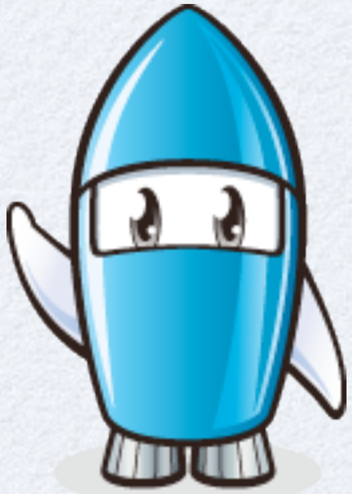
A light Higgs scenario based on the SUSY strong dynamics at multi TeV scale

Tetsuo Shindou (Kogakuin University)



S. Kanemura, T.S, and T. Yamada, PRD86,055023

S. Kanemura, E. Senaha, T.S,T. Yamada,JHEP1305,066

S. Kanemura, N. Machida, T.S, T. Yamada, arXiv:1309.xxxx

30/8/2013 SUSY2013@Trieste, Italy

Physics beyond the SM

Discovery of a Higgs boson&measurements of properties

↓

Essence of the electroweak symmetry breaking

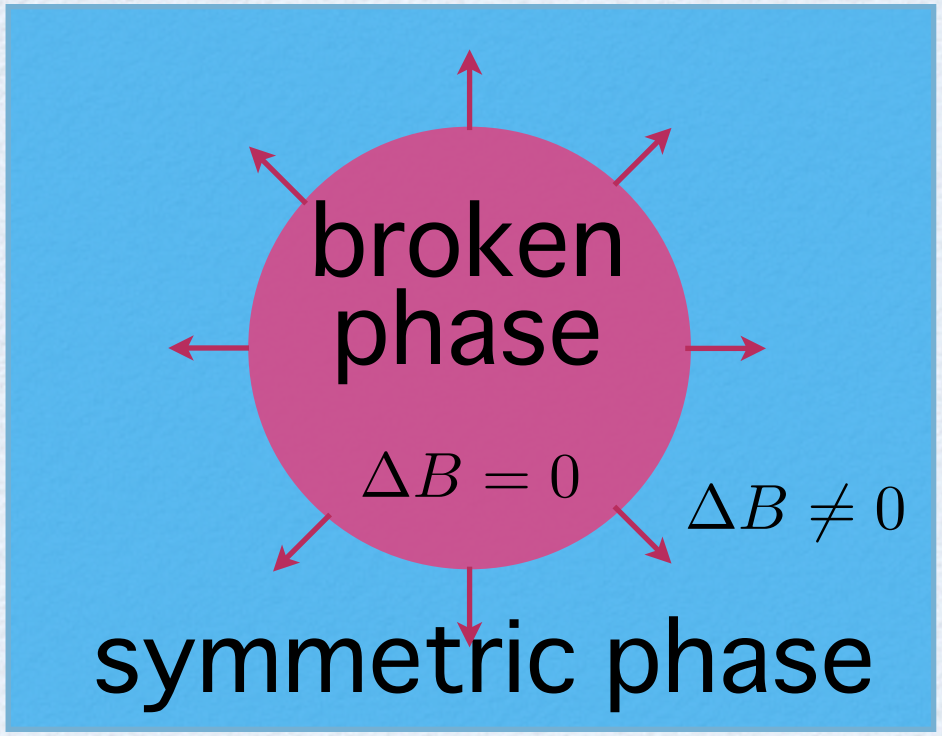
New Physics at TeV scale

It's quite interesting,
if the NP provides solutions on
the problems in the SM:

- Baryon asymmetry of the Universe
- Origin of the neutrino mass
- DM candidate

Electroweak Baryogenesis

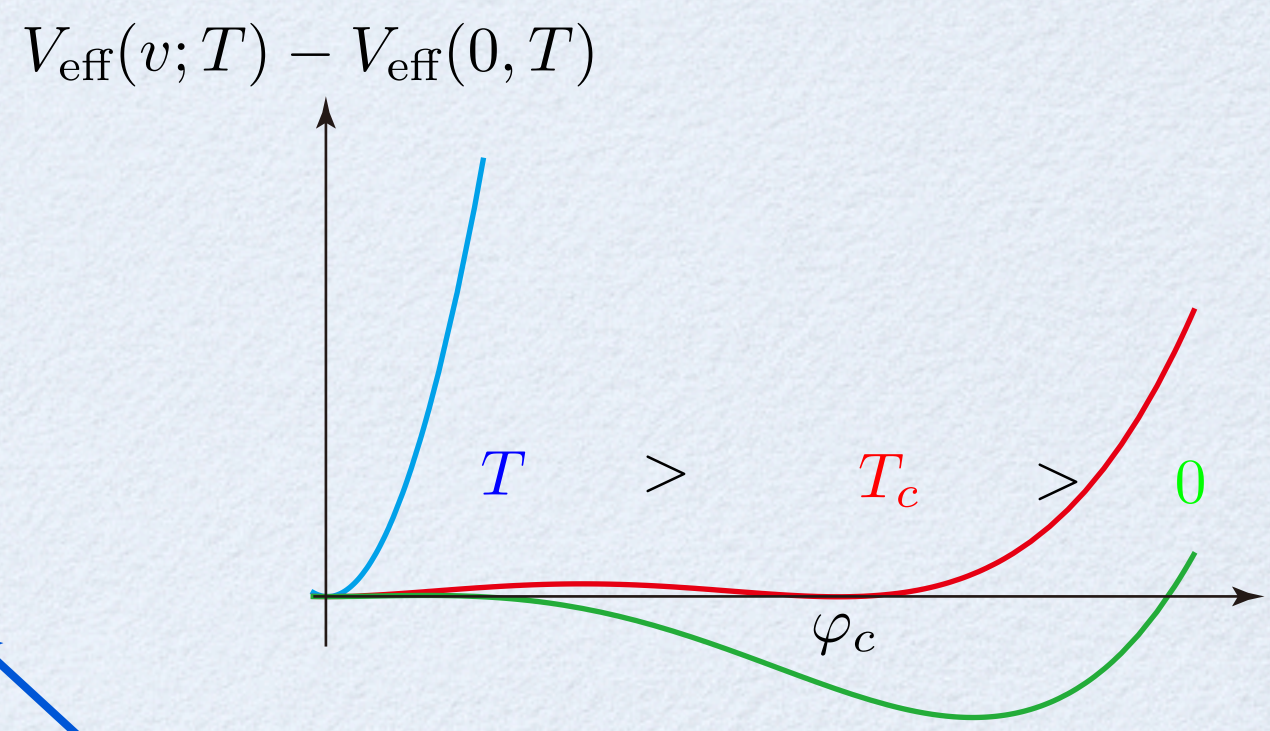
Electroweak Baryogenesis ⟷ essence of EWSB



1st order electroweak transition

+

Sphaleron



To avoid too strong washout

The strong enough first order electroweak phase transition is necessary

$\varphi_c/T_c > 1$

Higgs potential@EW scale

To get strong 1st order EWT

Strong 1st order EWPT requires extension of the SM

In the SM, the condition is satisfied only when $m_h < 50$GeV

(φ_c/T_c is suppressed by m_h)

