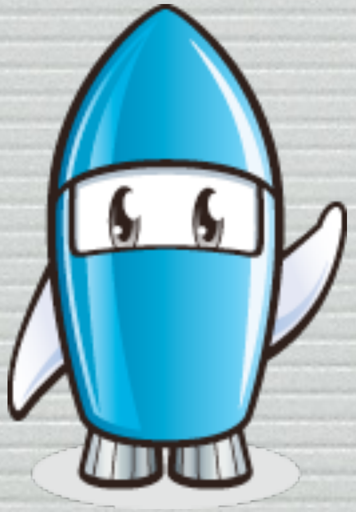
UV complete model for radiative seesaw scenario electroweak baryogenesis

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,



13/2/2014 BURI2014 @ Univ. of Toyama

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

the problems in the SM:

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

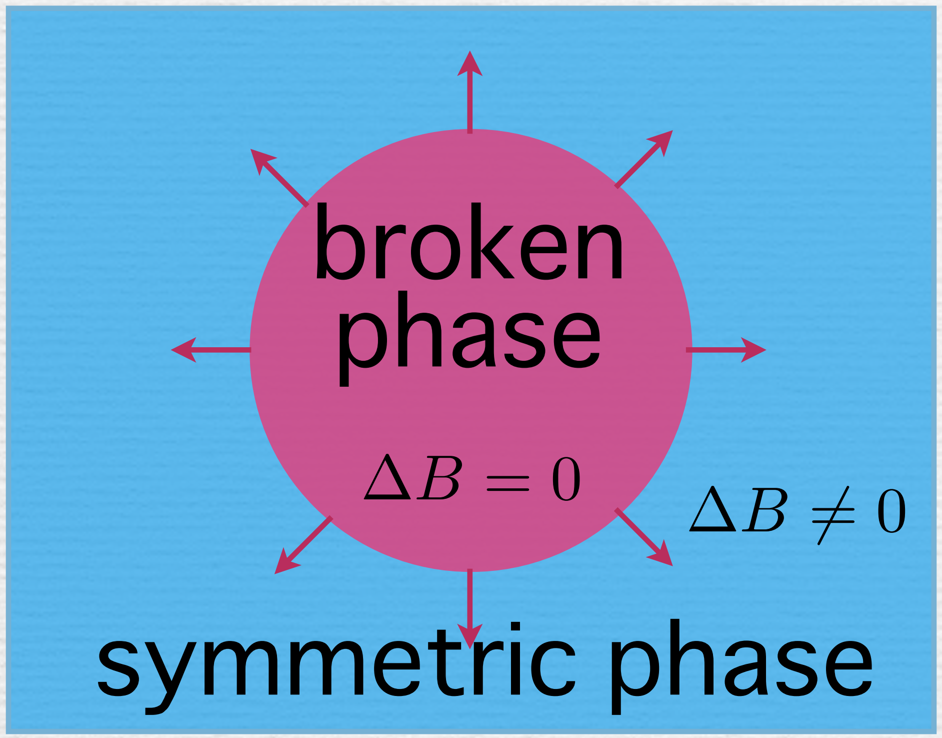
Solutions at TeV scale

There are examples of NP

- Baryon asymmetry of the Universe
  - Electroweak Baryogenesis
- Origin of the neutrino mass
  - Loop induced neutrino mass scenarios
- DM candidate
  - WIMP protected by some symmetry (e.g. Z

Electroweak Baryogenesis

Electroweak Baryogenesis ⟷ essence of EWSB

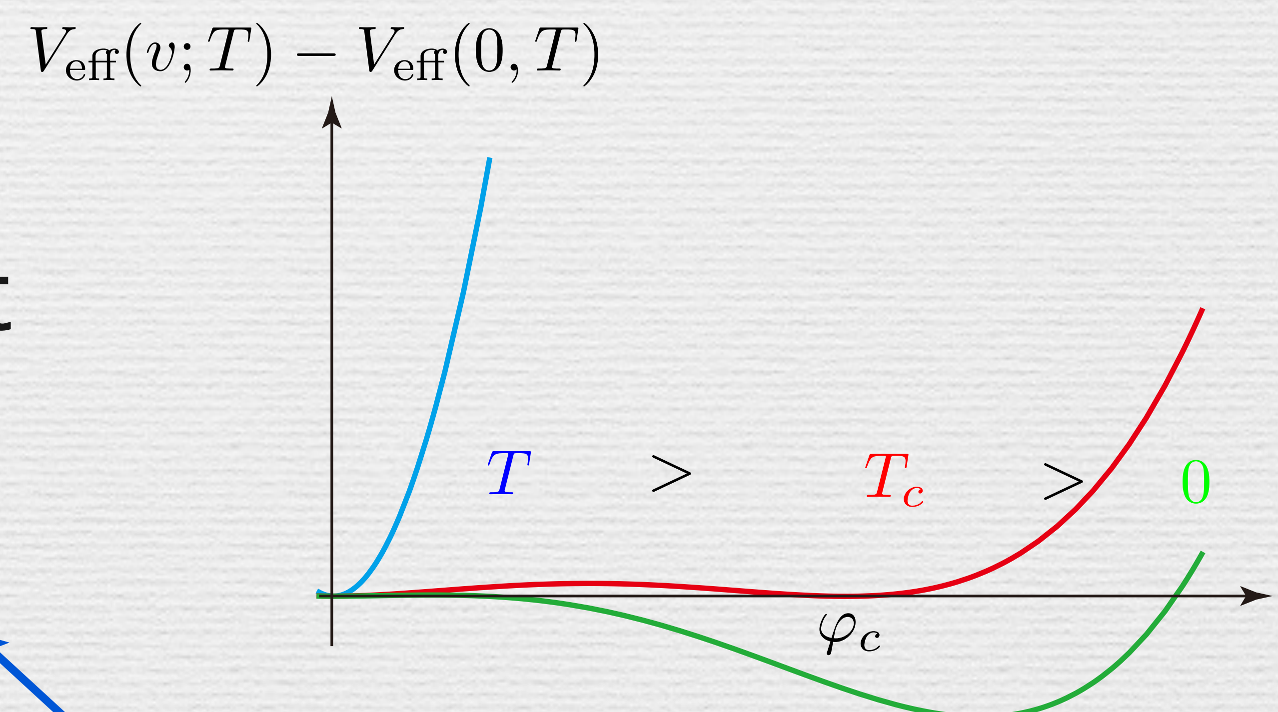


1st order electroweak transition

+

Sphaleron

To avoid too strong washout



The strong enough first order electroweak phase transition is necessary

ϕ

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

(ϕ

conflict with LHC data

Extra boson loop can enhance ϕ

↓

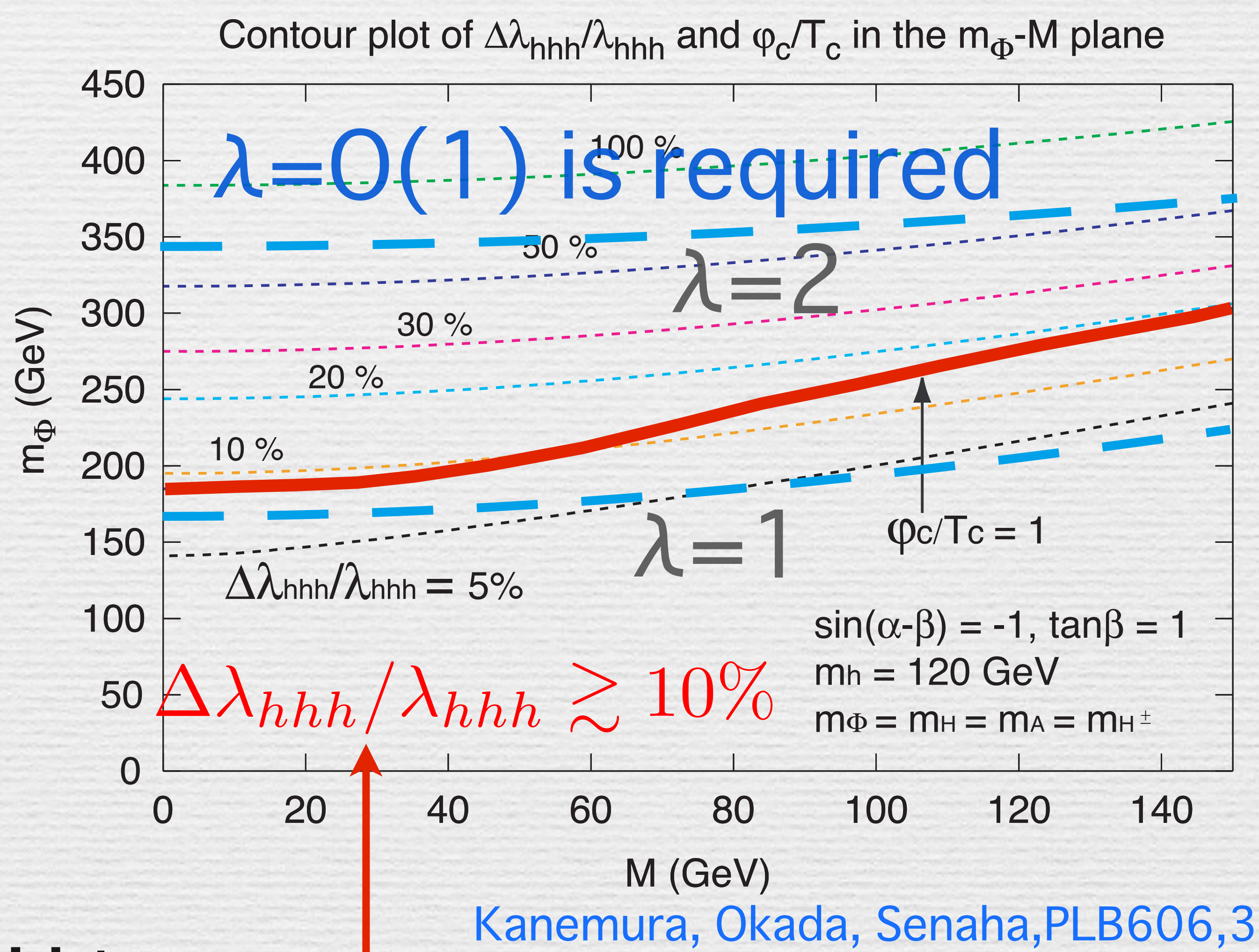
Extended Higgs sector!

