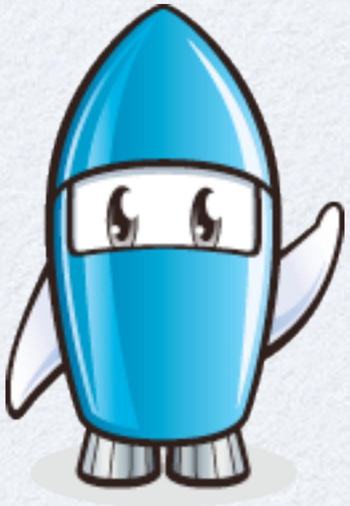
UV complete theory of SUSY radiative seesaw scenarios



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:1309.3207

14/11/2013 LCWS2013 @ Univ. of Tokyo Japan

Physics beyond the SM

Discovery of a Higgs boson&measurements of properties

↓

Essence of the electroweak symmetry breaking

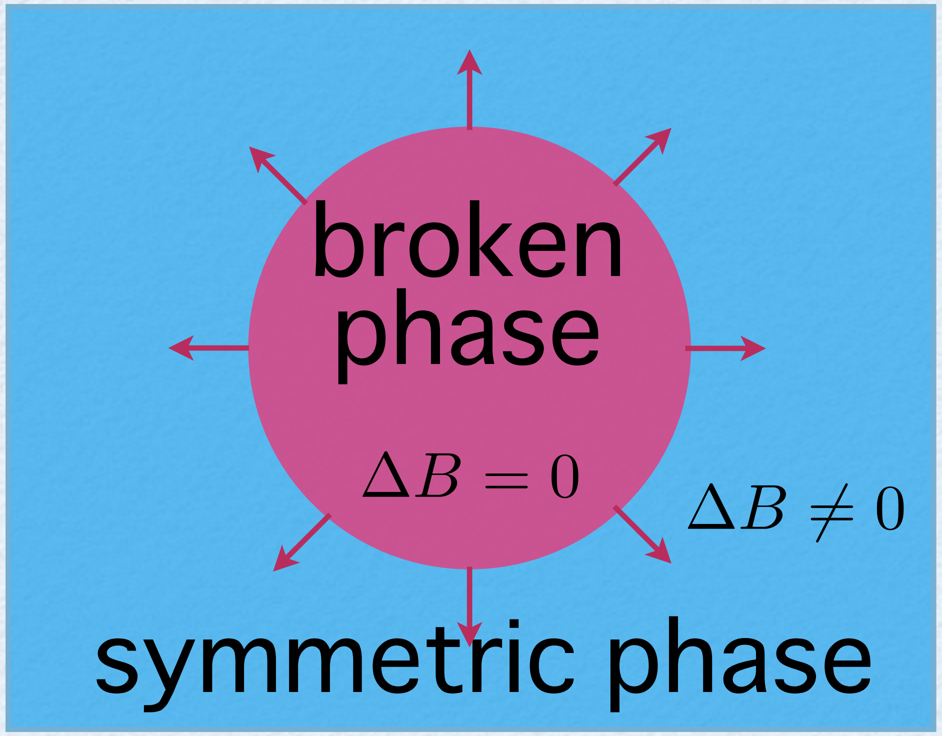
New Physics at TeV scale

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

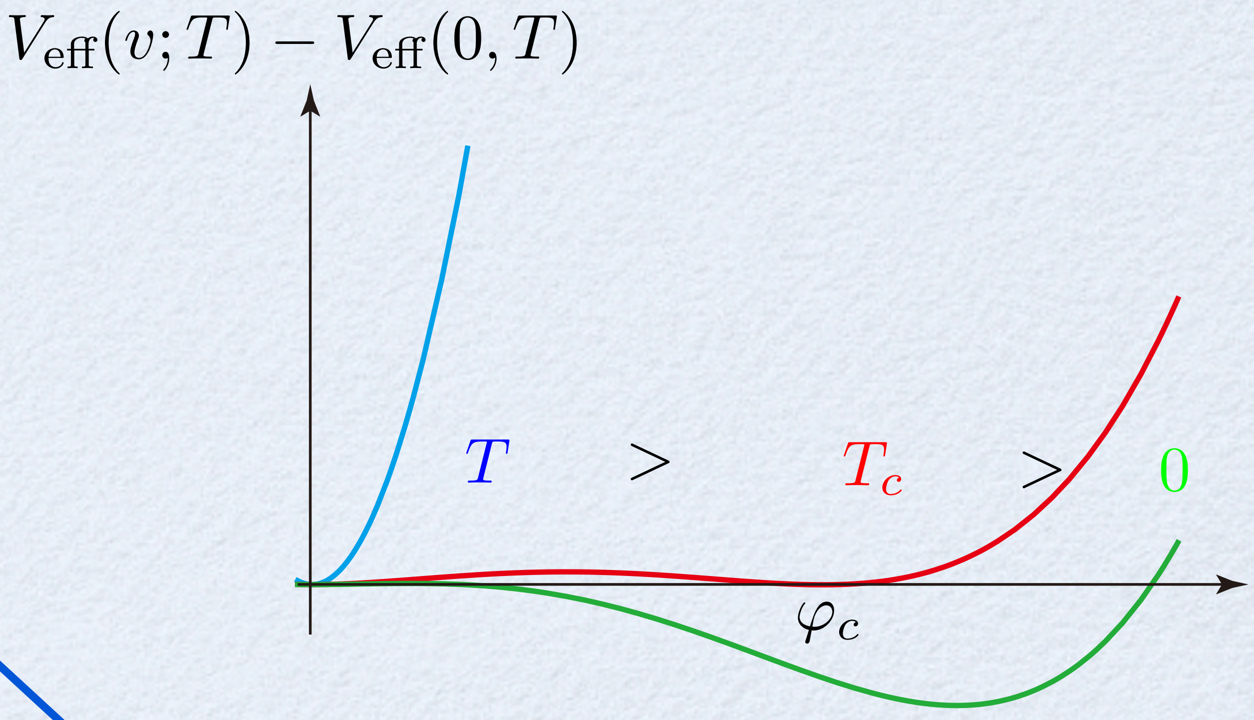
Electroweak Baryogenesis ⟷ essence of EWSB



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 $m_h < 50\mathrm{GeV}$

(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!

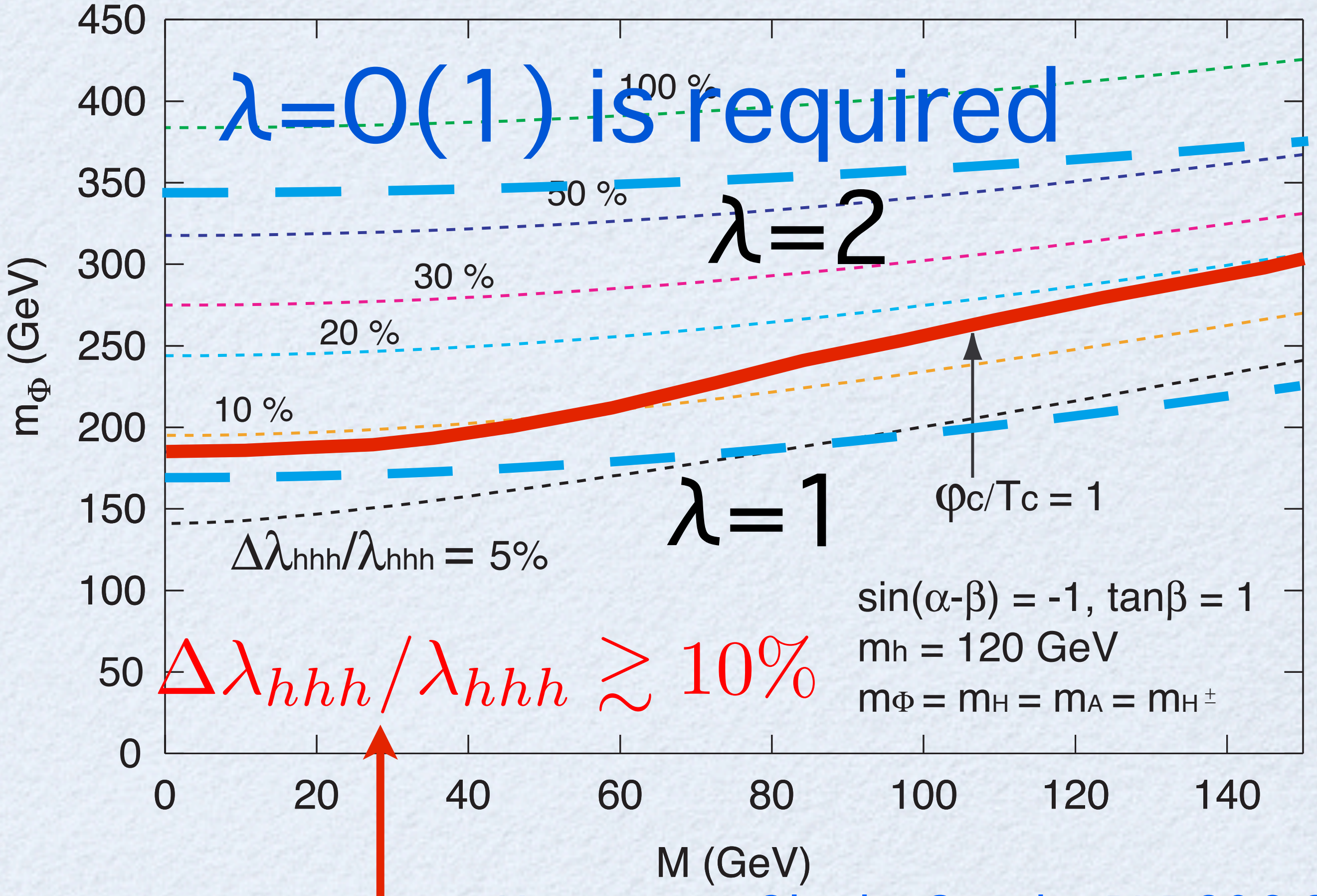
e.g. 2HDM

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

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

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

Contour plot of $\Delta\lambda_{hhh}/\lambda_{hhh}$ and φ_c/T_c in the m_Φ-M plane