conflict with LHC data

Extra boson loop can enhance φ_c/T_c

↓

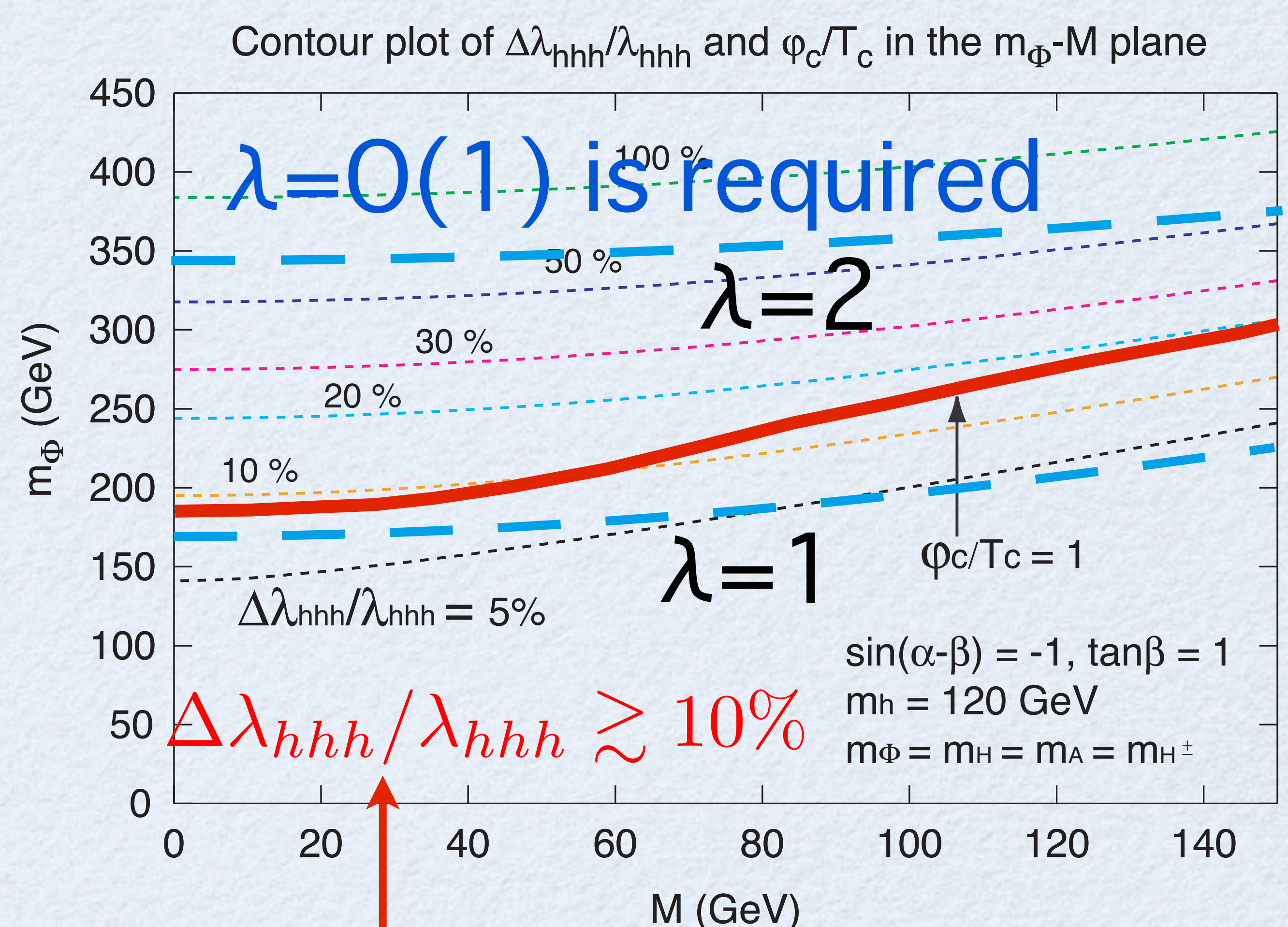
Extended Higgs sector!

e.g. 2HDM

$$\mathcal{L} = \frac{\lambda_i}{2} h^2 |\Phi_i|^2$$

$$m_\Phi^2(\varphi) = M^2 + \lambda_i \varphi^2$$

Extra Higgs bosons as H,A $H^\pm$



Kanemura, Okada, Senaha,PLB606,361

Testable@Collider exp.

In SUSY case

In the MSSM, there is no such a large coupling with SM-like Higgs

(The light stop scenario is the only possibility but it's almost dead)

The simplest example of strong but light Higgs scenario is SUSY 4HD+charged singlets

$\phi_c/T_c > 1$ with m_h=126GeV

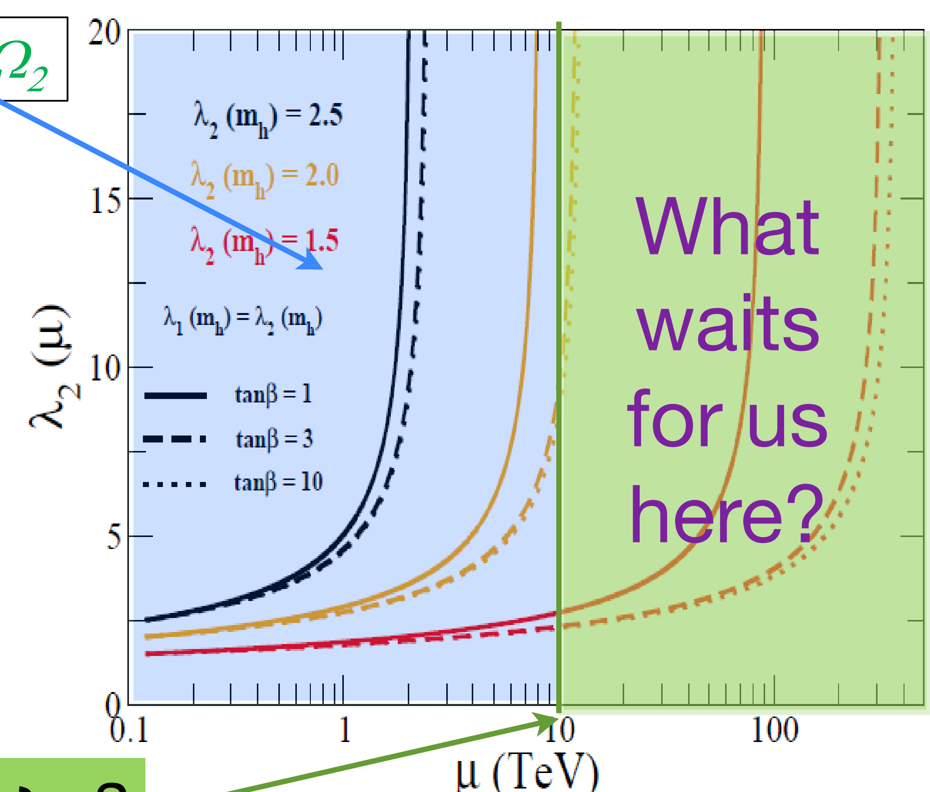
S.Kanemura, E. Senaha, T.S, PLB706,40

↓

$\lambda > 1.6$

$W = \lambda_1\, H_u\, H_u'\Omega_1 + \lambda_2\, H_d\, H_d'\Omega_2$

λ_2	Λ_{cutoff}
2.5	2 TeV
2.0	10 TeV
1.5	100 TeV



cutoff for λ=2

Kanemura, T.S, Yagyu, 2010

Radiative Seesaw scenarios

Origin of the neutrino mass at TeV scale

Alternative to the well-known seesaw model:

Idea of loop induced neutrino mass

Especially, radiative seesaw scenarios are interesting

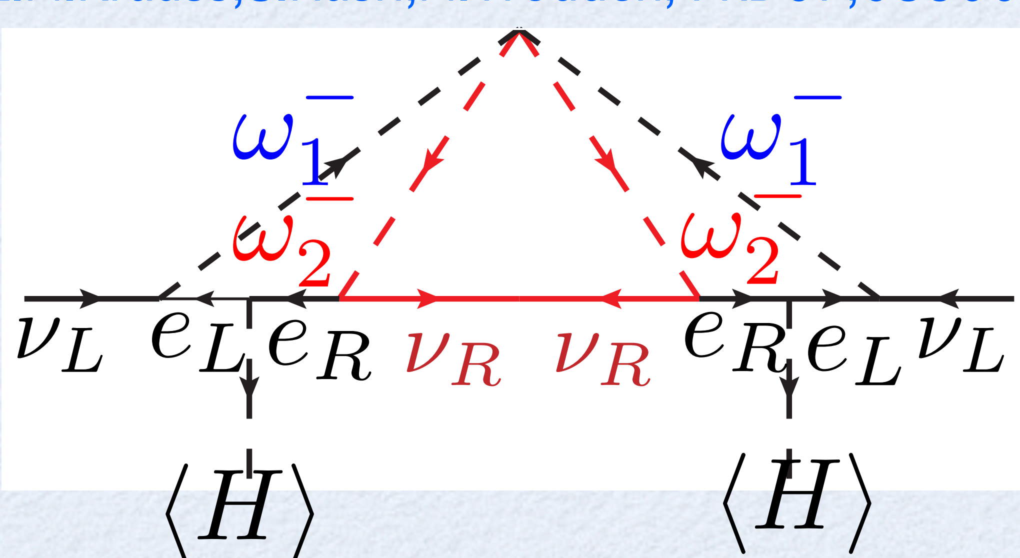
↓

Loop diagram with RH neutrinos give tiny neutrino mass

(Z_2-odd) ⟵ To avoid tree level contribution

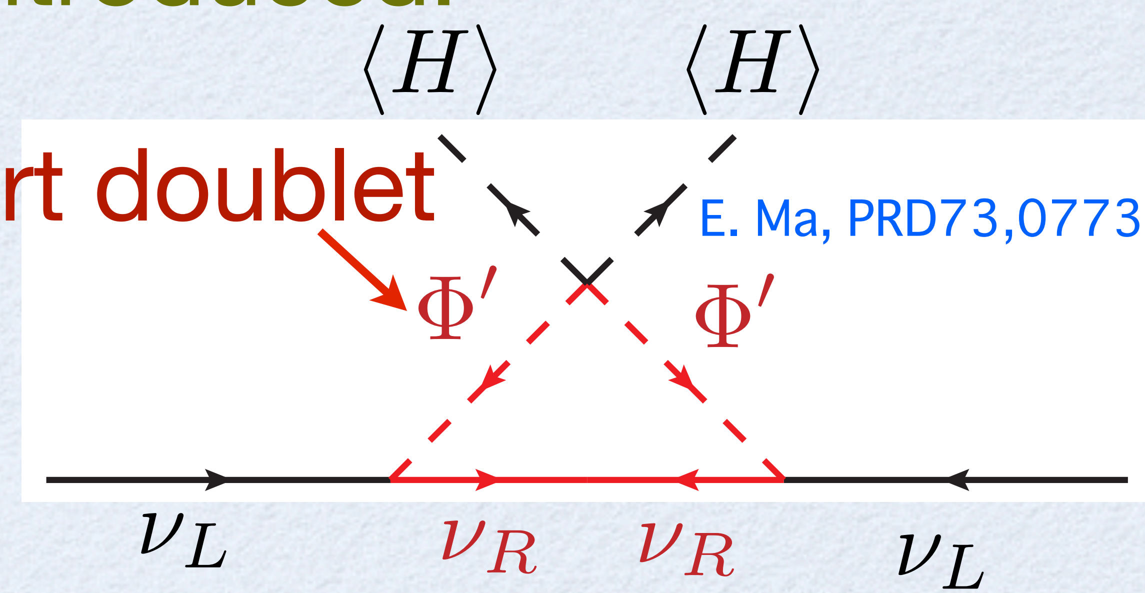
Some new scalars are introduced!