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±



Kanemura, Okada, Senaha,PLB606,361

Testable@Collider exp.

EWPT i

In the MSSM, there is no such a large enough

with SM-like Higgs

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

A

scenario is SUSY 4HD+charged singlets

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

ϕ

m

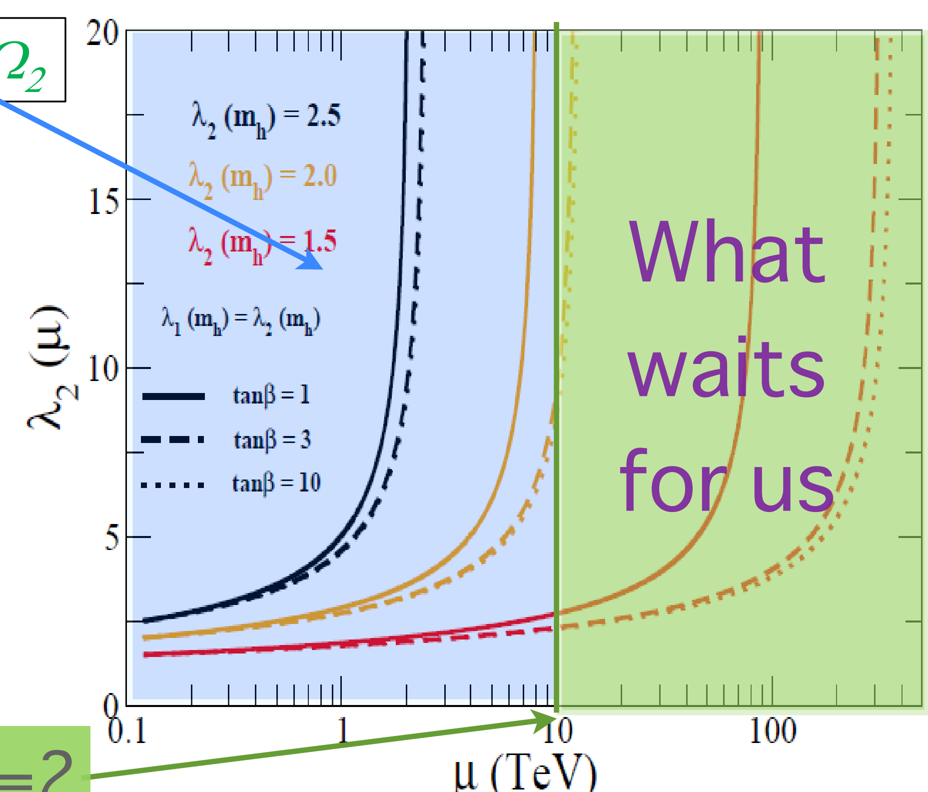
↓

$\lambda > 1.6$

EW baryogenesis can be realized in a SUSY model @TeV

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

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

How about neutrino mass?

Origin of the neutrino mass ___________

Alternative to the well-known seesaw model:

Idea of loop induced neutrino mass

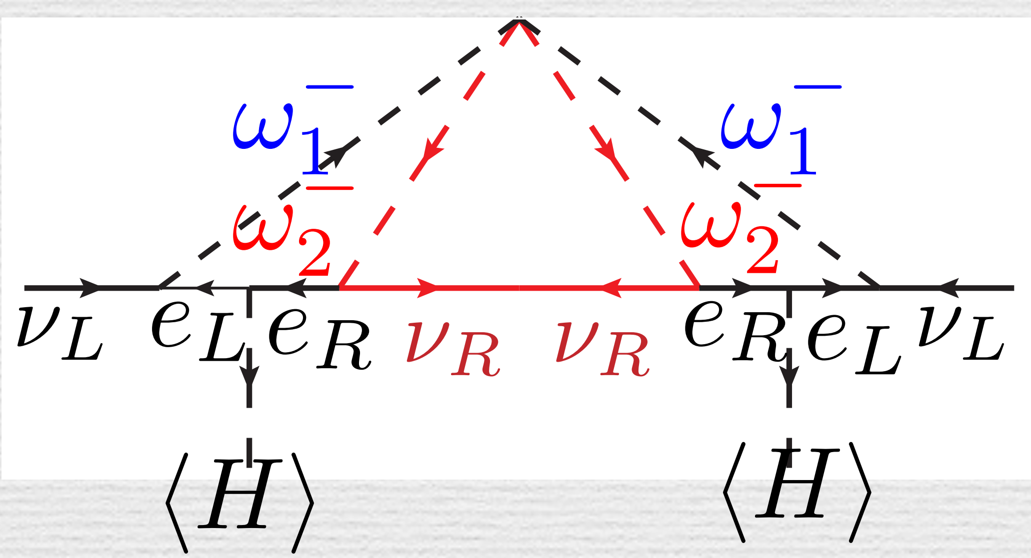
Especially,

Loop diagram with RH neutrinos give tiny neutrino mass

(Z ← To avoid tree level contribution

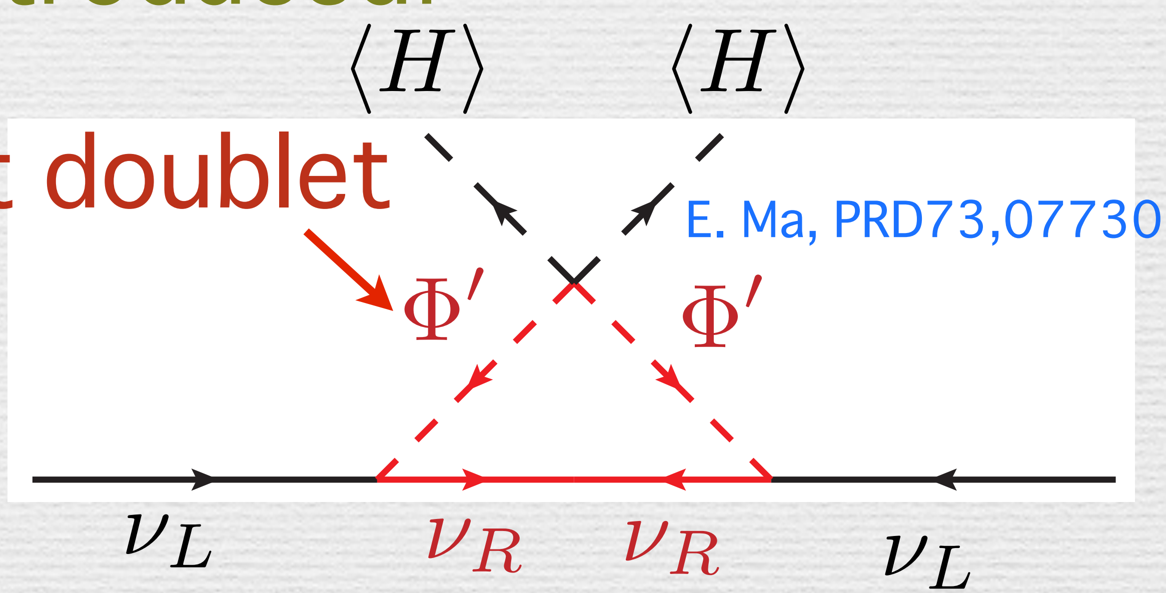
Some new scalars are introduced!