λ=O(1) is required

λ=2

λ=1

$\Delta\lambda_{hhh}/\lambda_{hhh} \gtrsim 10\%$

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

$$\downarrow$$

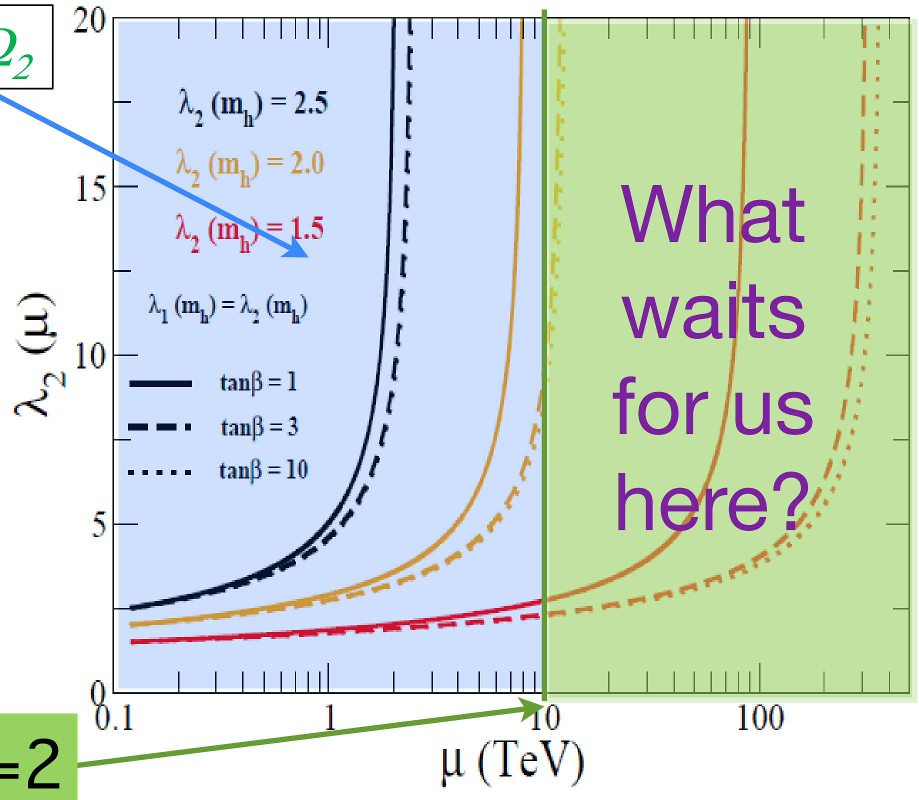
$$\lambda > 1.6$$

EW baryogenesis can be realized in a SUSY model @TeV

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

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

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



What waits for us here?

cutoff for λ=2

Kanemura, T.S, Yagyu, 2010

Fundamental theory?

- Electroweak baryogenesis
  - Enhancement of EWPT by bosonic loop requires strong Higgs coupling(>1) but light(125GeV) Higgs
- What is the fundamental theory of such models?
  - Large coupling constant → Landau pole (cutoff)
  - What is the origin of Higgs force?

Fundamental theory?

- Electroweak baryogenesis
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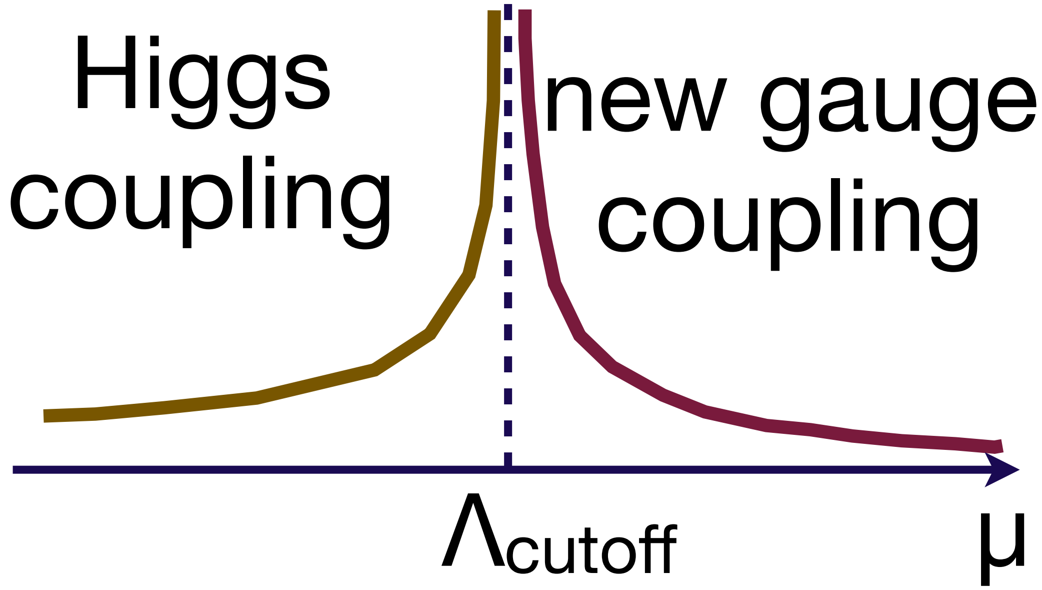
  - Large coupling constan
  - What is the origin of Hig

Our expectation:



SUSY SU(2)$_H$ model

In SUSY QCD: $\boxed{N_f=N_c+1 \Rightarrow \text{confinement}}$

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

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

SUSY SU(2)$_H$×SU(2)$_L$×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")

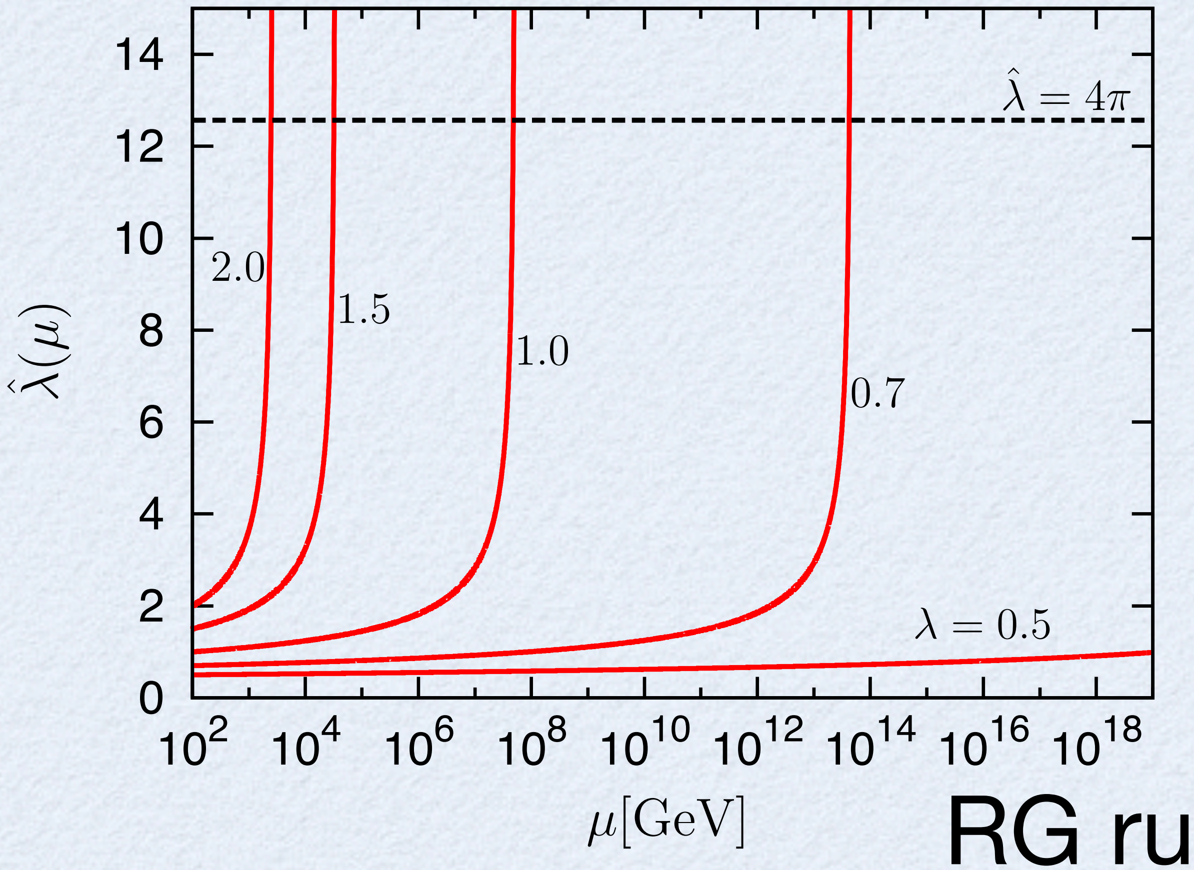
Effective theory of $\mathrm{SU(2)_H}$ model