L.M.Krauss,S.Nasri,M.Trodden, PRD67,085002



inert doublet

E. Ma, PRD73,077301



Lightest Z_2-odd neutral particle can be a DM

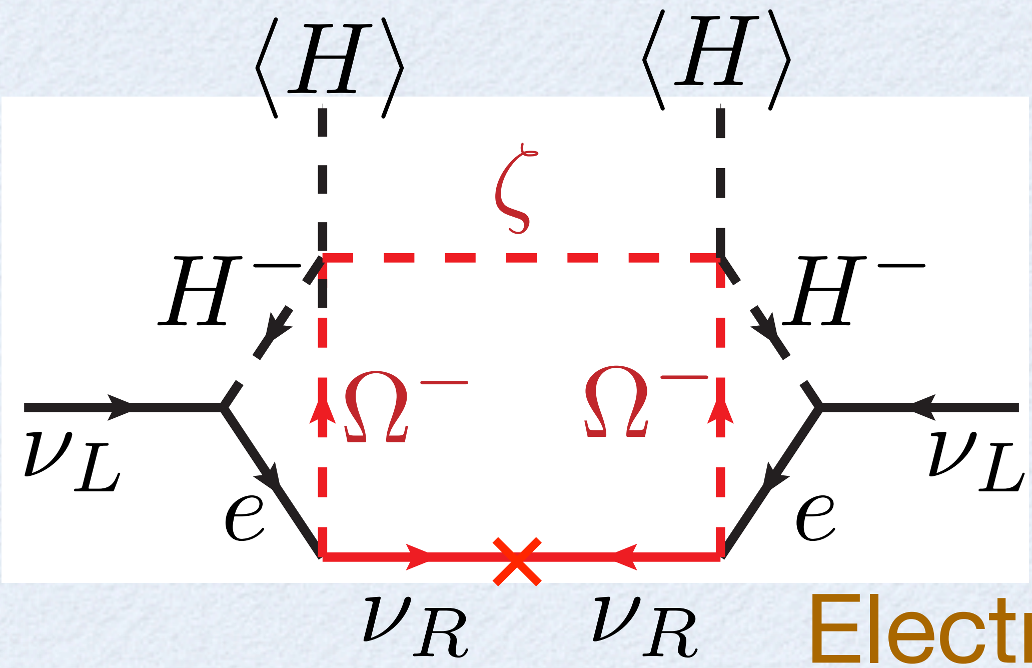
AKS model

Aoki-Kanemura-Seto model

Aoki, Kanemura, Seto, PRL102, 051805

(2HD+Z_2-odd charged and neutral singlet+Z_2-odd RHN)

Lighter one can be a DM



$\longrightarrow$ neutrino mass

Electroweak baryogenesis also can work

As a phenomenological model, this is quite interesting

But ...

Large couplings $\longrightarrow$ Landau pole at low energy scale

Many extra scalars $\longrightarrow$ It seems artificial

What is the fundamental theory of this model?

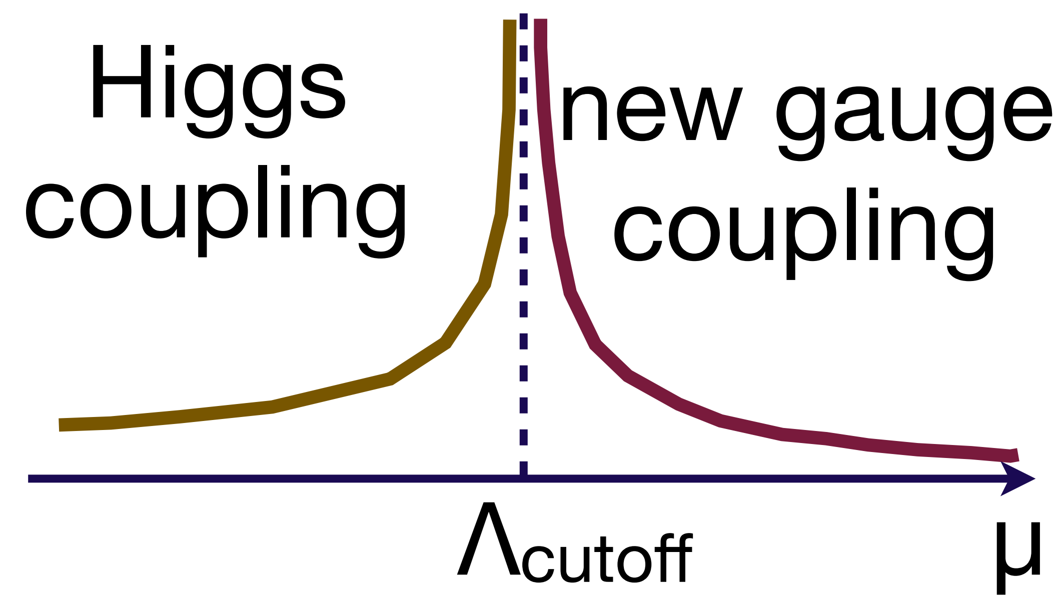
Fundamental theory?

- Radiative seesaw with electroweak baryogenesis
  - Enhancement of EWPT by bosonic loop requires strong Higgs coupling(>1) but light(125GeV) Higgs
  - Radiative seesaw requires several extra scalars
- What is the fundamental theory of such models?
  - Large coupling constant → Landau pole (cutoff)
  - Scalar fields required for radiative seesaw are naturally provided?
  - What is the origin of Higgs force?

Fundamental theory?

- Radiative seesaw with electroweak baryogenesis
  - Enhancement of EWPT by bosonic loop requires strong Higgs coupling(>1) but light(125GeV) Higgs
  - Radiative seesaw req
- What is the fundament
  - Large coupling const
  - Scalar fields required naturally provided?
  - What is the origin of Higgs force?

Our expectation:



SUSY SU(2)$_H$ model

In SUSY QCD: $N_f = N_c + 1 \Rightarrow$ confinement

See e.g. Intriligator, Seiberg, hep-th/9509006

Let us consider the simplest case (N_c=2&N_f=3)

SUSY $SU(2)_H \times SU(2)_L \times U(1)_Y$ S.Kanemura, T.S, and T. Yamada, PRD86,055023

It's asymptotic free!

It's the same setup as the minimal SUSY fat Higgs
R Harnik, et al., PRD70, 015002

Fields	$SU(2)_L$	$U(1)_Y$
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	2	0
T_3	1	$+1/2$
T_4	1	$-1/2$
T_5	1	$+1/2$
T_6	1	$-1/2$

Field	$SU(2)_L$	$U(1)_Y$
$H_u = \begin{pmatrix} H_{13} \\ H_{23} \end{pmatrix}$	2	$+1/2$
$H_d = \begin{pmatrix} H_{14} \\ H_{24} \end{pmatrix}$	2	$-1/2$
$N = H_{56}, N_\Phi = H_{34}, N_\Omega = H_{12}$	1	0
$\Phi_u = \begin{pmatrix} H_{15} \\ H_{25} \end{pmatrix}$	2	$+1/2$
$\Phi_d = \begin{pmatrix} H_{16} \\ H_{26} \end{pmatrix}$	2	$-1/2$
$\Omega_+ = H_{35}$	1	$+1$
$\Omega_- = H_{46}$	1	-1
$\zeta = H_{36}, \xi = H_{45}$	1	0

Below the confinement scale Λ_H, the effective theory is described by $H_{ij} \sim T_i T_j$

cf. In the minimal SUSY fat Higgs, only H_u, H_d, and N are made light
(The effective theory is "minimal")