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



Lightest Z

inert doublet

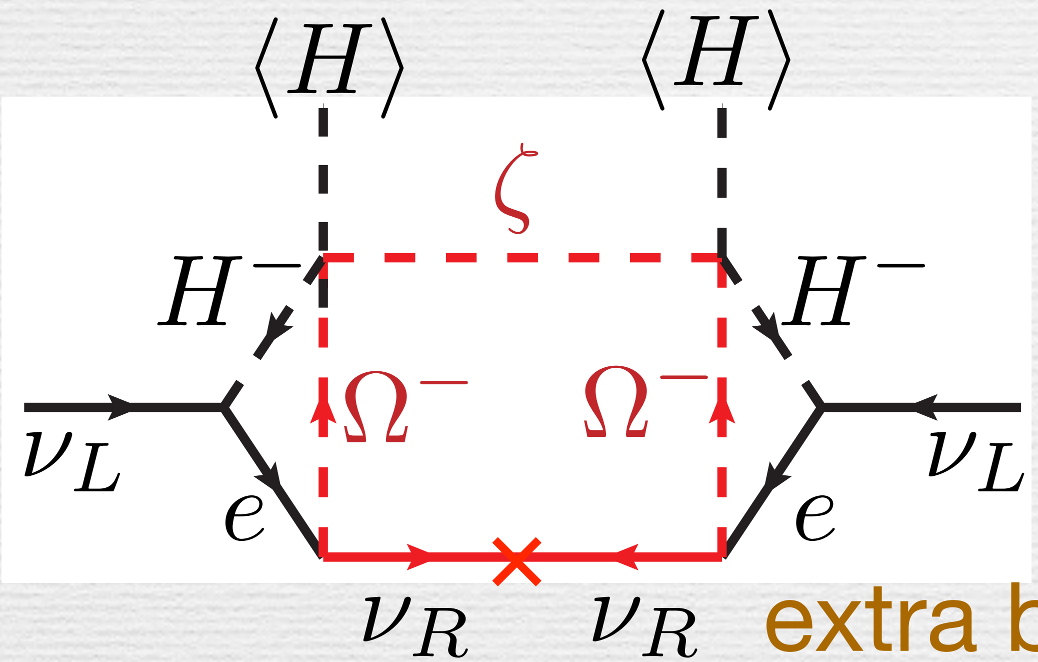


AKS model

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

Three problems are solved at TeV scale

→ neutrino mass

extra boson loop → strong 1st order EWPT

As a phenomenological model, this is quite interesting

But ...

Many extra scalars ⟶ It seems artificial

Large couplings ⟶ Landau pole at low energy scale

What is the fundamental theory of this model?

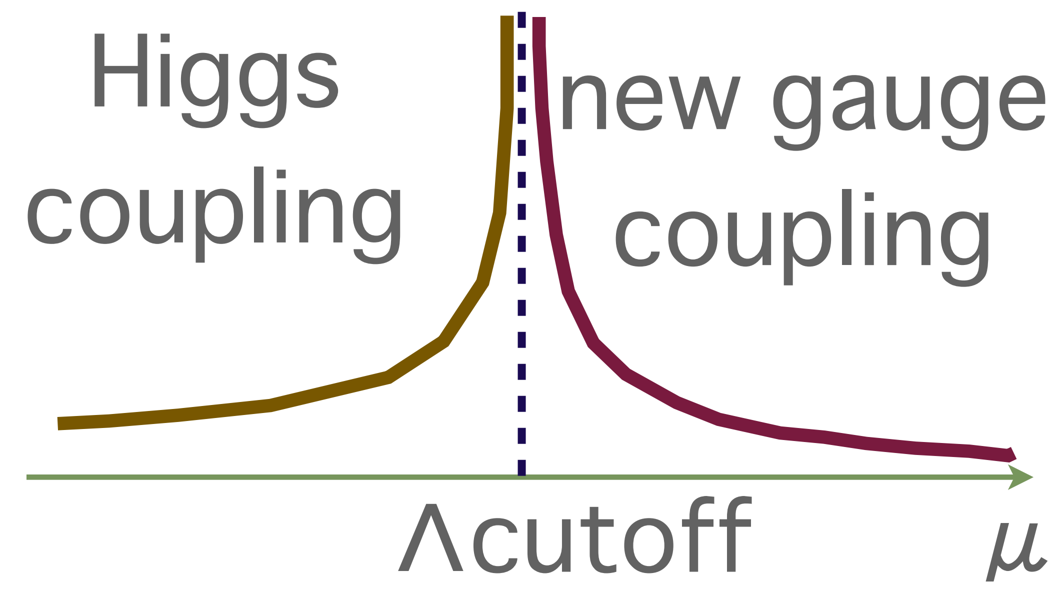
Fundamental theory?

- What is the fundamental theory of such a
    - Large coupling constant → Landau pole (cutoff)
    - What is the origin of strong Higgs force?
    - Where extra (non-matter) scalar fields come from ?

Fundamental theory?

- What is the fundamental theory of such a
  - Large coupling constant → Landau pole (cutoff)
  - What is the origin of strong Higgs force?
  - Where extra (non-matter) scalar fields come from ?

Our expectation:

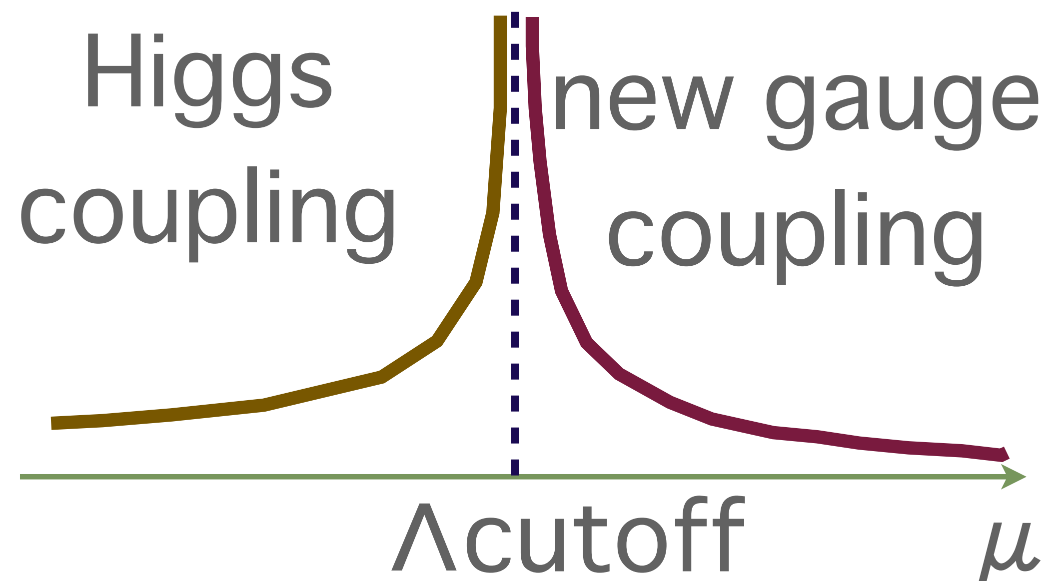


Fundamental theory?

- What is the fundamental theory of such a
  - Large coupling constant → Landau pole (cutoff)
  - What is the origin of strong Higgs force?
  - Where extra (non-matter) scalar fields come from ?

We have a nice candidate!
SUSY $SU(2)_H$ model

Our expectation:



SUSY SU(2)

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!

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 $H_{ij} \sim T_i T_j$

It's the same setup as the minimal SUSY fat Higgs, where only H_u, H_d, and N are made light
(The effective theory is "minimal") R Harnik, et al., PRD70, 015002