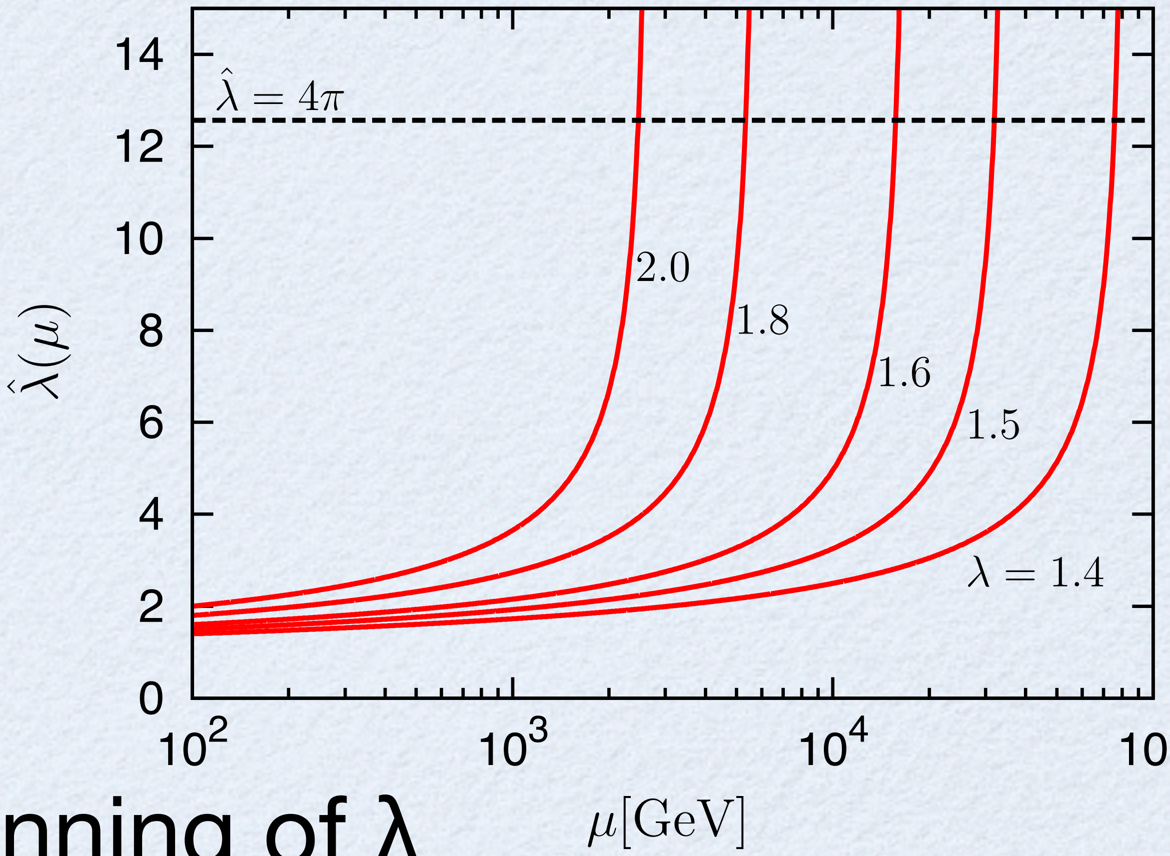
S.Kanemura,E. Senaha, T.S,T.Yamada,JHEP1305,066

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:

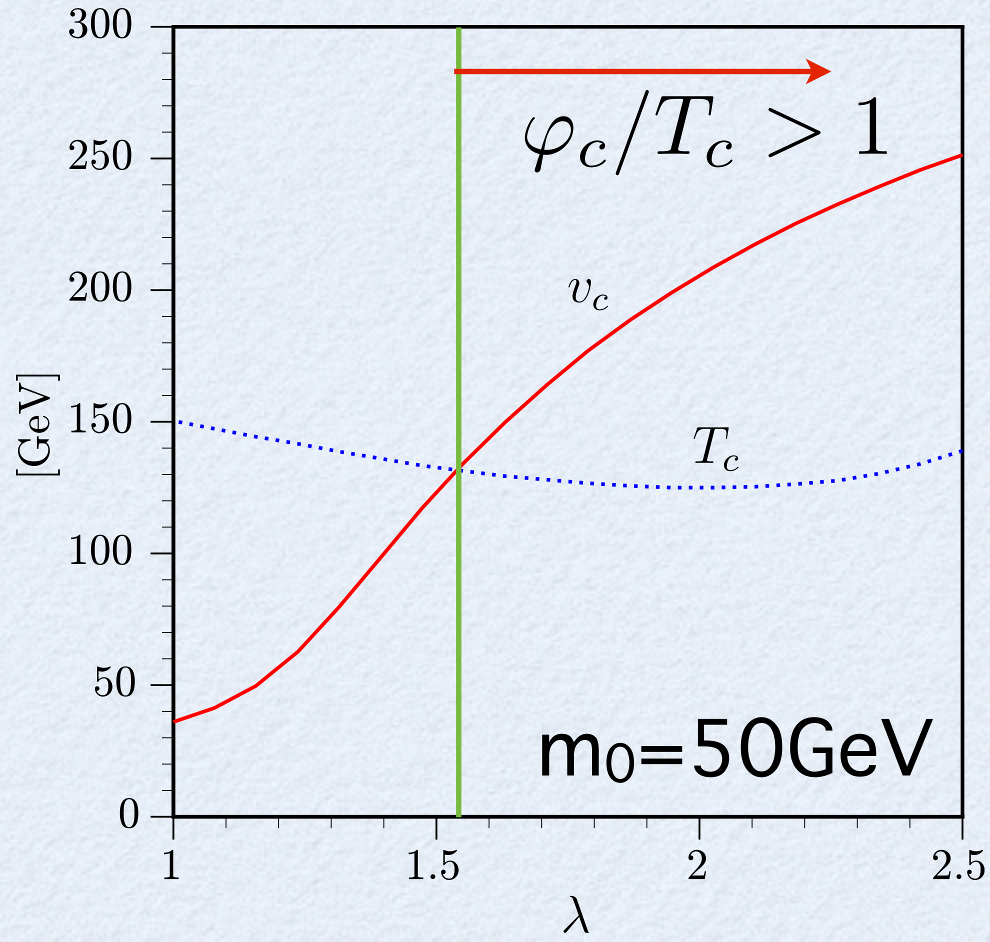
m_h=126GeV

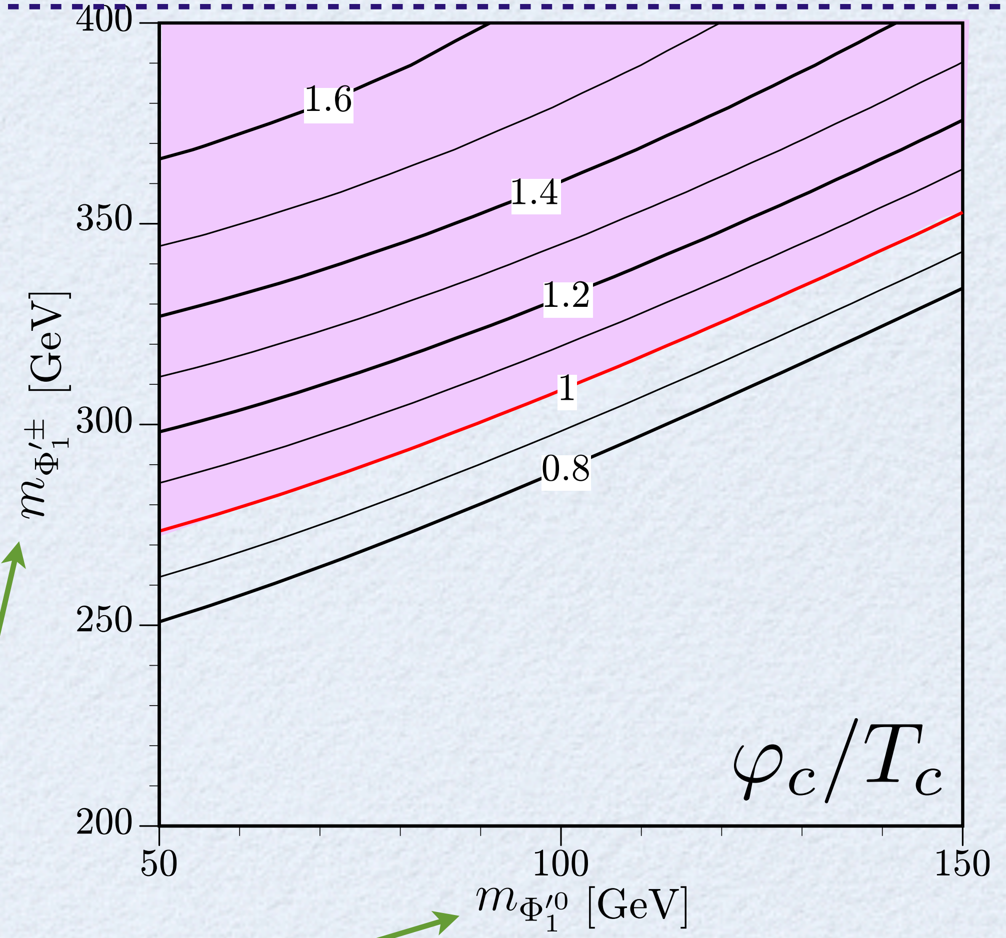
$$\tan\beta = 15, m_{H^+} = 350\text{GeV}, \mu = 200\text{GeV}, M_{\tilde{t}} = M_{\tilde{q}} = 2000\text{GeV}$$

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

$m_0^2 \equiv \bar{m}^2_{\Phi_u} = \bar{m}^2_{\Omega_-}$ (Scanned)