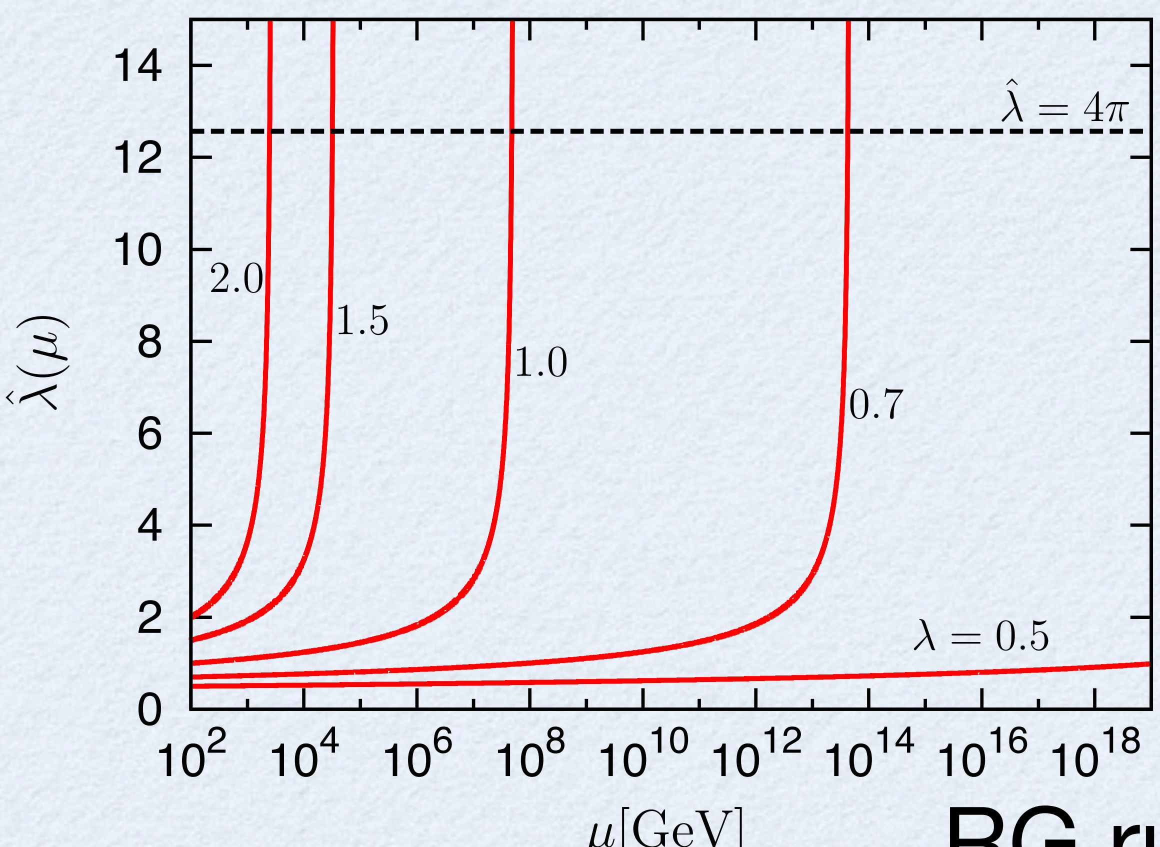
Effective theory of SU(2)$_H$ model

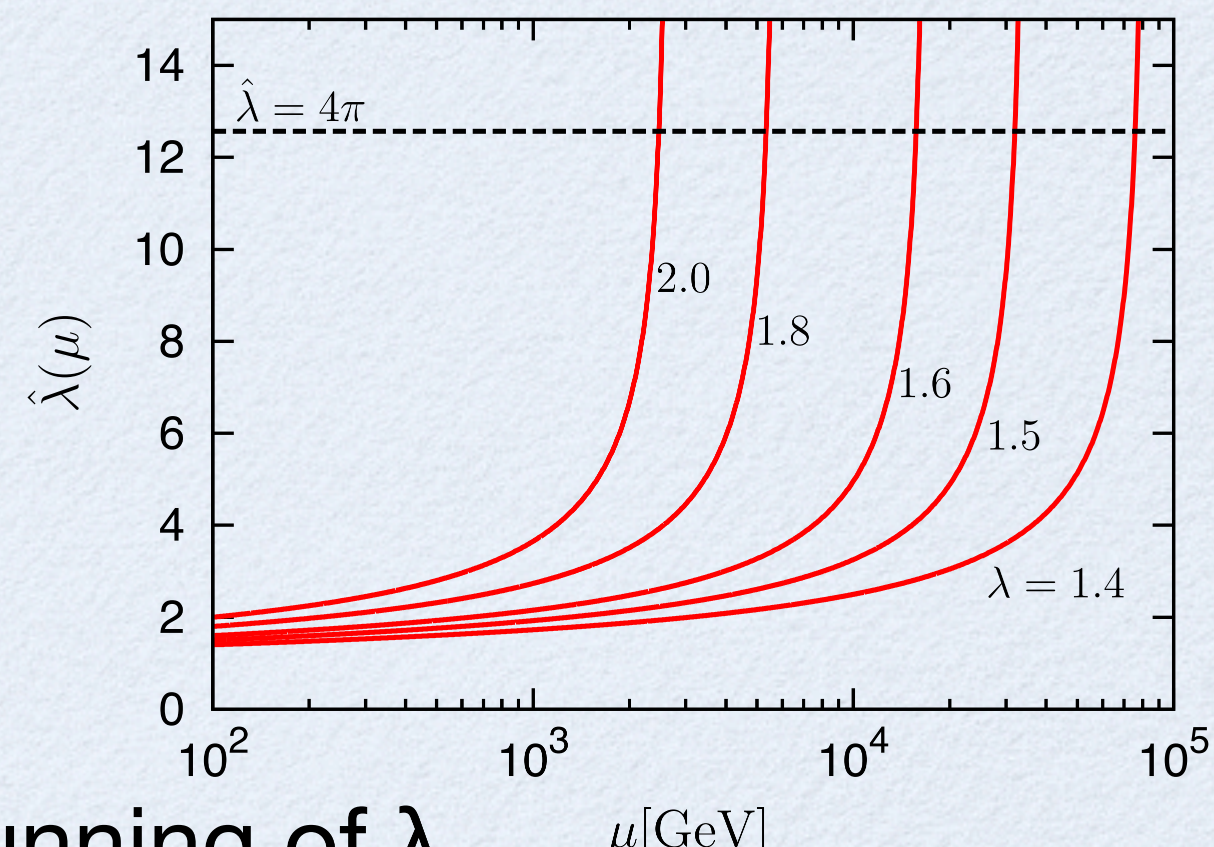
S.Kanemura,E. Senaha, T.S,T.Yamada,JHEP1305,066

MSSM-like Higgs doublets

$$W = -\mu H_u H_d - \mu_\Phi \Phi_u \Phi_d - \mu_\Omega(\Omega_+\Omega_- - \zeta\eta)$$
$$+\hat{\lambda}\{H_d\Phi_u\zeta + H_u\Phi_d\eta - H_u\Phi_u\Omega_- - H_d\Phi_d\Omega_+\}$$

$\hat{\lambda}(\Lambda_H) \simeq 4\pi$ (Naive dimensional analysis)





RG running of λ

$\lambda = \lambda(\mu_{EW})$ determines the cutoff scale

1st order EWPT

S.Kanemura,E. Senaha, T.S, T.Yamada,JHEP1305,066

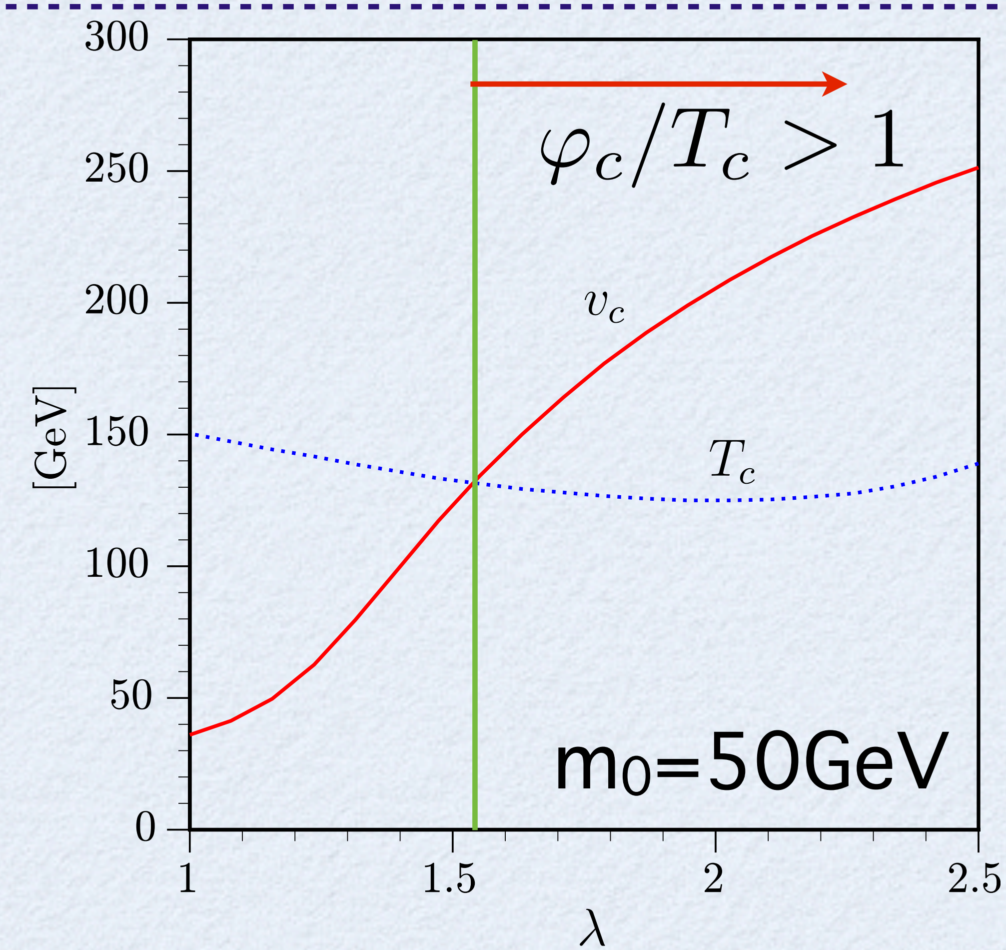
Benchmark:

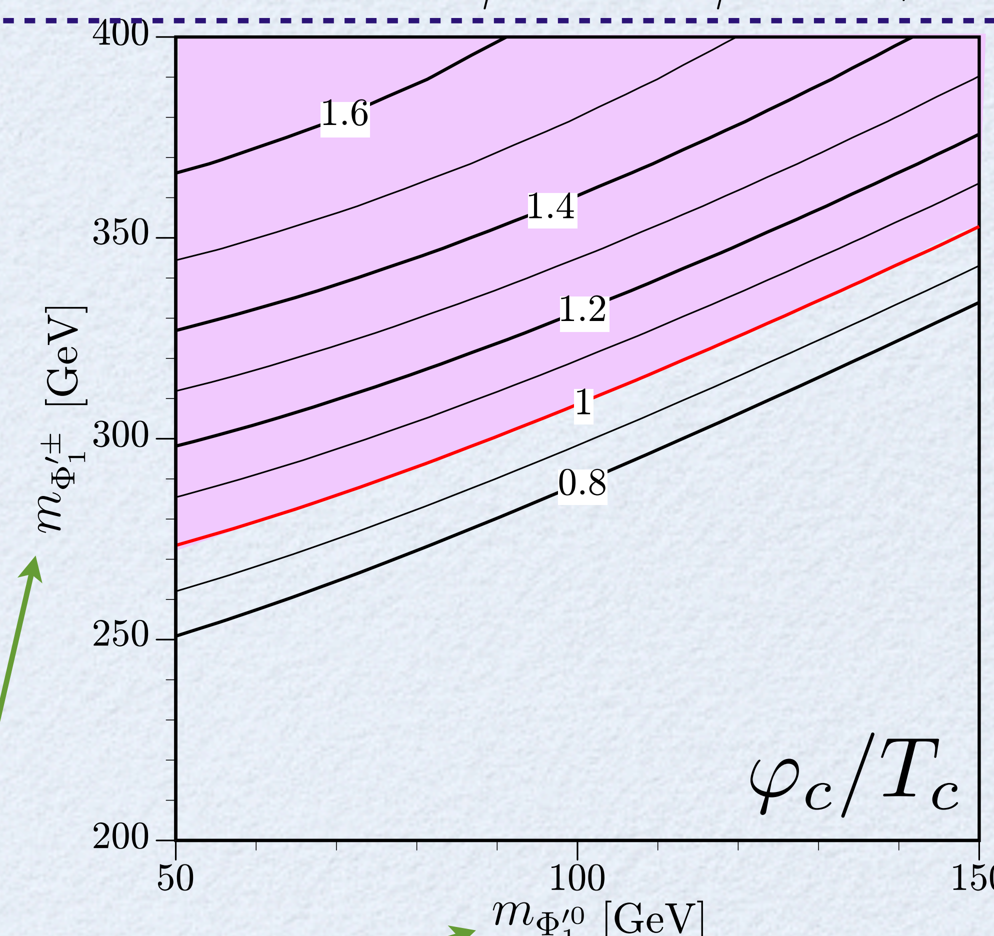
m_h=126GeV

$$\tan\beta = 15, m_{H^+} = 350\text{GeV}, \mu = 200\text{GeV}, M_{\tilde{t}} = M_{\tilde{q}} = 2000\text{GeV}$$

$$\bar{m}^2_{\Omega^+} = \bar{m}^2_{\Phi_d} = \bar{m}^2_{\zeta} = (1500\text{GeV})^2, \bar{m}^2_{\eta} = (2000\text{GeV})^2, \mu_\Phi = \mu_\Omega = 550\text{GeV}$$

$m_0^2 \equiv \bar{m}^2_{\Phi_u} = \bar{m}^2_{\Omega_-}$ (Scanned) $\quad (m_\phi^2 = \bar{m}_\phi^2 + c_\phi \lambda^2 v^2)$



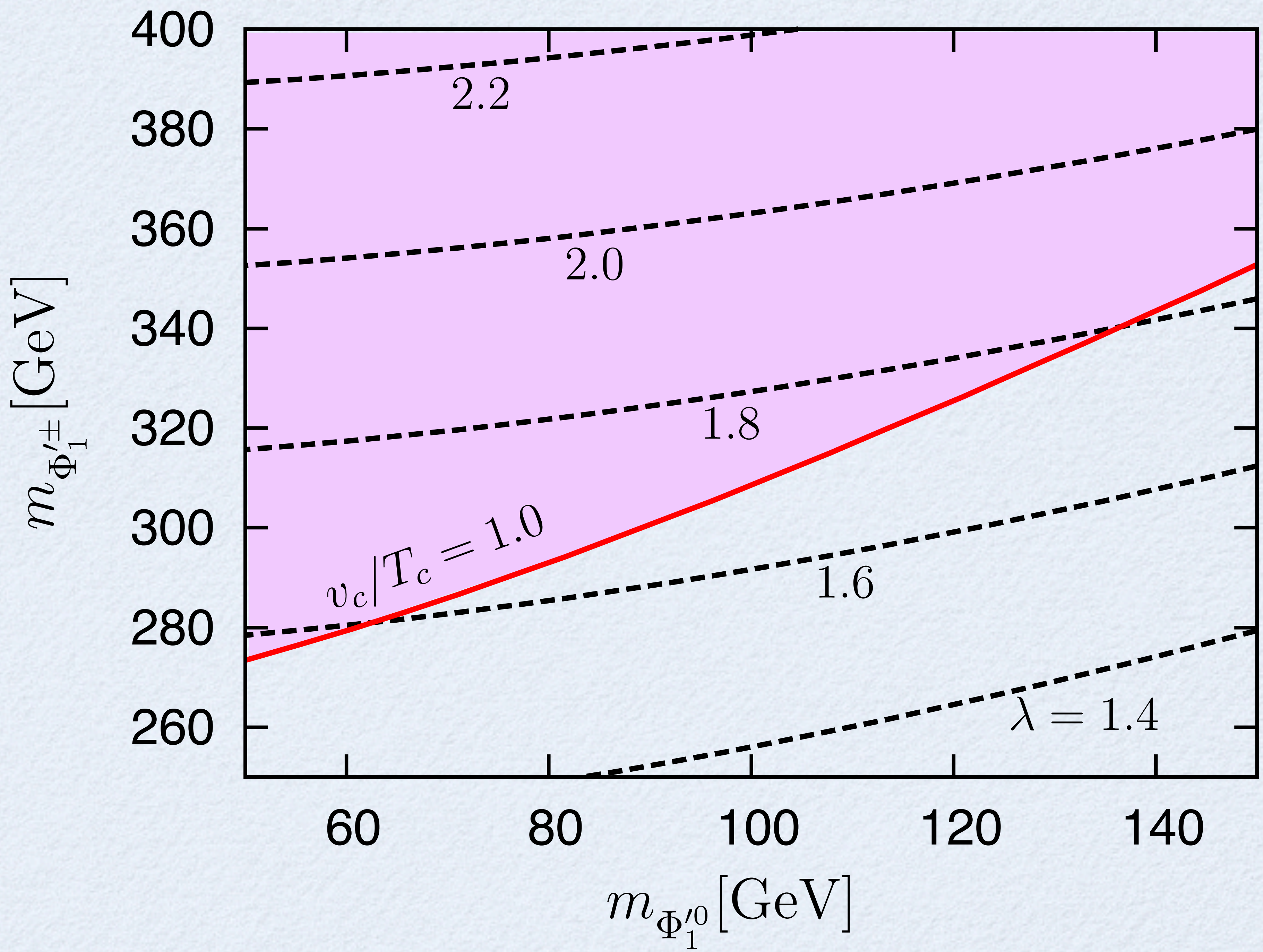


$\varphi_c/T_c > 1$ can be satisfied!!