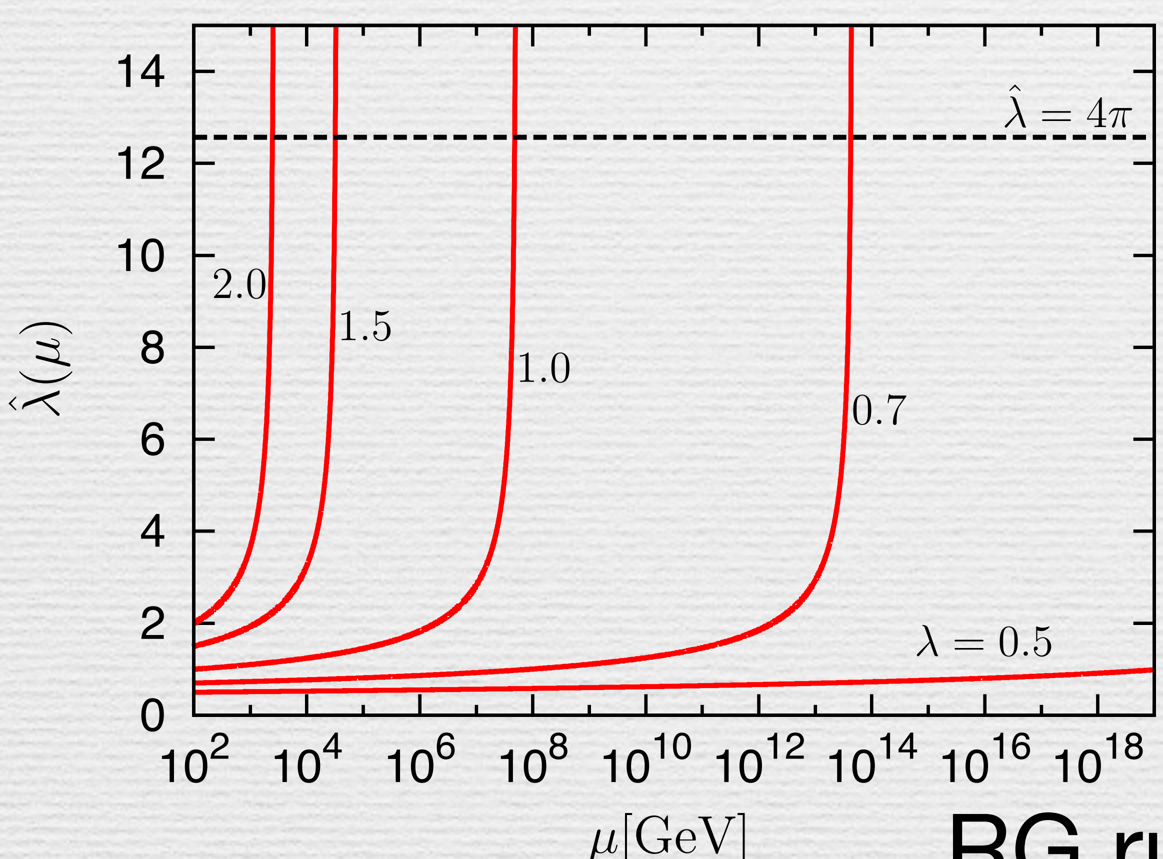
Effective theory of SU(2)H

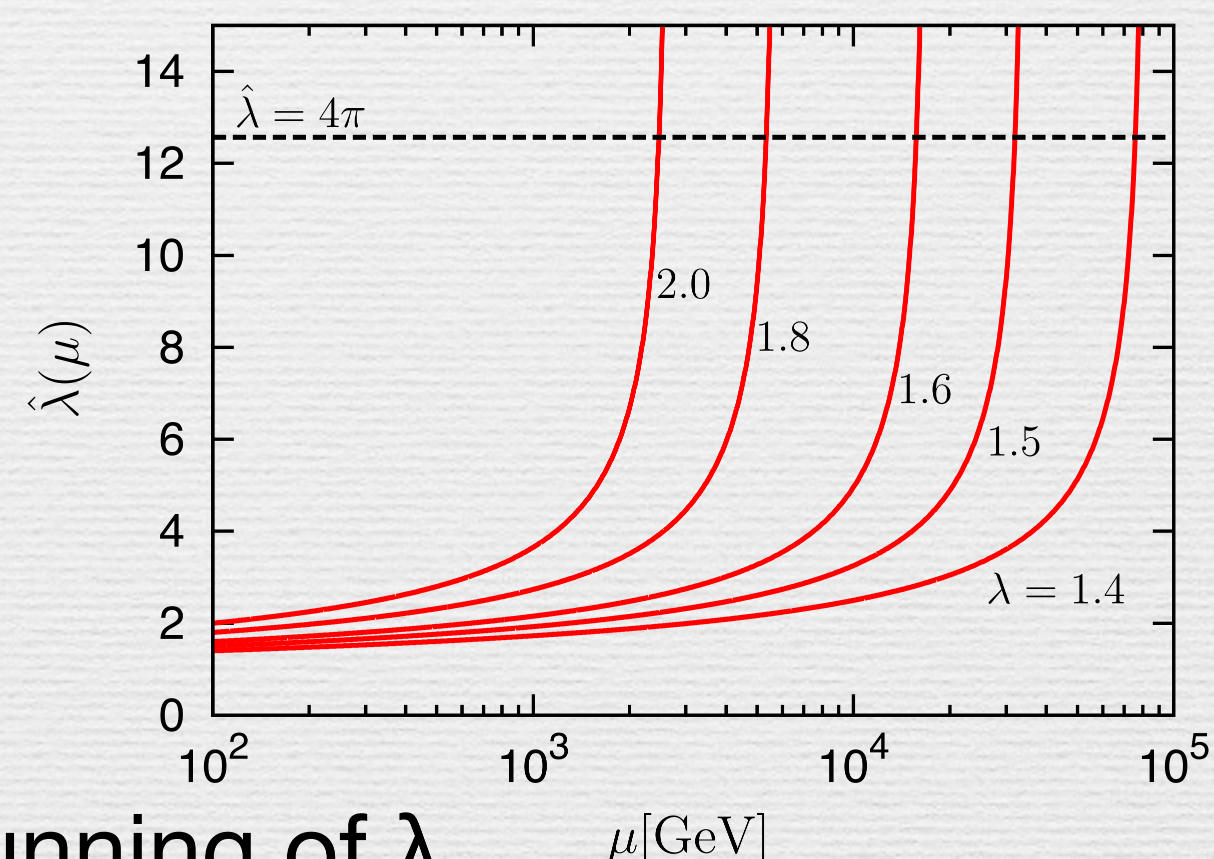
S.Kanemura, E. Senaha, T.S, T.Yamada, JHEP1305,066

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:

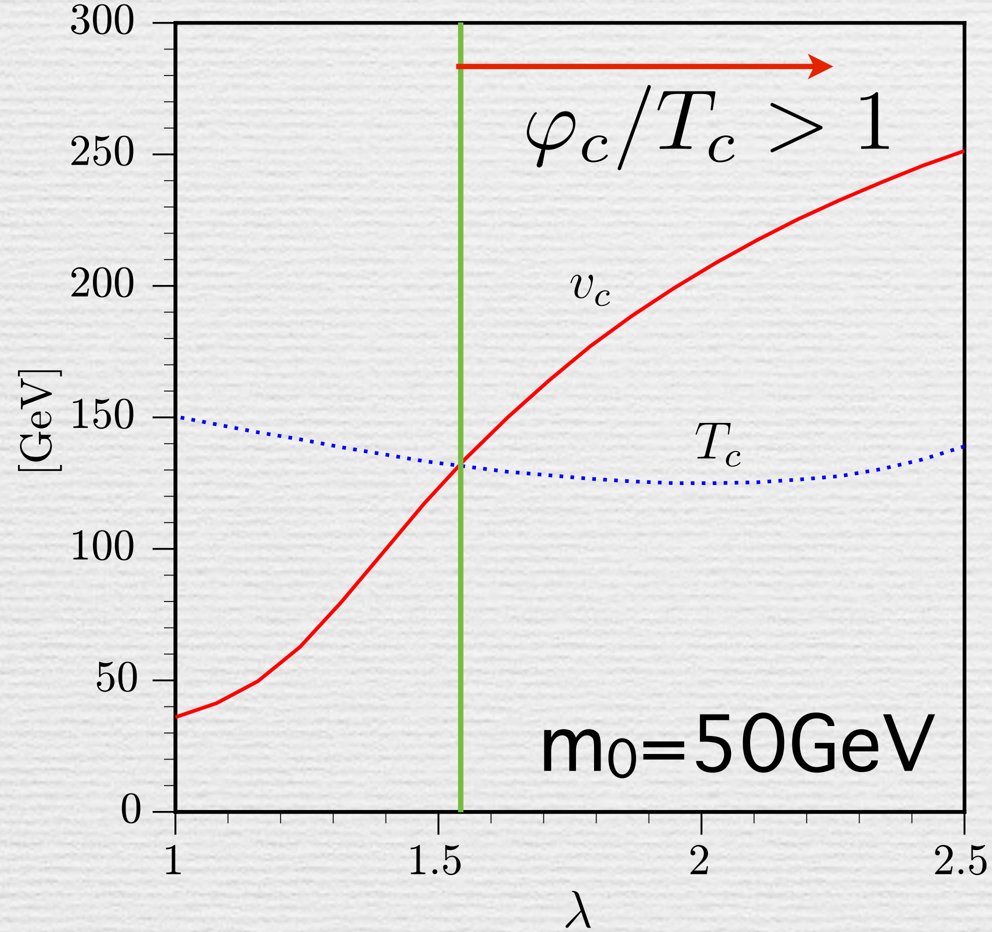
m_h=126GeV

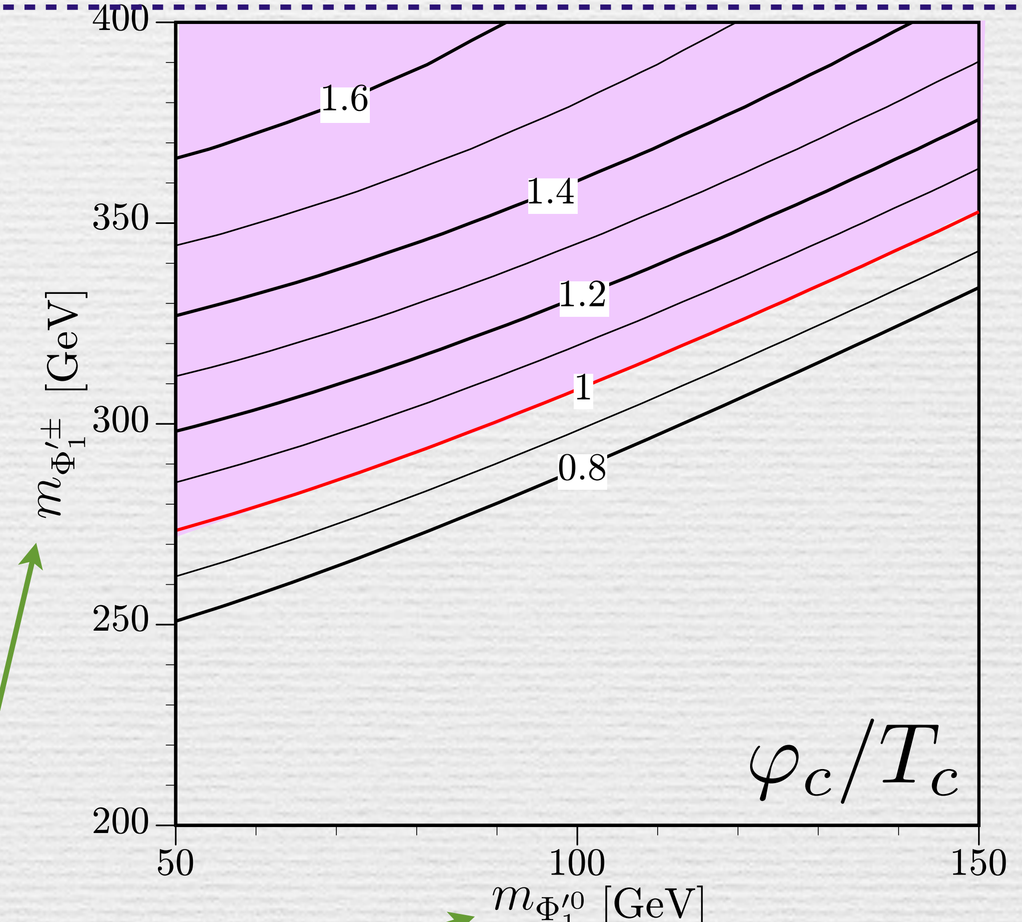
$$\tan\beta = 15, m_{H^+} = 350\text{GeV}, \mu = 200\text{GeV}, M_{\tilde{t}} = M_{\tilde{q}} = 2000\text{GeV}$$