$$(m_\phi^2 = \bar{m}_\phi^2 + c_\phi \lambda^2 v^2)$$



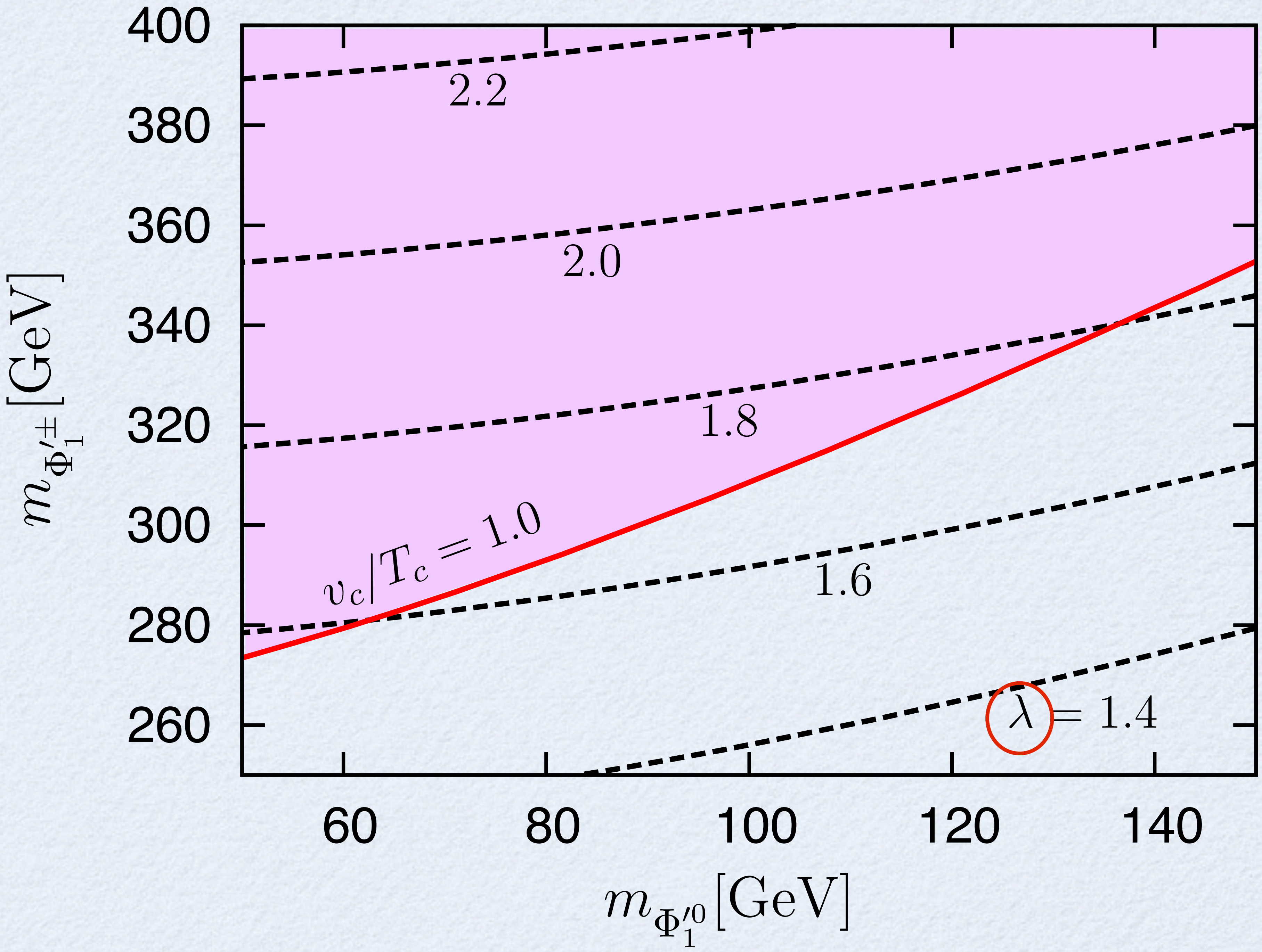


$\varphi_c/T_c > 1$ can be satisfied!!

Lightest Z_2 odd masses

1st order EWPT

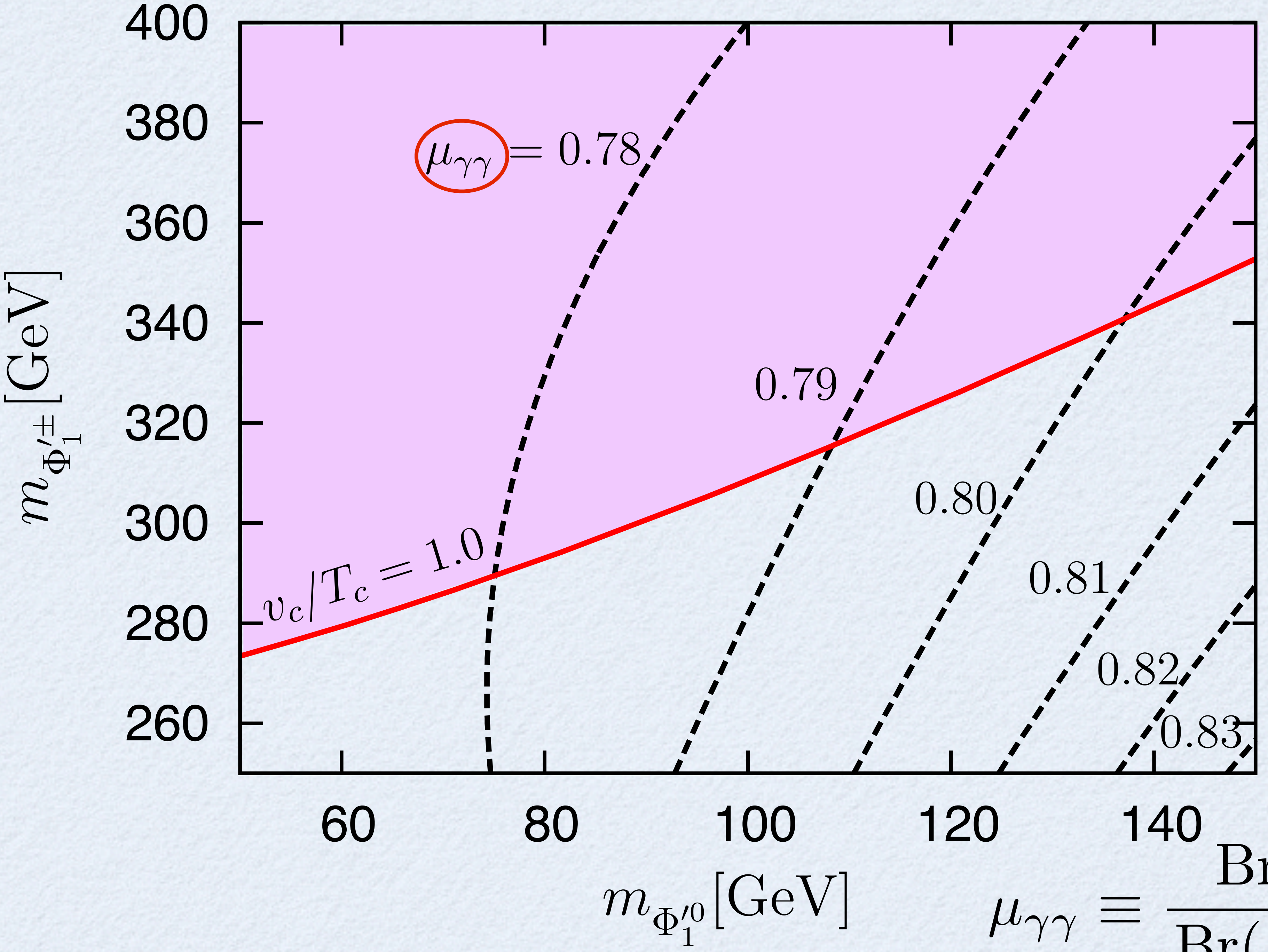
S.Kanemura,E. Senaha, T.S, T.Yamada,JHEP1305,066



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

Contribution to hγγ

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

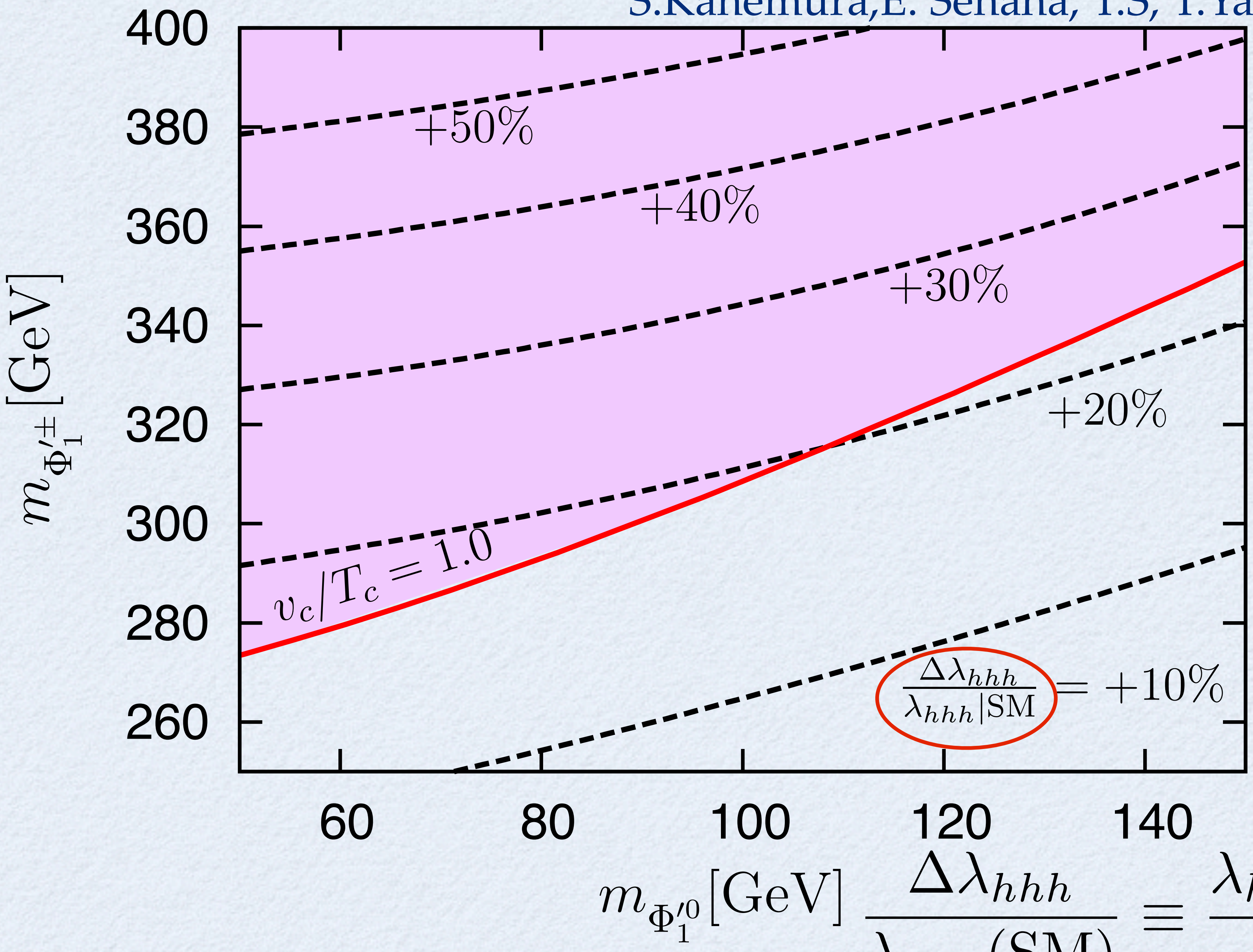


$$\mu_{\gamma\gamma} \equiv \frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to \gamma\gamma)|_{\mathrm{SM}}}$$

~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 $v_c/T_c>1$

How about neutrino mass?