Lightest Z_2 odd masses

1st order EWPT

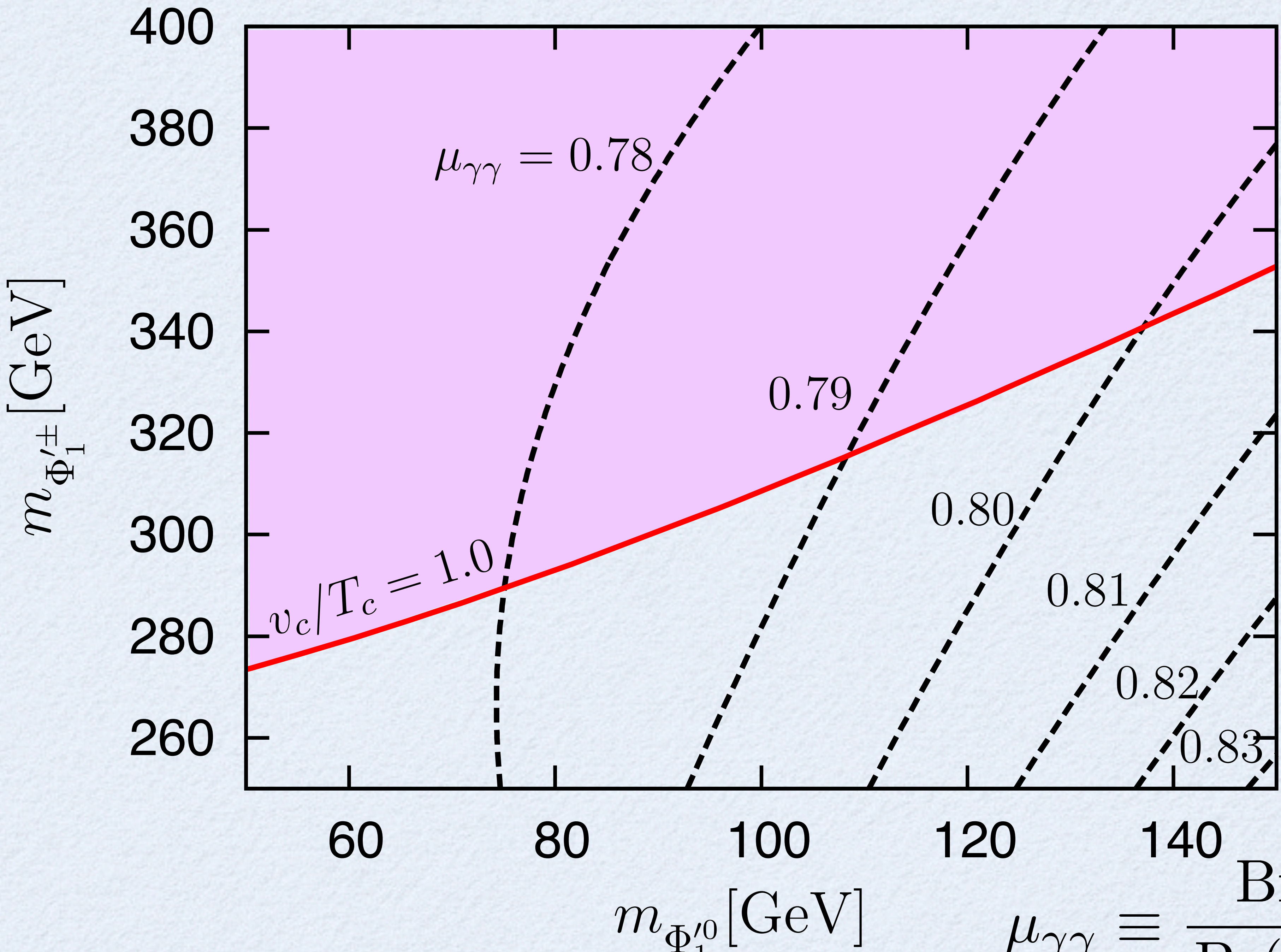
S.Kanemura,E. Senaha, T.S, T.Yamada,JHEP1305,066



$$\varphi_c/T_c > 1 \Longrightarrow \lambda \gtrsim 1.5 \quad (\Lambda_H \lesssim 20\text{TeV})$$

Contribution to hγγ

S.Kanemura,E. Senaha, T.S, T.Yamada,JHEP1305,066

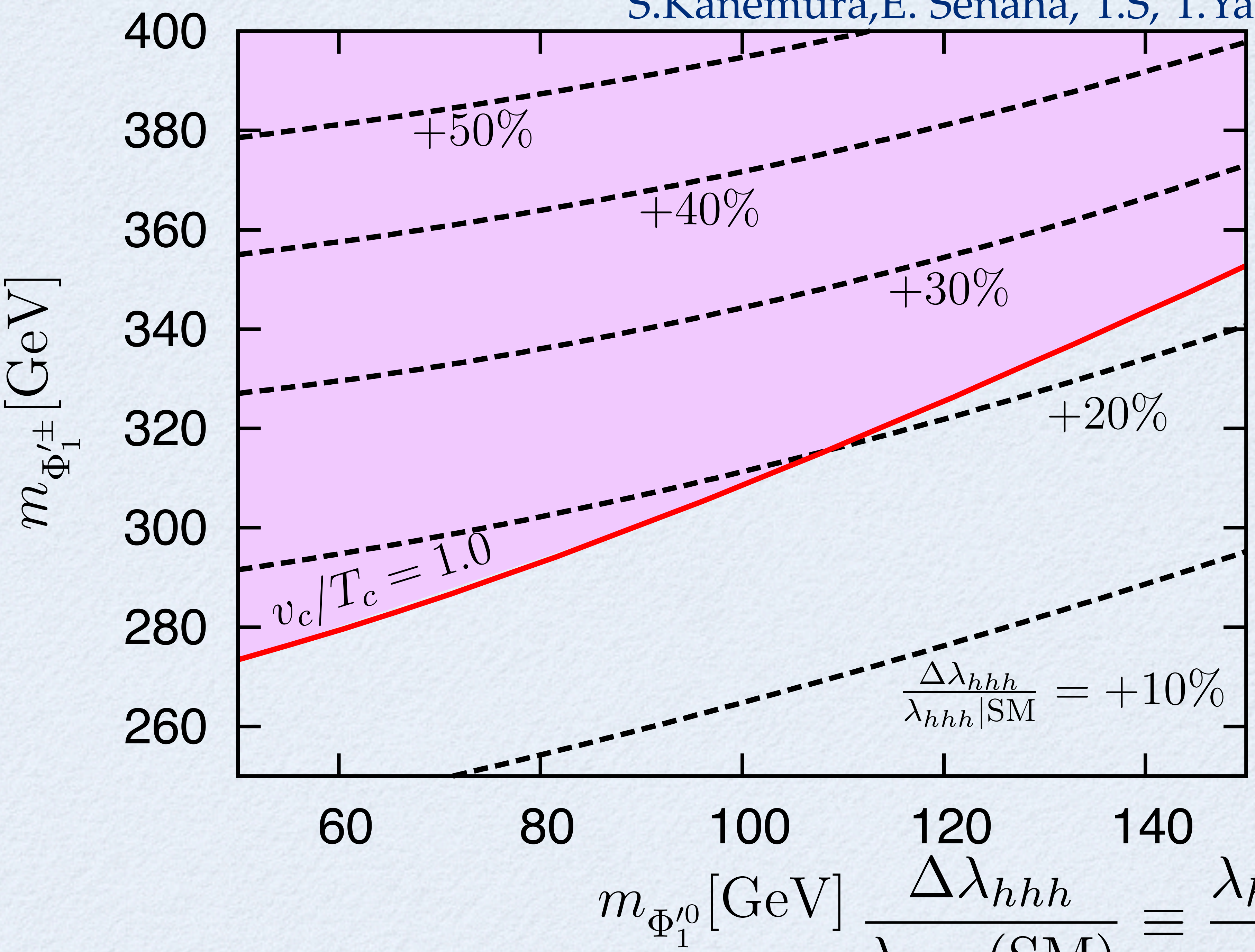


$$\mu_{\gamma\gamma} \equiv \frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to \gamma\gamma)|_{\mathrm{SM}}}$$

~20% deviation is possible in the region of $v_c/T_c>1$

hhh coupling

S.Kanemura,E. Senaha, T.S, T.Yamada,JHEP1305,066



$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}(\mathrm{SM})} \equiv \frac{\lambda_{hhh} - \lambda_{hhh}(\mathrm{SM})}{\lambda_{hhh}(\mathrm{SM})}$$

~20% deviation is possible in the region of $v_c/T_c>1$

For radiative seesaw

S.Kanemura, N. Machida, T.S, T.Yamada,in preparation

Fields	$SU(2)_L$	$U(1)_Y$	Z_2
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	2	0	+
T_3	1	+1/2	+
T_4	1	−1/2	+
T_5	1	+1/2	−
T_6	1	−1/2	−

→

Field	$SU(2)_L$	$U(1)_Y$	Z_2
$H_u = \begin{pmatrix} H_{13} \\ H_{23} \end{pmatrix}$	2	+1/2	+
$H_d = \begin{pmatrix} H_{14} \\ H_{24} \end{pmatrix}$	2	−1/2	+
$N = H_{56}, N_\Phi = H_{34}, N_\Omega = H_{12}$	1	0	+
$\Phi_u = \begin{pmatrix} H_{15} \\ H_{25} \end{pmatrix}$	2	+1/2	−
$\Phi_d = \begin{pmatrix} H_{16} \\ H_{26} \end{pmatrix}$	2	−1/2	−
$\Omega_+ = H_{35}$	1	+1	−
$\Omega_- = H_{46}$	1	−1	−
$\zeta = H_{36}, \xi = H_{45}$	1	0	−

Then, Z_2-odd RH neutrinos are introduced as $SU(2)_H$ singlet fields

In the low energy effective theory,

$$W_N = (y_N)_i N_i^c L_j \Phi_u + (h_N)_{ij} N_i^c E_j^c \Omega^- + \frac{M_i}{2} N_i^c N_i^c$$