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

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

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



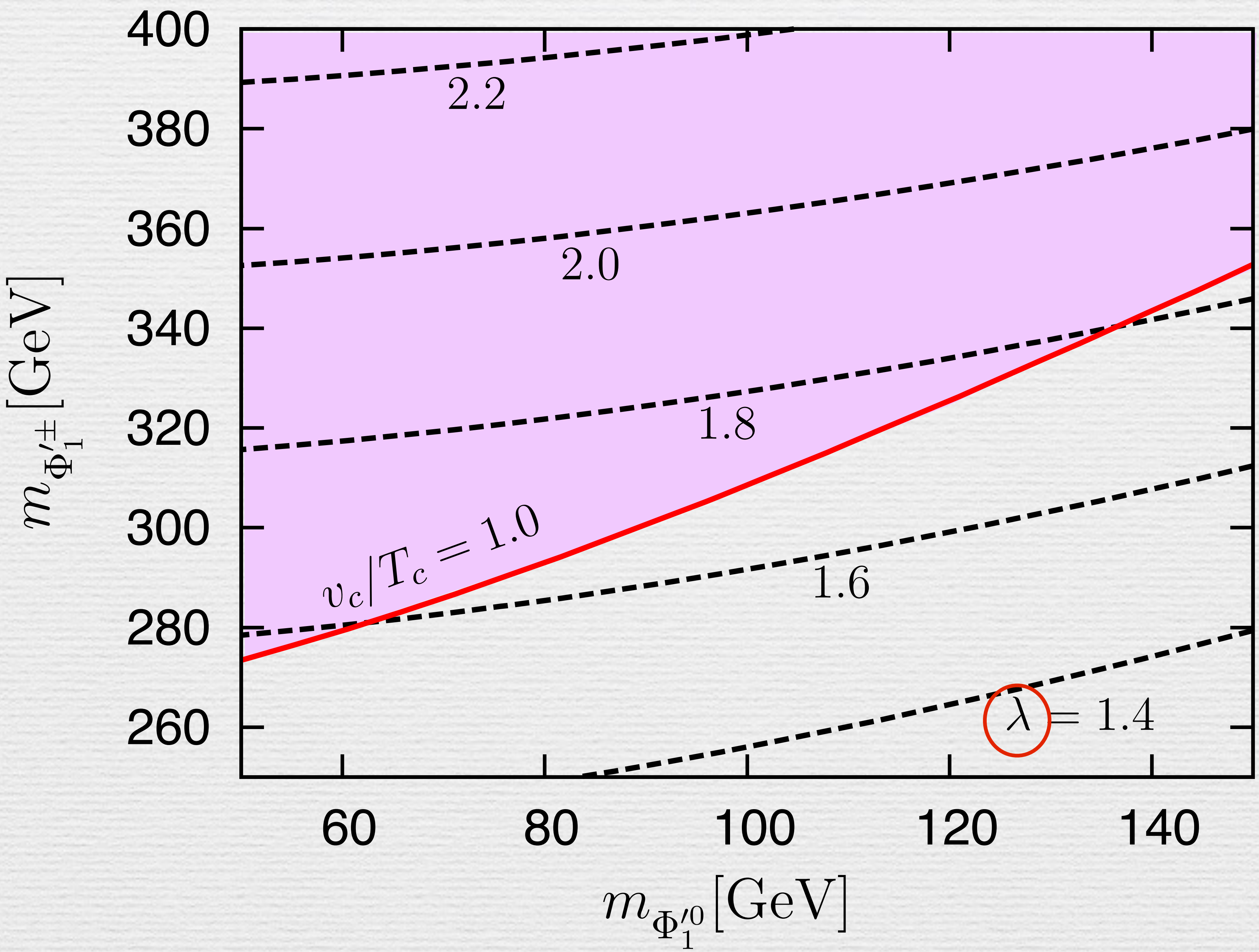


$\varphi_c/T_c > 1$ can be satisfied!!

Lightest Z_2 odd masses

1st order EWPT

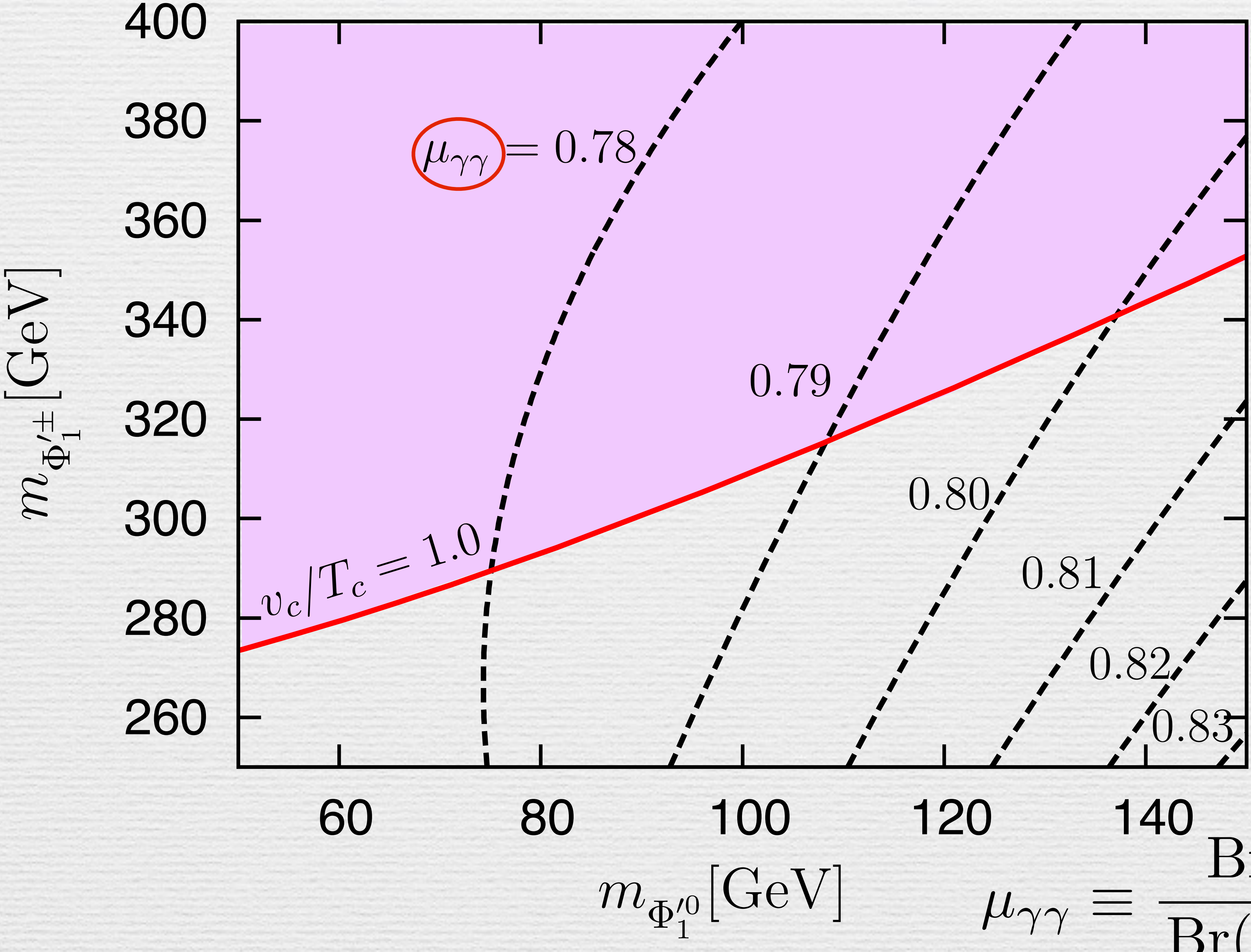
S.Kanemura,E. Senaha, T.S, T.Yamada,JHEP1305,066