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

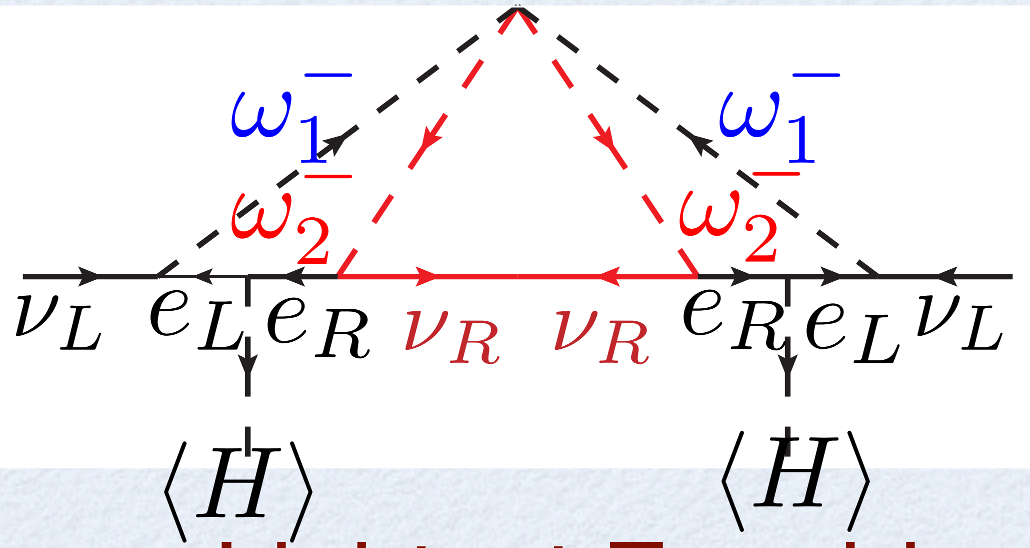
↓

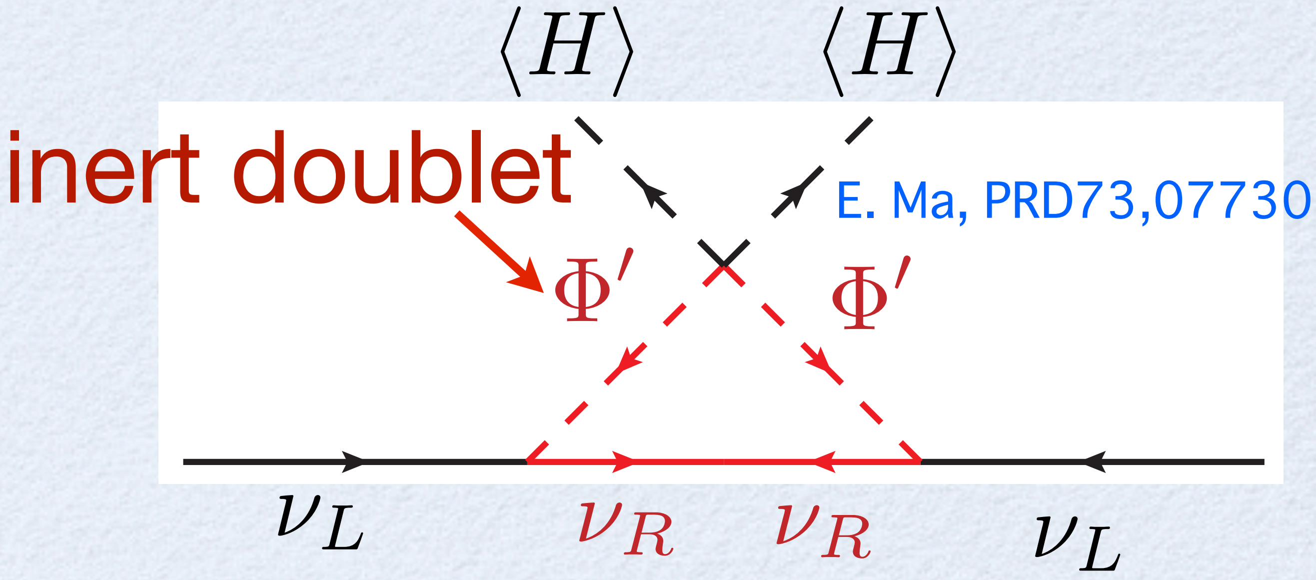
Loop diagram with RH neutrinos give tiny neutrino mass

(Z_2-odd) ← To avoid tree level contribution

Some new scalars are introduced!

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





E. Ma, PRD73,077301

Lightest Z_2-odd neutral particle can be a DM

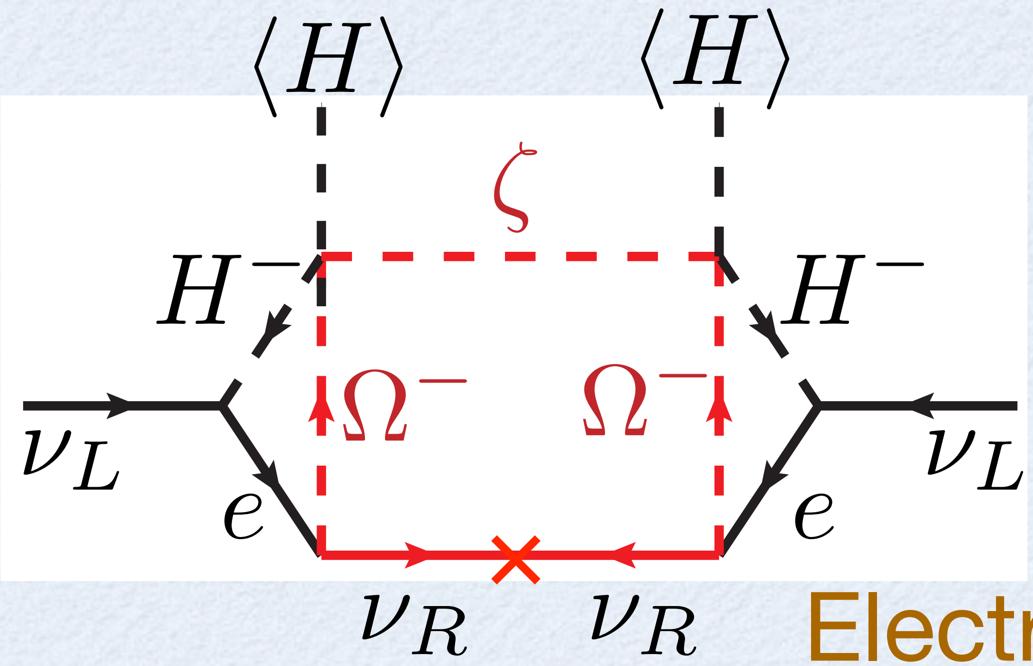
AKS model

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



→ neutrino mass

Electroweak baryogenesis also can work

As a phenomenological model, this is quite interesting

But ...

Large couplings → Landau pole at low energy scale

Many extra scalars → It seems artificial

What is the fundamental theory of this model?

