Higgs pot. =0 at $O(10^{10})$ GeV

$\rightarrow$ above the scale as M_{GUT}, M_P, Higgs pot. is unbounded.

Higgs pot. becomes stable up to M_p

BSM must exist (GUT)

Naturalness (no intermediate scale)

A: completely new physics at 10^{10} GeV

(GH)

B: Higgs potential is stable up to Mp

new particles effects which do not be contained in SM

(GCU)

125 GeV Higgs mass with current top mass may suggests

Higgs pot. =0 at O(10^{10}) GeV

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Higgs pot. vanishes at M_p

BSM must exist (origin of EWSB)

Naturalness (no intermediate scale)

→ **A: completely new physics at 10^{10} GeV**

(GH)

B: Higgs potential is stable up to Mp

new particles effects which do not be contained in SM
(GCU)

C: Higgs potential vanishes at Mp

(flatland scenario: Z' mass < 3.7 TeV in N_ν=1 case, or O(10) TeV)