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

Contribution to hγγ

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

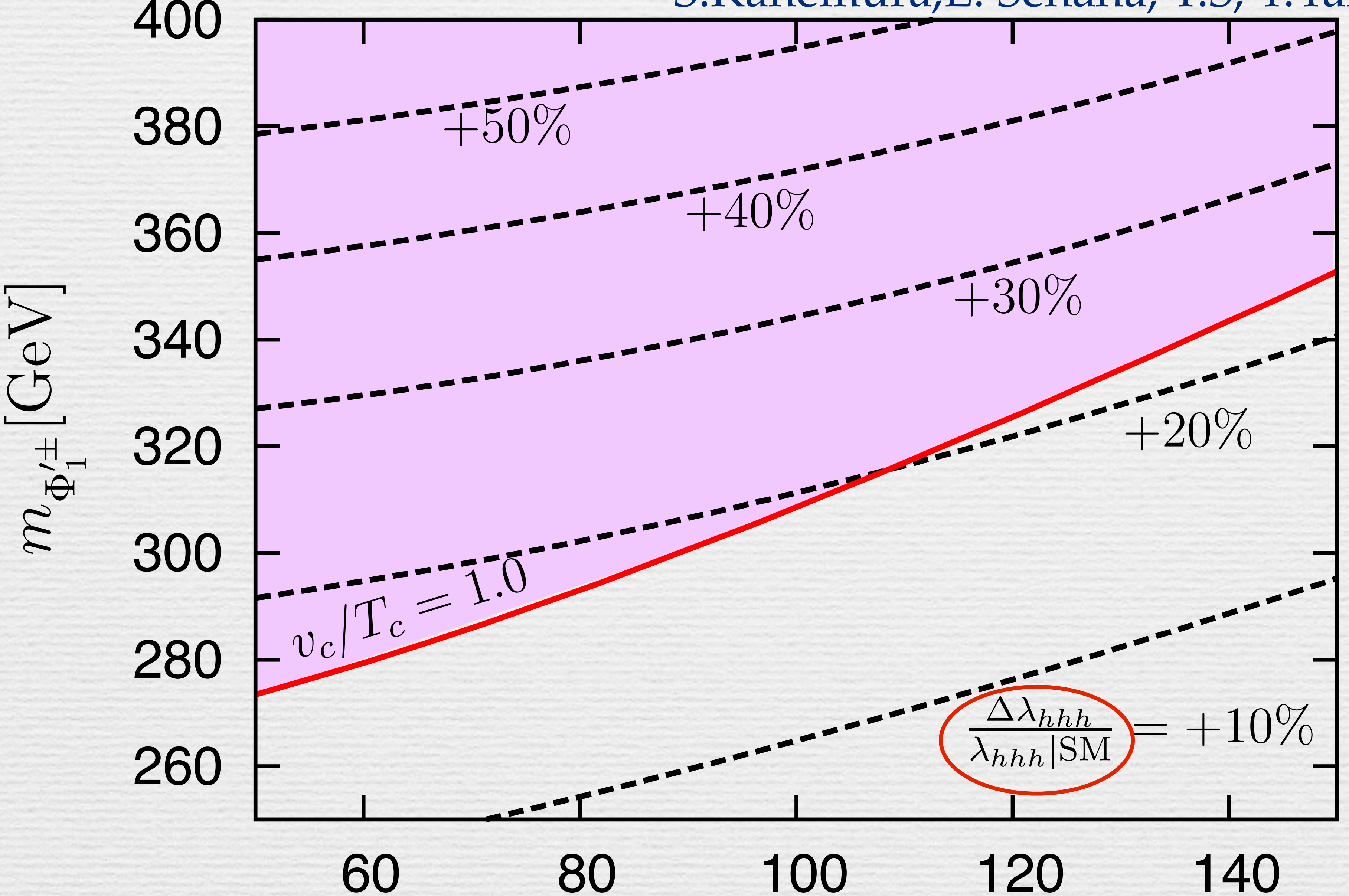


$$\mu_{\gamma\gamma} \equiv \frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to \gamma\gamma)|_{\mathrm{SM}}}$$

~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



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

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

For radiative seesaw

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

We will introduce a Z

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
neutrinos are
introduced as SU(2)
singlet fields