For radiative seesaw

S.Kanemura, N. Machida, T.S, T.Yamada,arXiv:1309.3207

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	$-1/2$	−

→

We can use the SU(2)$_H$ model

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,

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

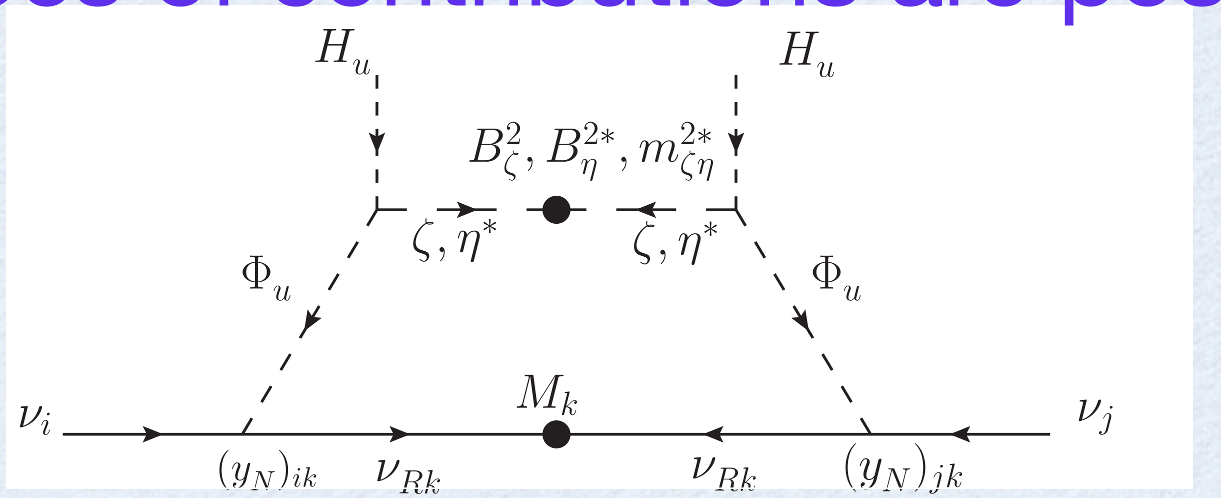
Neutrino mass generation

S.Kanemura, N. Machida, T.S, T.Yamada, arXiv:1309.3207

Two different types of contributions are possible

1-loop

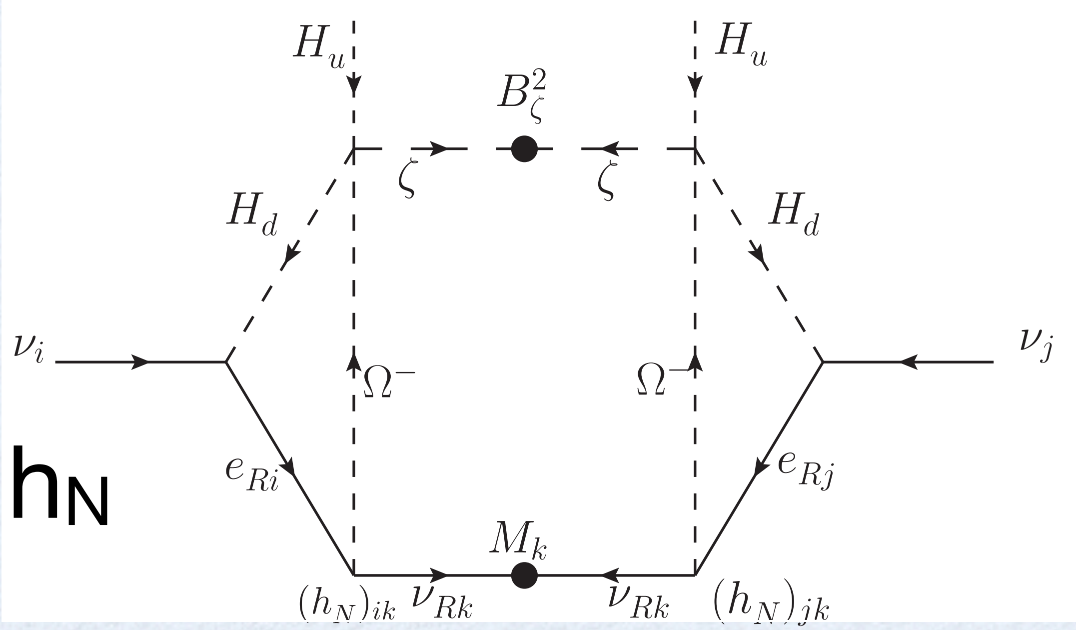
driven by y_N

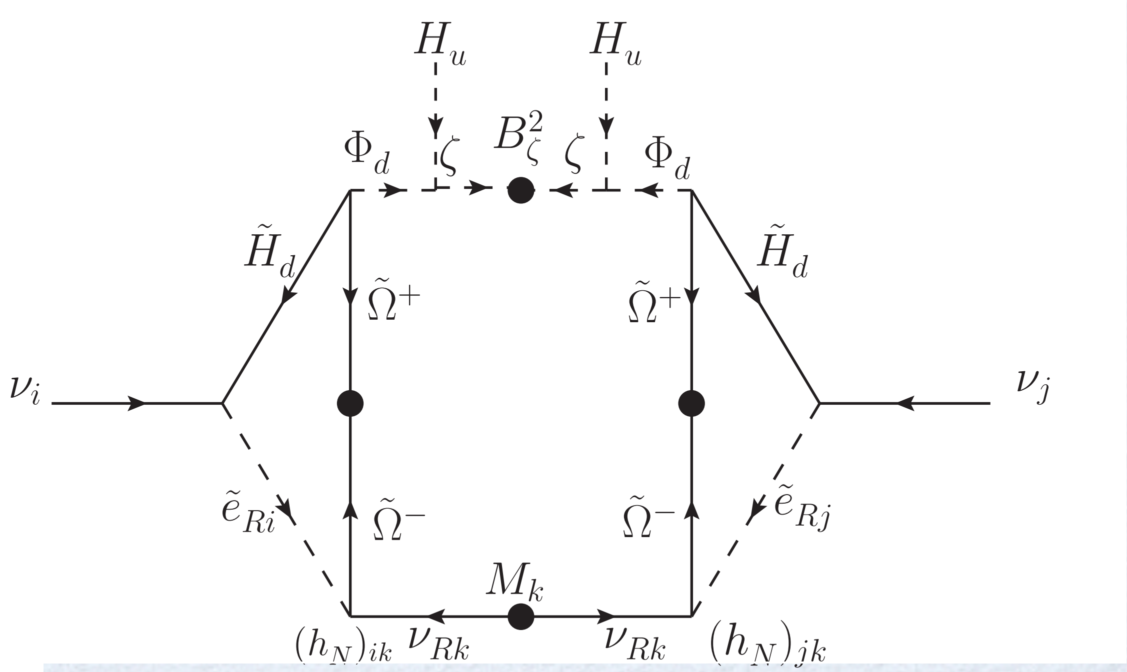


It corresponds to SUSY Ma model

3-loop

driven by h_N





They correspond to SUSY AKS model

Comment on SUSY AKS

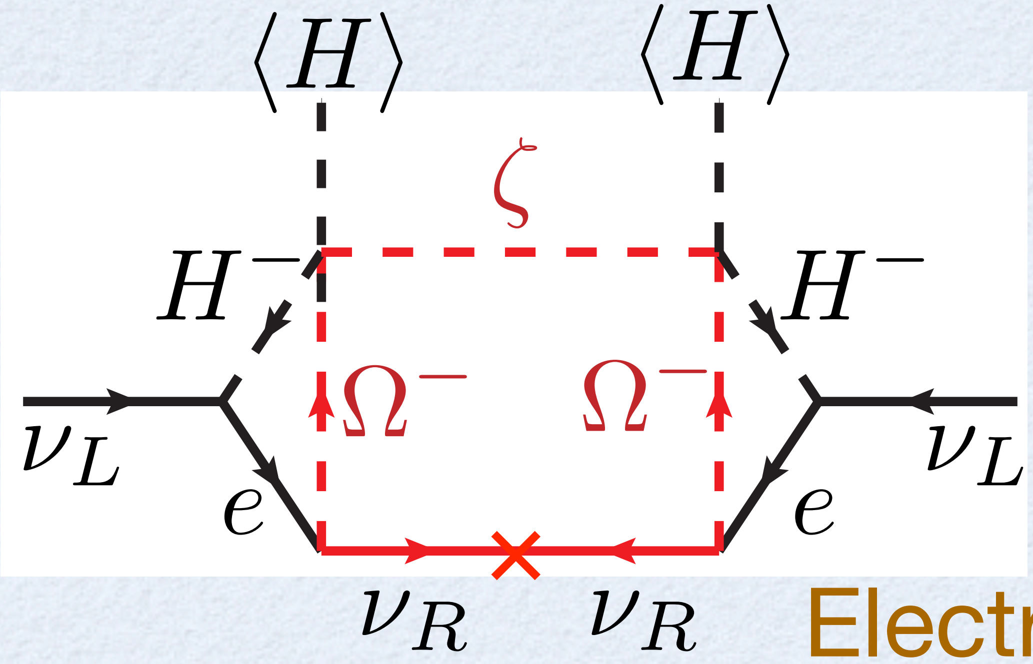
S.Kanemura, N. Machida, T.S, T.Yamada,arXiv:1309.3207

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!!

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

$\phi_c/T_c>1$ is realized!

Serious LFV constraints are also satisfied

Comments on direct detection

Our model is characterized by the Z_2 odd sector

↓

Z_2-odd particle search is important

colorless → ILC

Case (A): light inert doublet

$$e^+e^- \to H'A' \to ZH'H'$$
$$e^+e^- \to H^{+\prime}H^{-\prime} \to W^+W^-H'H'$$

@ILC

Mass determination can be done with a few GeV accuracy

M. Aoki, S. Kanemura and H. Yokoya, PLB725,302.

Case (B): Singlet-like charged particle Ω^+

$$e^+e^- \to \Omega_1^+\Omega_1^-$$

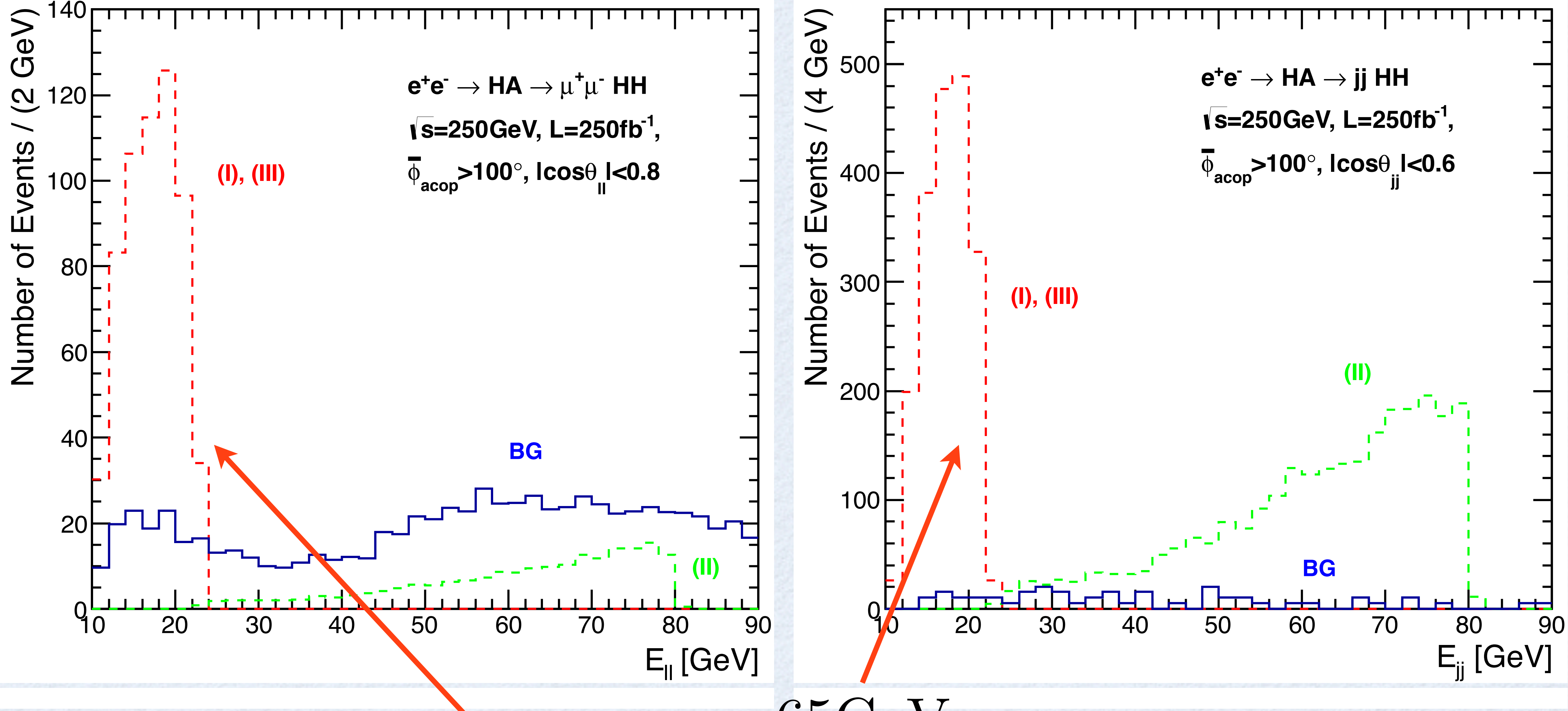
$e^-e^- \to \Omega_1^-\Omega_1^-$ ← Strong evidence of the model

Aoki&Kanemura&Seto, PRD80,033007; Aoki&Kanemura, PLB689,28.