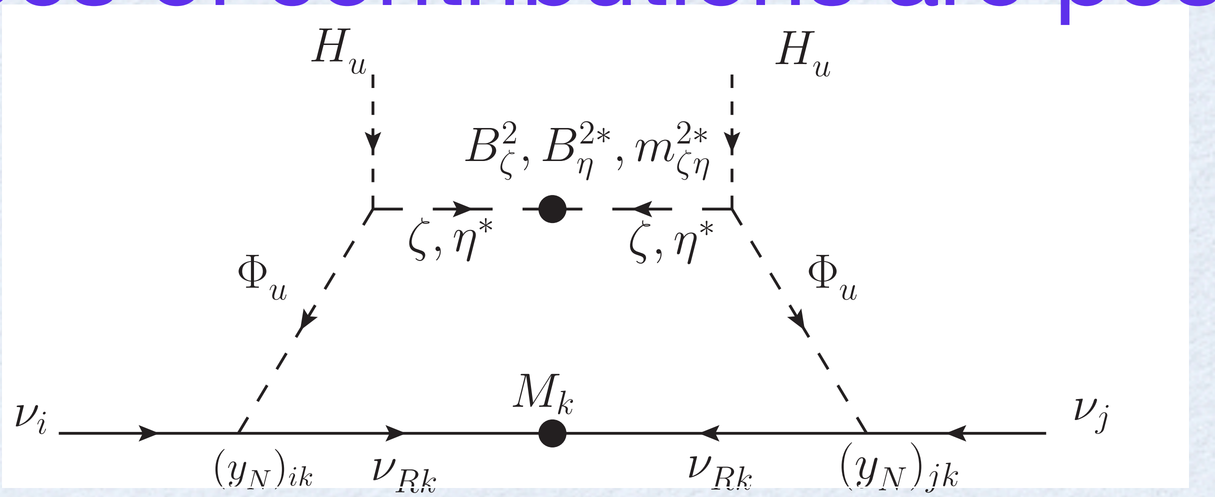
Neutrino mass generation

S.Kanemura, N. Machida, T.S, T.Yamada,in preparation

Two different types of contributions are possible

1-loop

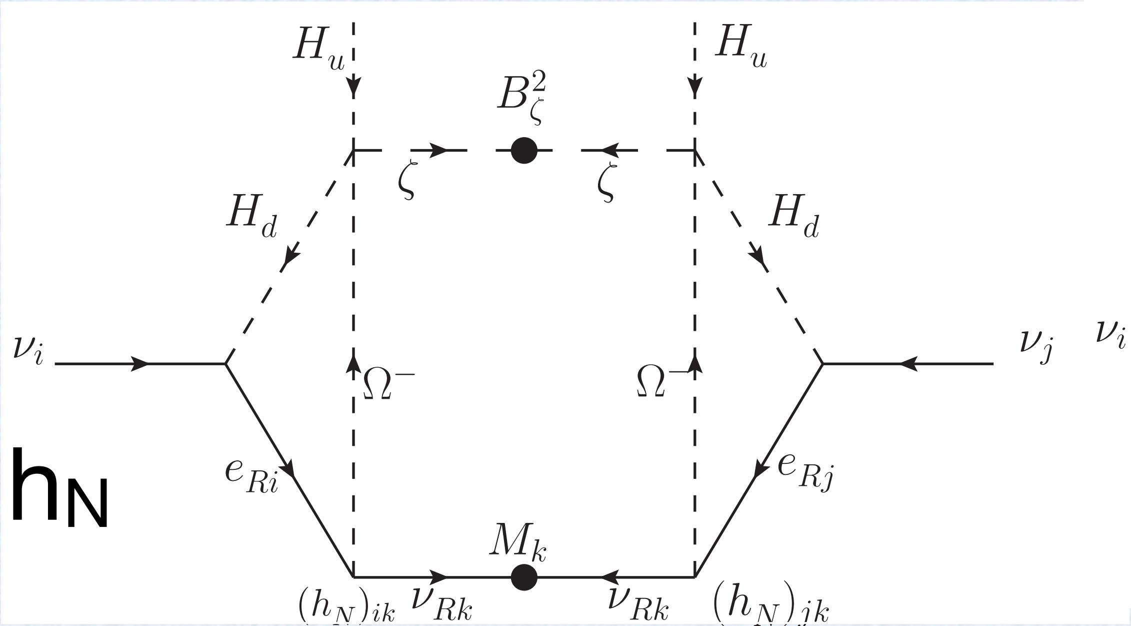
driven by y_N

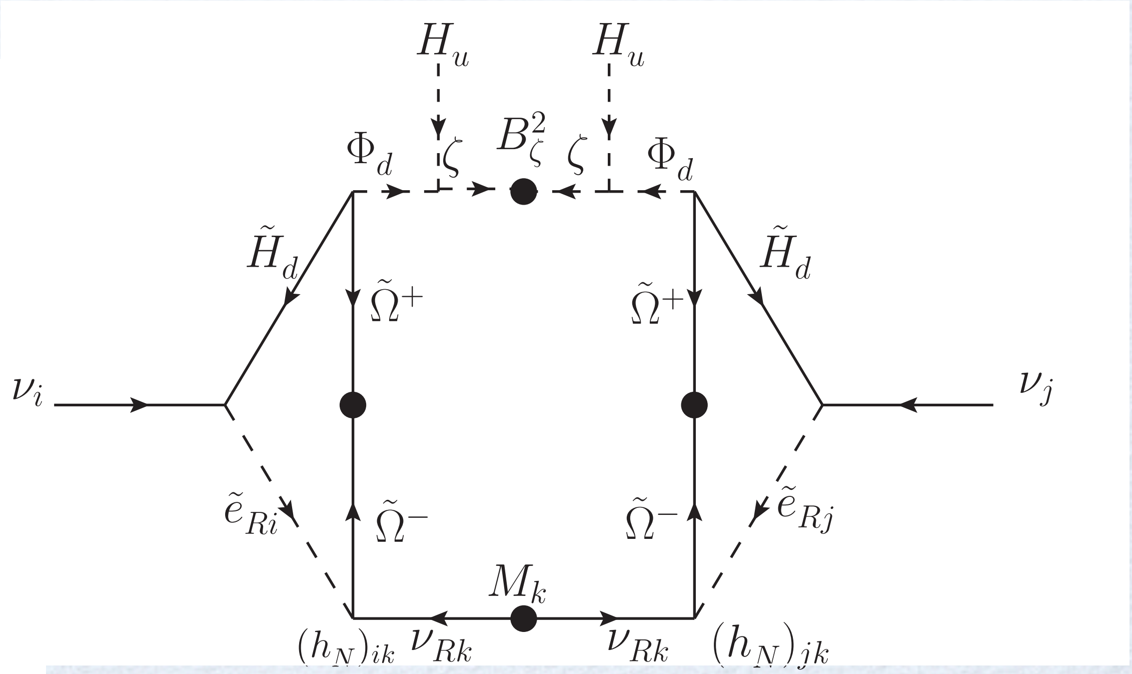


It corresponds to SUSY Ma model

3-loop

driven by h_N





They correspond to SUSY AKS model

Benchmark points

(A):1-loop dominant point
(B):3-loop dominant point

Case	λ	$\tan\beta$	$m_{H^\pm}$	$m_{\tilde{W}}$	μ	μ_Φ	μ_Ω
(A)	1.8	15	350GeV	500GeV	100GeV	550GeV	-550GeV
(B)	1.8	30	350GeV	500GeV	100GeV	550GeV	-550GeV

Case	$\bar{m}^2_{\Phi_u}$	$\bar{m}^2_{\Phi_d}$	$\bar{m}^2_{\Omega^+}$	$\bar{m}^2_{\Omega^-}$	$\bar{m}^2_\zeta$	$\bar{m}^2_\eta$
(A)	$(100\text{GeV})^2$	$(1500\text{GeV})^2$	$(1500\text{GeV})^2$	$(100\text{GeV})^2$	$(1500\text{GeV})^2$	$(2000\text{GeV})^2$
(B)	$(1500\text{GeV})^2$	$(1500\text{GeV})^2$	$(1500\text{GeV})^2$	$(30\text{GeV})^2$	$(1410\text{GeV})^2$	$(30\text{GeV})^2$

Case	B^2_ζ	B^2_η	$m^2_{\zeta\eta}$
(A)	$(100\text{GeV})^2$	$(100\text{GeV})^2$	$(100\text{GeV})^2$
(B)	$(1400\text{GeV})^2$	0	0

Case	M_1	M_2	M_3	$m_{\tilde{\nu}_{R1}}$	$m_{\tilde{\nu}_{R2}}$	$m_{\tilde{\nu}_{R3}}$	$m_{\tilde{e}_{Ri}}(i=1,2,3)$
(A)	60GeV	120GeV	180GeV	60GeV	120GeV	180GeV	6000GeV
(B)	100GeV	2000GeV	4000GeV	100GeV	4000GeV	8000GeV	6000GeV

Case	$(y_N)_{ij}$	$(h_N)_{ij}$
(A)	$\begin{pmatrix} -0.45 & -0.44 & 0.51 \\ 0.23 & 0.23 & -0.26 \\ 0.19 & 1.37 & 1.37 \end{pmatrix} \times 10^{-4}$	$\sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
(B)	$\sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0.001 & 0 & 0 \\ -0.0624+0.16i & -0.0314-0.0016i & -0.0022+0.000297i \\ 0.902+2.46i & 0.000681-0.00126i & -0.000755-0.00161i \end{pmatrix}$

Case	m_1	m_2	m_3	$\sin^2\theta_{12}$	$\sin^2 2\theta_{23}$	$\lvert\sin\theta_{13}\rvert$
(A)	0.0eV	0.0090eV	0.050eV	0.31	1.0	0.1
(B)	0.0eV	0.0089eV	0.050eV	0.31	1.0	0.1

The neutrino mass and angles are reproduced

Case	$\text{B}(\mu \to e\gamma)$	$\text{B}(\mu \to eee)$
(A)	4.6×10^{-19}	7.2×10^{-21}
(B)	5.2×10^{-14}	4.7×10^{-13}

Serious LFV constraints are also satisfied

And $\phi_c/T_c>1$ is realized!