In the low energy effective theory,

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

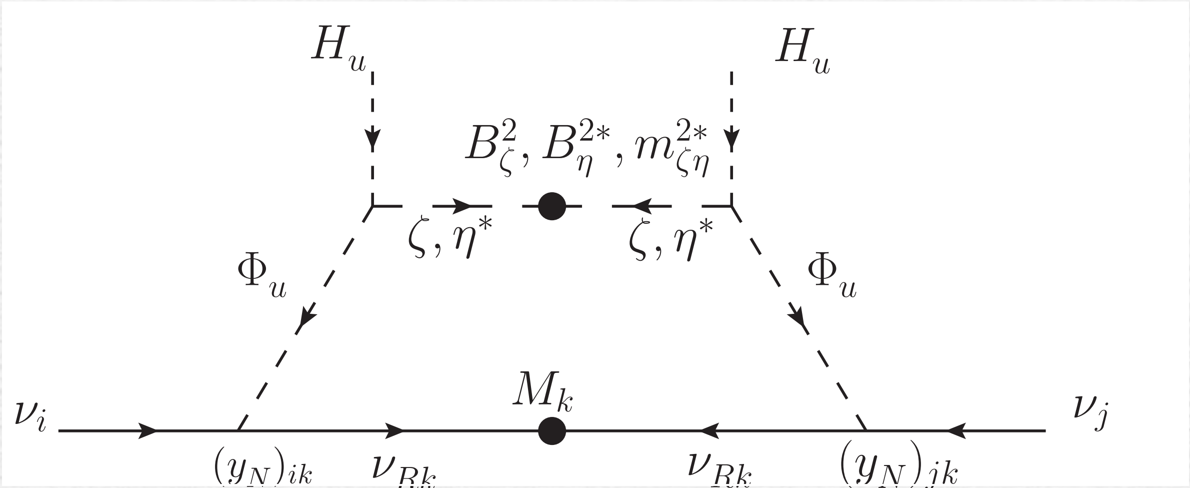
Neutrino mass generation

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

Two different types of contributions are possible

1-loop

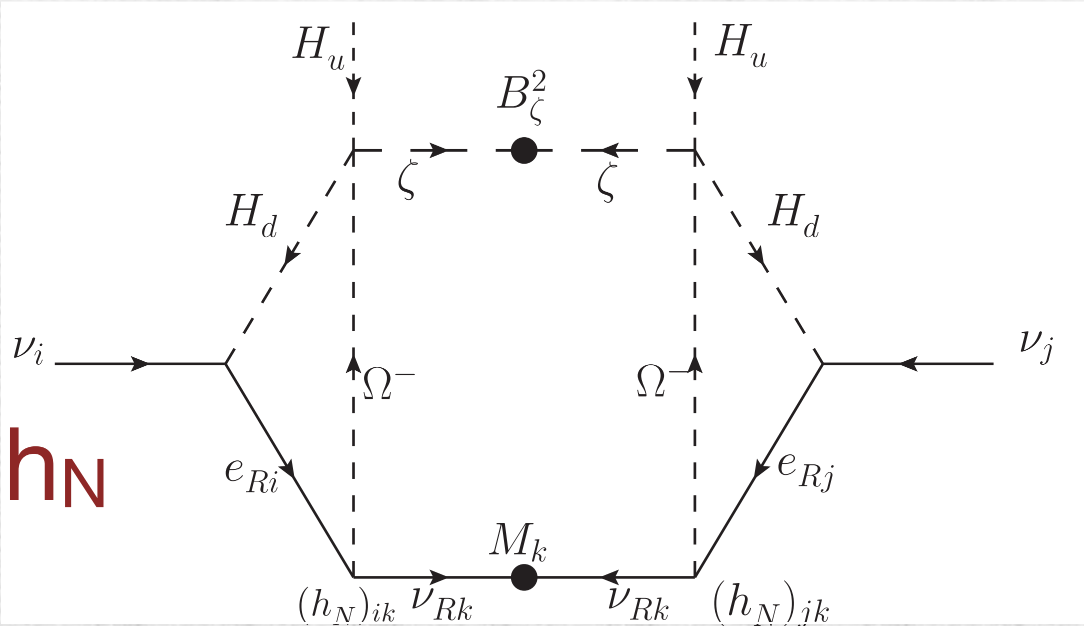
driven by y_N

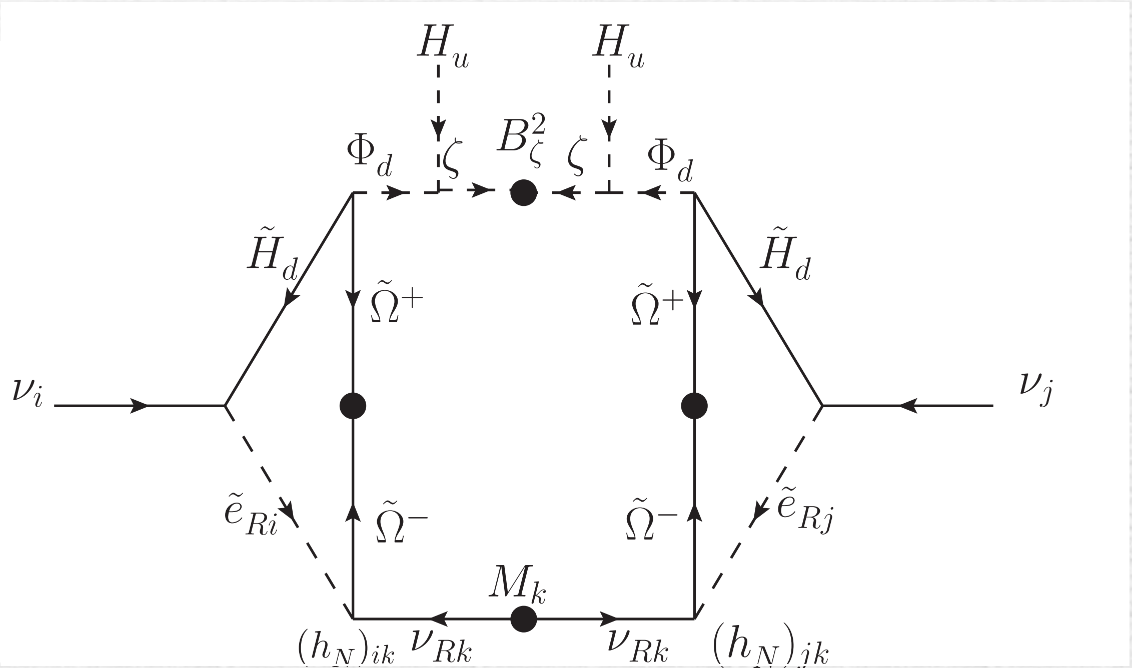


It corresponds to SUSY Ma model

3-loop

driven by h_N





They correspond to SUSY AKS model

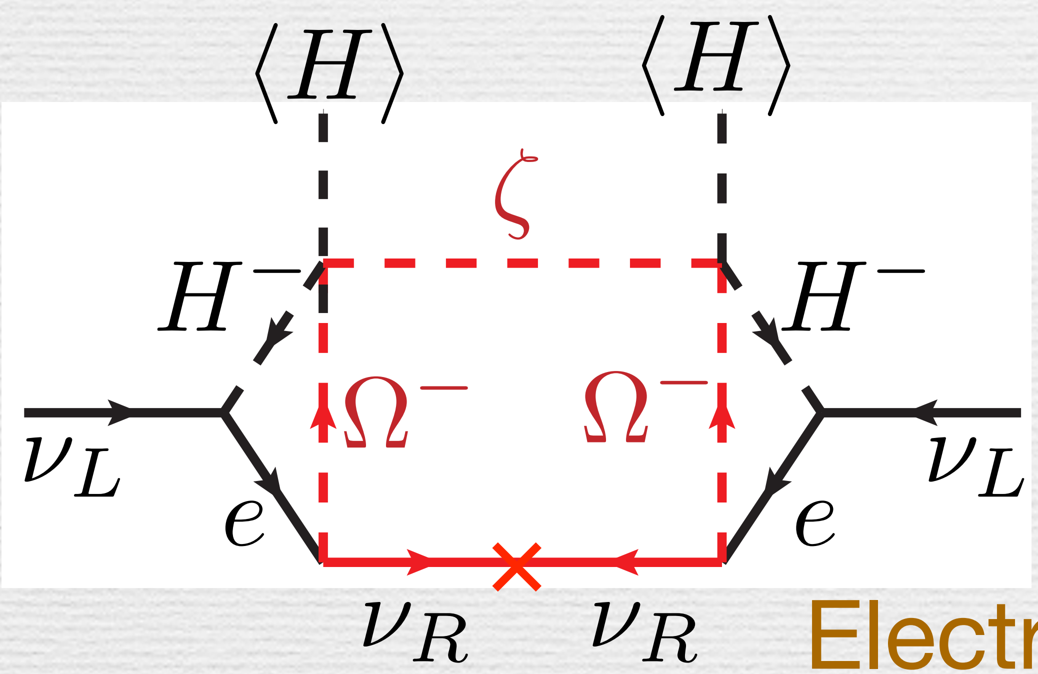
Fields in SUSY AKS

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

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

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)	$(100\ \mathrm{GeV})^2$	$(1500\ \mathrm{GeV})^2$	$(1500\ \mathrm{GeV})^2$	$(100\ \mathrm{GeV})^2$	$(1500\ \mathrm{GeV})^2$	$(2000\ \mathrm{GeV})^2$
(B)	$(1500\ \mathrm{GeV})^2$	$(1500\ \mathrm{GeV})^2$	$(1500\ \mathrm{GeV})^2$	$(30\ \mathrm{GeV})^2$	$(1410\ \mathrm{GeV})^2$	$(30\ \mathrm{GeV})^2$

Case	B^2_ζ	B^2_η	$m^2_{\zeta\eta}$
(A)	$(100\ \mathrm{GeV})^2$	$(100\ \mathrm{GeV})^2$	$(100\ \mathrm{GeV})^2$
(B)	$(1400\ \mathrm{GeV})^2$	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)	60 GeV	120 GeV	180 GeV	60 GeV	120 GeV	180 GeV	5000 GeV
(B)	100 GeV	2000 GeV	4000 GeV	100 GeV	3000 GeV	5000 GeV	5000 GeV

Case	$(y_N)_{ij}$	$(h_N)_{ij}$
(A)	$\begin{pmatrix} -0.439 & -0.424 & 0.512 \\ 0.226 & 0.218 & -0.263 \\ 0.272 & 1.36 & 1.36 \end{pmatrix} \times 10^{-4}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
(B)	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0.003 & 0 & 0 \\ -0.0164 - 1.26i & -0.02424 + 0.0049i & -0.0022 + 0.00097i \\ 0.491 - 1.581i & 0.02461 + 0.00537i & 0.0016 + 0.0019i \end{pmatrix}$

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

Case	m_1	m_2	m_3	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\lvert\sin\theta_{13}\rvert$
(A)	0.0 eV	0.0087 eV	0.050 eV	0.31	0.50	0.14
(B)	0.0 eV	0.0084 eV	0.050 eV	0.32	0.50	0.14

The neutrino

Case	Λ_H	φ_c/T_c	$\lambda_{hhh}/\ \lambda_{hhh}\rvert_{\mathrm{SM}}$	$\mathrm{B}(h \to \gamma\gamma)/\ \mathrm{B}(h \to \gamma\gamma)\rvert_{\mathrm{SM}}$
(A)	5 TeV	1.0	1.18	0.80
(B)	5 TeV	1.2	1.09	0.89

ϕ

Case	$\mathrm{B}(\mu \to e\gamma)$	$\mathrm{B}(\mu \to eee)$
(A)	5.2×10^{-19}	8.1×10^{-21}
(B)	5.0×10^{-13}	8.5×10^{-13}

LFV constraints:O.K.