Light inert doublet @ ILC

M. Aoki, S. Kanemura and H. Yokoya, PLB725,302.

$$e^+e^- \to H'A' \to ZH'H'$$



$$m_{H'} = 65\mathrm{GeV}$$

$$m_{A'} = 73\mathrm{GeV}$$

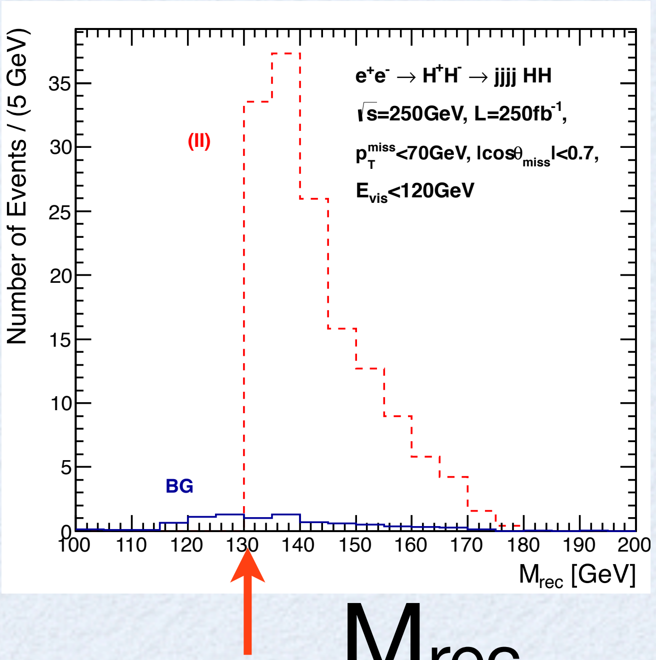
(Similar to Case (A))

$$m_{H^{\pm\prime}} = 120\mathrm{GeV}$$

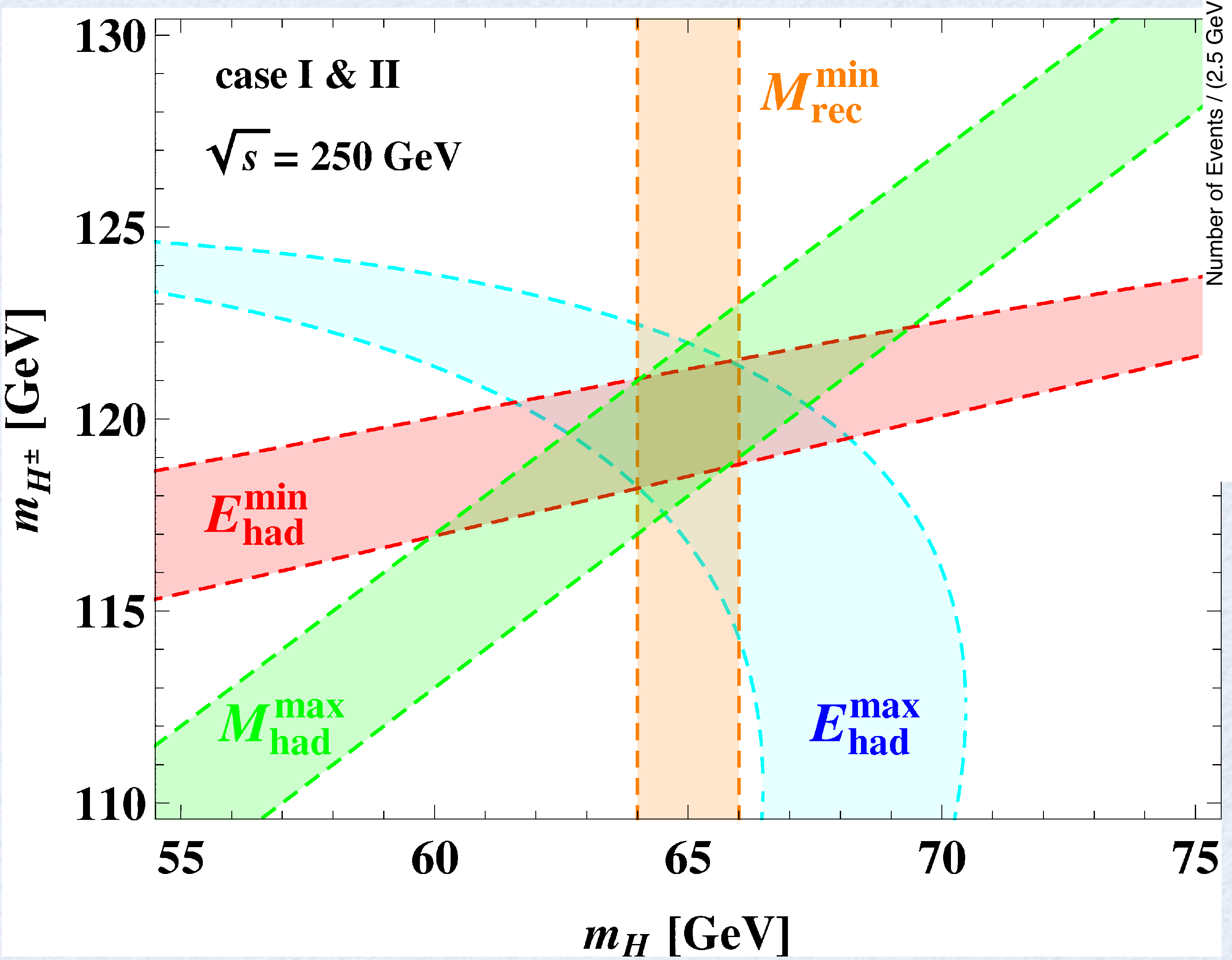
Light inert doublet @ ILC

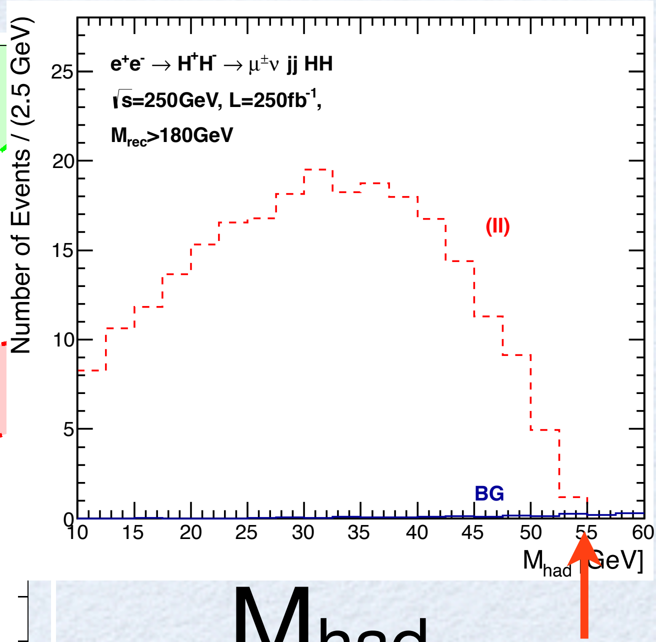
M. Aoki, S. Kanemura and H. Yokoya, PLB725,302.