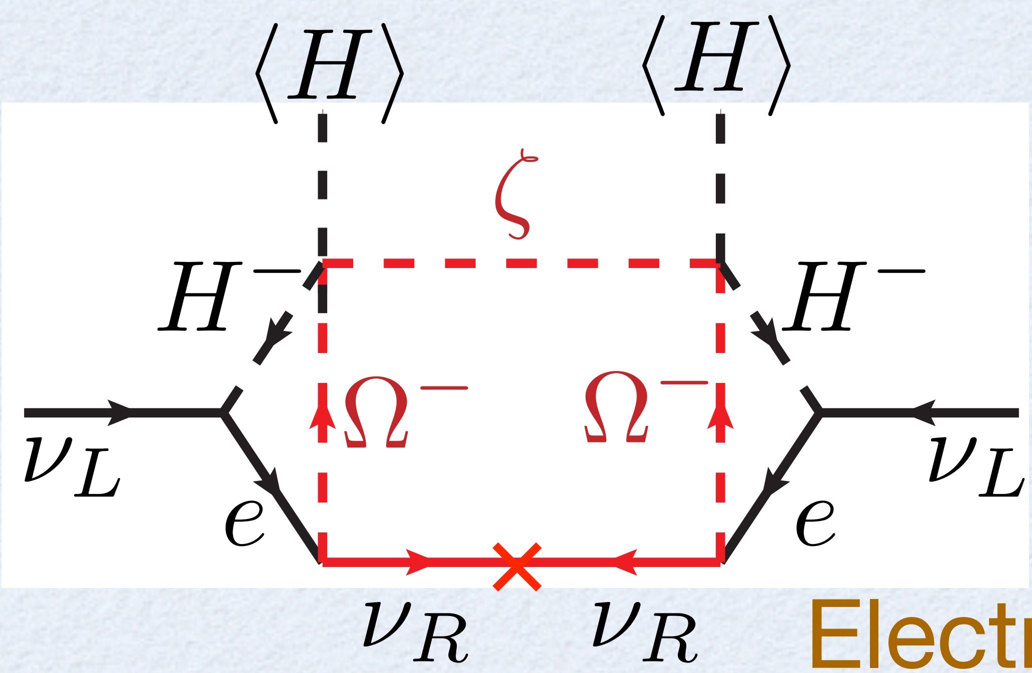
Comment on SUSY AKS

S.Kanemura, N. Machida, T.S, T.Yamada,in preparation

e.g. Aoki-Kanemura-Seto model — Aoki, Kanemura, Seto, PRL102, 051805

(2HD+Z_2-odd charged and neutral singlet+Z_2-odd RHN)

Lighter one can be a DM



→ neutrino mass

Electroweak baryogenesis also can work

In SUSY version,

H_u, H_d (MSSM-like Higgs)

Ω^+, Ω^-	Φ_u, Φ_d
ζ	N^c (RHN)

Many new fields are required

$SU(2)_H$ model automatically provides all the fields in the Higgs sector!!

Summary

- It is quite interesting, NP in the Higgs sector provides solutions for baryogenesis, neutrino mass, DM.
    - Electroweak baryogenesis, radiative generation of neutrino mass,...
    - It can be tested at collider experiments
    - Many models have been considered but they have been developed purely phenomenologically
- We have succeeded to provide a candidate of fundamental theory of such models
- SUSY $SU(2)_H$ with N_f=3 + Z_2-odd RHN is attractive simple candidate

  ↓ It provides new DM candidate
- It's very different from GUT beyond the grand desert

  Rich field will be there!

Back up

Top Yukawa coupling

Murayama hep-ph/0307293; Harnik et al.,PRD70,015002

Introducing several new fields ($SU(2)_H$ singlets) as

$$W_f = M_f(\varphi_u\bar{\varphi}_u + \bar{\varphi}_d\varphi_d) + \bar{\varphi}_d T T_4 + \bar{\varphi}_u T T_3 + h_u^{ij} Q_i u_j \varphi_u + h_d^{ij} Q_i d_j \varphi_d + h_e^{ij} L_i e_j \varphi_d$$

$$T = \begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$$

Q,L,u,d,e: Matter fields in the SM

conformal enhancement

$\varphi_{u,d}$ and $\bar{\varphi}_{u,d}$ are integrated out

$$W = \frac{4\pi}{M_f}\left\{h_u^{ij} Q_i u_j (TT_3) + h_d Q_i d_j (TT_4) + h_e L_i e_j (TT_4)\right\}$$

Below Λ_H

$$(TT_3) \to \frac{\Lambda_H}{4\pi} H_u \qquad (TT_4) \to \frac{\Lambda_H}{4\pi} H_d$$

$$W = h_u^{ij} Q_i u_j H_u + h_d^{ij} Q_i d_j H_d + h_e^{ij} L_i e_j H_d$$

for $M_f \sim \Lambda_H$

EWBG in the SM

In the high temperature approximation,

$$V(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

$$\varphi_c/T_c = 2E/\lambda_{T_c}$$

1st order PT is possible due to the cubic term

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3)$$

$$\lambda_T = \frac{m_h^2}{2v^2} + \log \text{ corrections}$$

$$\varphi_c/T_c \propto 1/m_h^2$$

Light Higgs is required !!

In SM, Higgs should be lighter than 50GeV

excluded by LEP data

NEW CP phases are also necessary for successful baryogenesis

Extension of the SM at TeV scale is necessary

It can be tested by experiments

- New bosonic loop contribution
- Higher dim. term in the potential
- …

EWBG in the MSSM

Carena et al.,PLB380,81;···

Lighter stop loop can contribute

enhance

$$\varphi_c/T_c = 2E/\lambda_{T_c} > 1$$

large top Yukawa coupling

$$E \simeq \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) + \frac{m_t^3}{2\pi v^3}\left(1 - \frac{|A_t + \mu\cot\beta|^2}{M_{\tilde{q}}^2}\right)^{3/2}$$

where the maximal contribution case is considered;

$$m_{\tilde{t}_1}^2(\varphi,\beta) = M_{T_R}^2 + \frac{y_t^2 s_\beta^2}{2}\left(1 - \frac{|A_t + \mu\cot\beta|^2}{M_{\tilde{q}^2}}\right)\varphi^2$$

$M_{T_R}^2 \sim 0$

For larger M_{TR}, the effect is smaller

Light stop is necessary ⟷ No new coloured particles at LHC···

Even with such a maximal case, it's not easy to get $\varphi_c/T_c>1$

Carena et al.,NPB812,243; Funakubo,Senaha,PRD79,115024

MSSM should be also modified at TeV scale for EWBG

What kind of modification?

$\varphi_c/T_c \propto 1/m_h^2$ → Small m_h is preferable ← support — m_h=126GeV@LHC

We want to keep it!

A Good point of MSSM :h^4 coupling is from gauge coupling→Light Higgs → **strong but light!**

Large bosonic loop contribution

- A strong Higgs coupling with additional bosons (h-Φ'-Φ')
- Mass of ϕ' is dominated by vev $m_{\Phi'}^2 = M^2 + \lambda^2 v^2$

A natural realization of "strong but light" in SUSY model:

MSSM Higgs Z_2 odd new fields

$$W = \lambda \Phi_{u,d} \Phi'_1 \Phi'_2 \rightarrow \Delta V = |\lambda|^2 h^2 \varphi'^{\dagger}_{1,2} \varphi'_{1,2}$$

It provides strong coupling but m_h is kept small!

Tests of the scenario

Enhancement of φ_c/T_c

destructive

Extra bosonic loop

Ino loop

positive contribution

negative contribution

contribution to hhh coupling

Linear Collider

Inert scalar mass: $m^2_{\Phi'} = M'^2 + \lambda^2 v^2$

Inert ino mass: $m_{\tilde{\Phi}'} = \mu' + \lambda v$

The loop contributions are significant when λv dominates the masses.

Z_2 odd scalars as light as ~λv

Large μ' and small M'^2 provides large deviation in hhh and large φ_c/T_c