$$e^+e^- \to H^{+\prime}H^{-\prime} \to W^+W^-H'H'$$

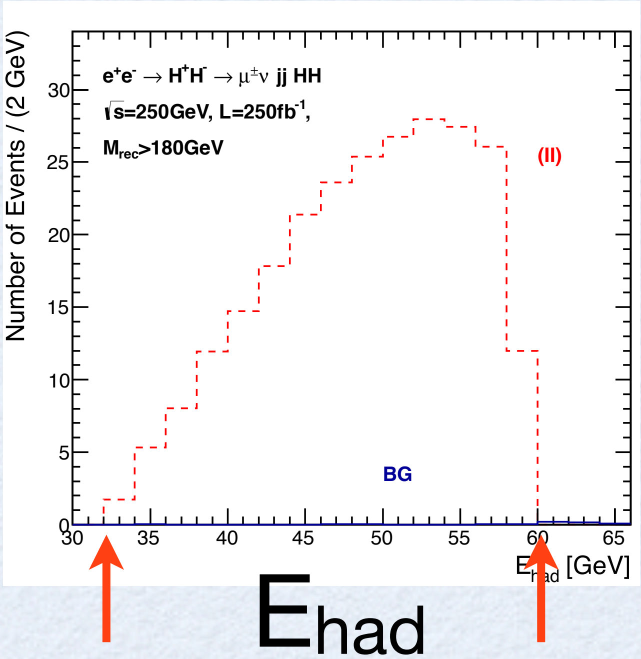


M_{rec}





M_{had}



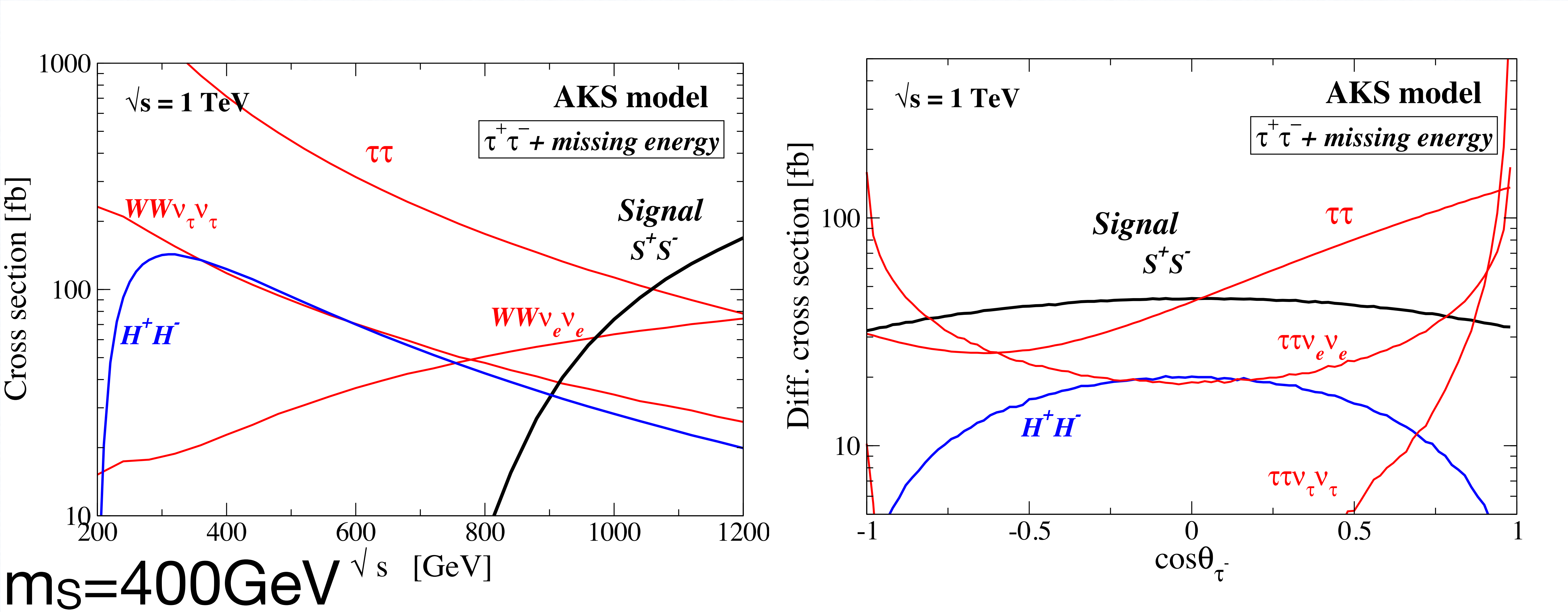
E_{had}

The masses can be precisely determined

Singlet-like scalar @ ILC

Aoki&Kanemura, PLB689,28.

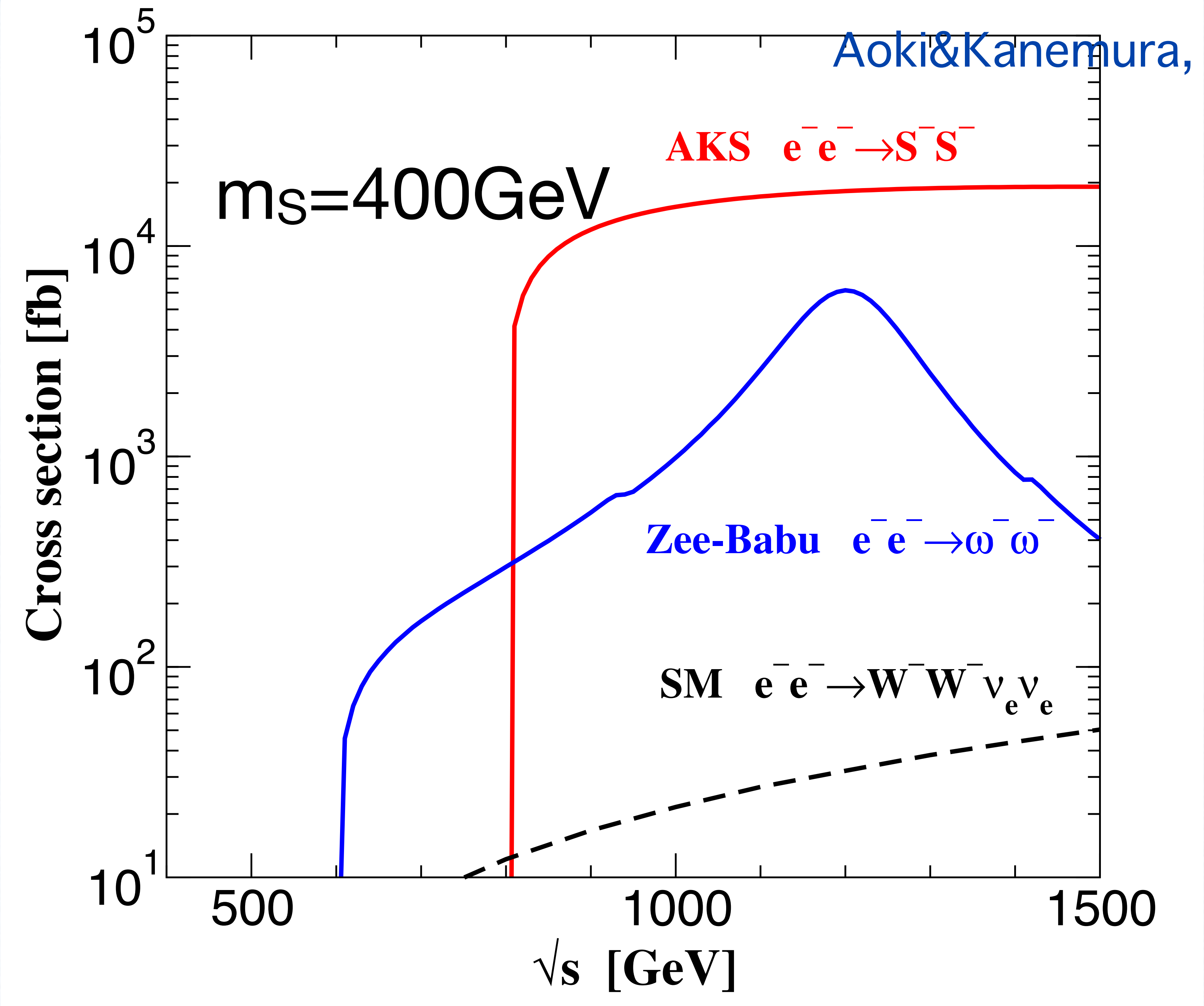
$$e^+e^- \to S^+S^- \to \tau^+\tau^- + \text{missing}$$



m_S=400GeV

A signal can be seen at the ILC@1TeV

Singlet-like scalar @ILC-e^-e^-



Aoki&Kanemura, PLB689,28.

The signal is quite clear evidence of the Majorana nature and the scenario

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

  $\downarrow$ 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

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

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

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

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

conformal enhancement

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

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

Below Λ$_H$

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

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

for M$_f$~Λ$_H$

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;

$$m_{\tilde{t}_1}^2(\varphi, \beta) = \underset{\underset{0}{\wr}}{M_{T_R}^2} + \frac{y_t^2 s_\beta^2}{2}\left(1 - \frac{|A_t + \mu\cot\beta|^2}{M_{\tilde{q}^2}}\right)\varphi^2$$

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 $m_{\Phi'}^2 = M^2 + \lambda^2 v^2$

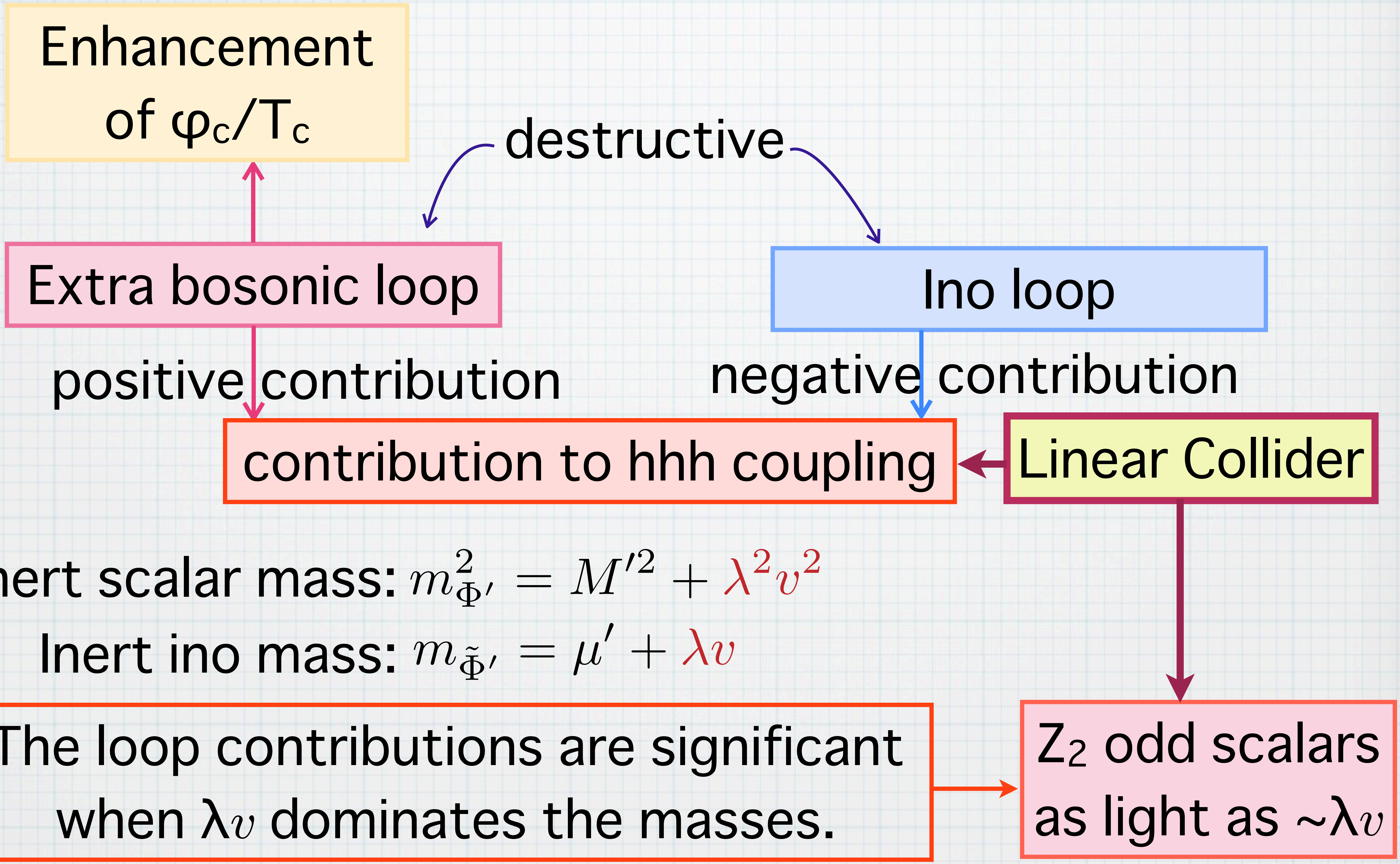
A natural realization of “strong but light” in SUSY model:

MSSM Higgs Z2 odd new fields

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

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: $m_{\Phi'}^2 = M'^2 + \lambda^2 v^2$

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