We have not taken care of DM in these points yet

We are now making new BP which includes DM

Comments on direct detection

Our model is characterized by the Z_2 odd sector

↓

<u>Z_2-odd particle</u> 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^+

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

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

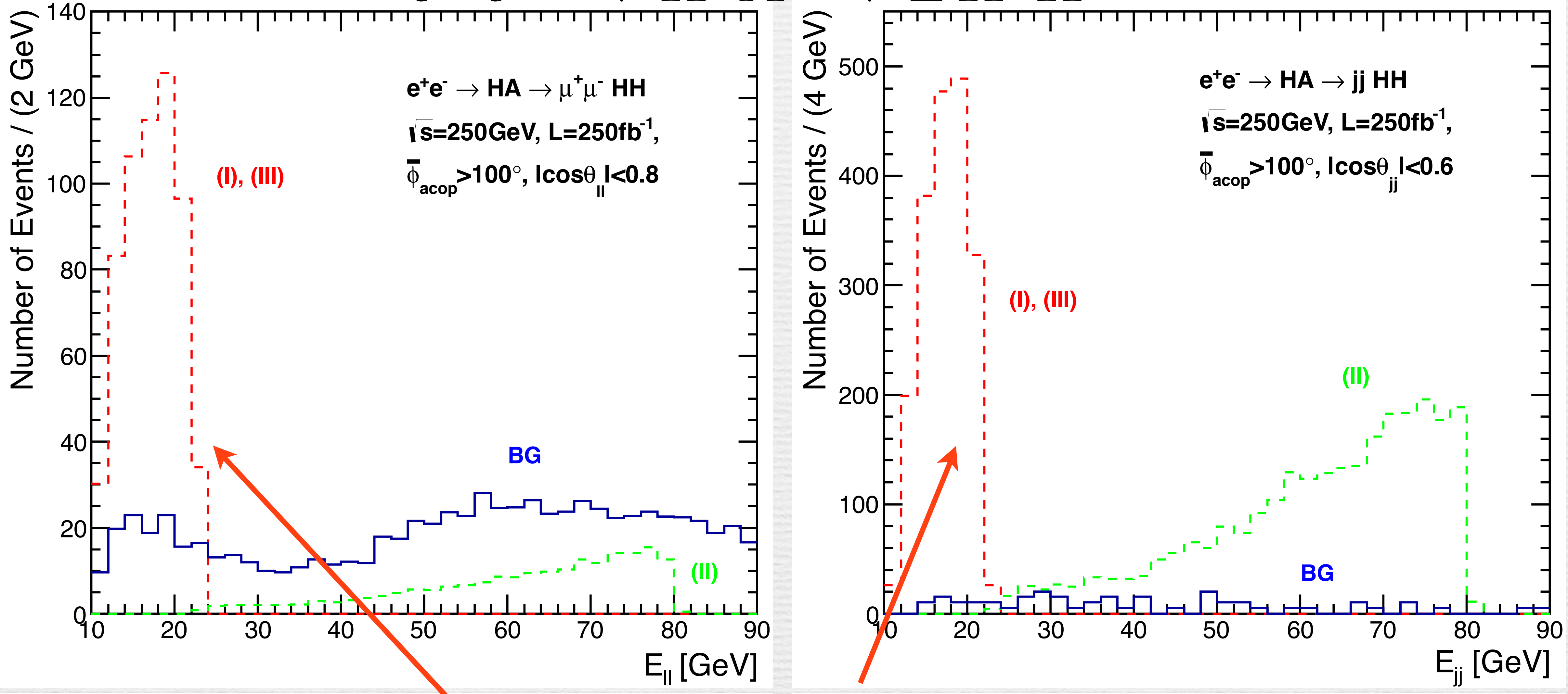
← Strong evidence of the model

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

Light inert doublet @ ILC

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

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



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

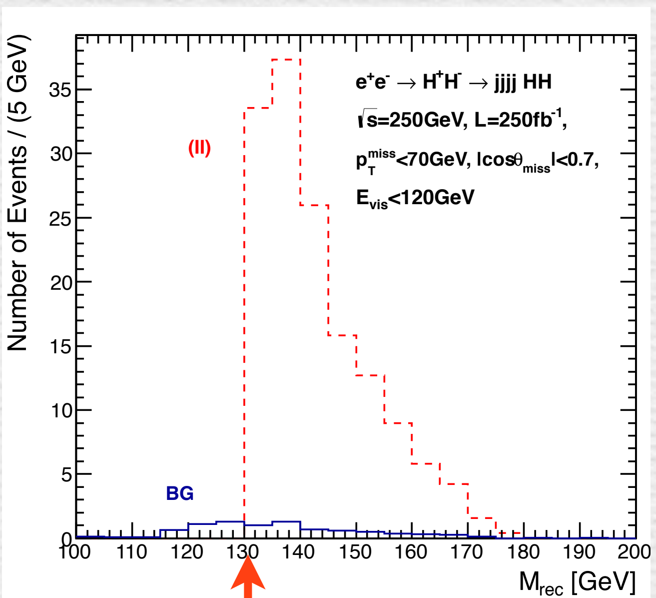
$m_{A'} = 73\text{GeV}$ (Similar to Case (A))

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

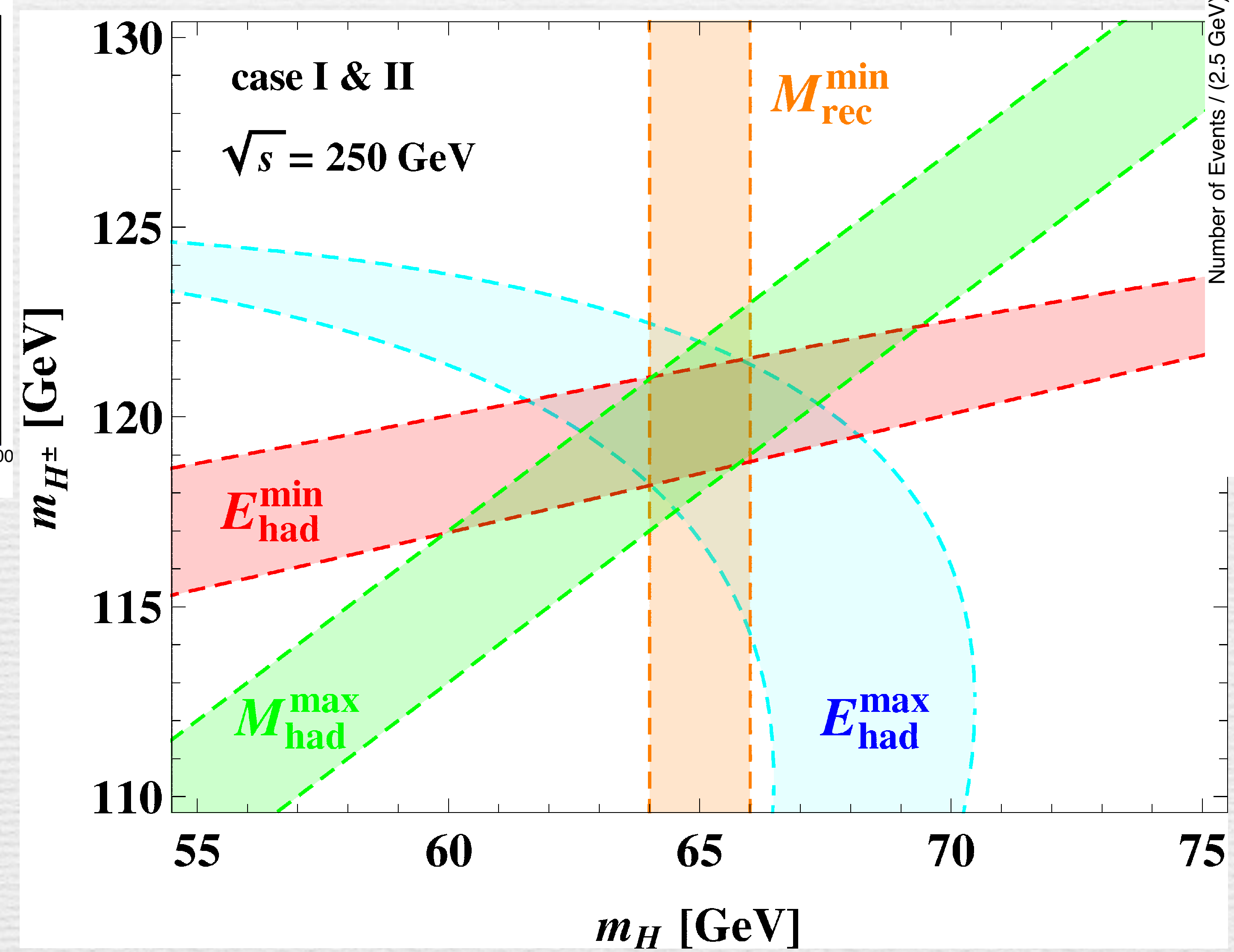
Light inert doublet @ ILC

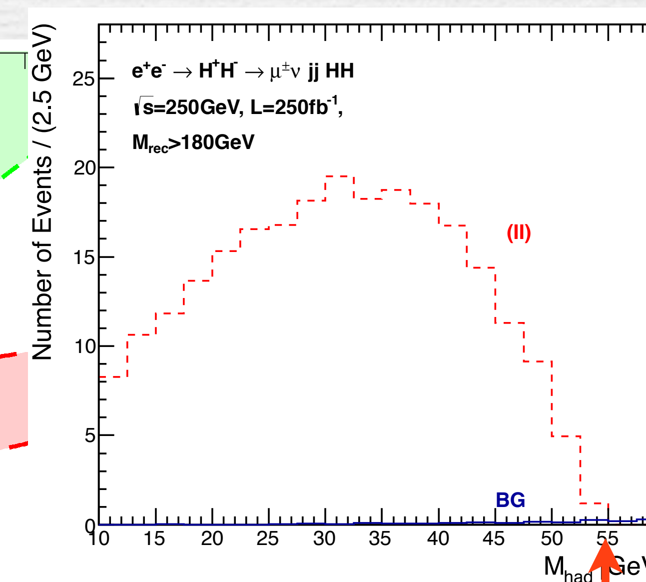
M. Aoki, S. Kanemura and H. Yokoya, PLB725,302.

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

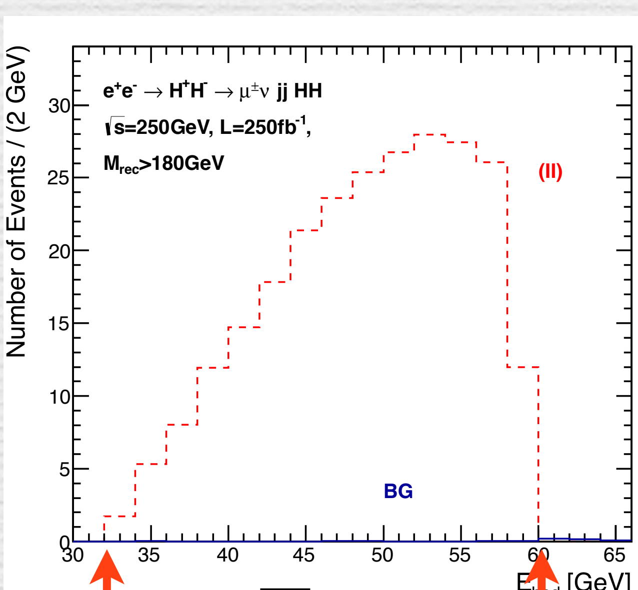


M_{rec}





M_{had}



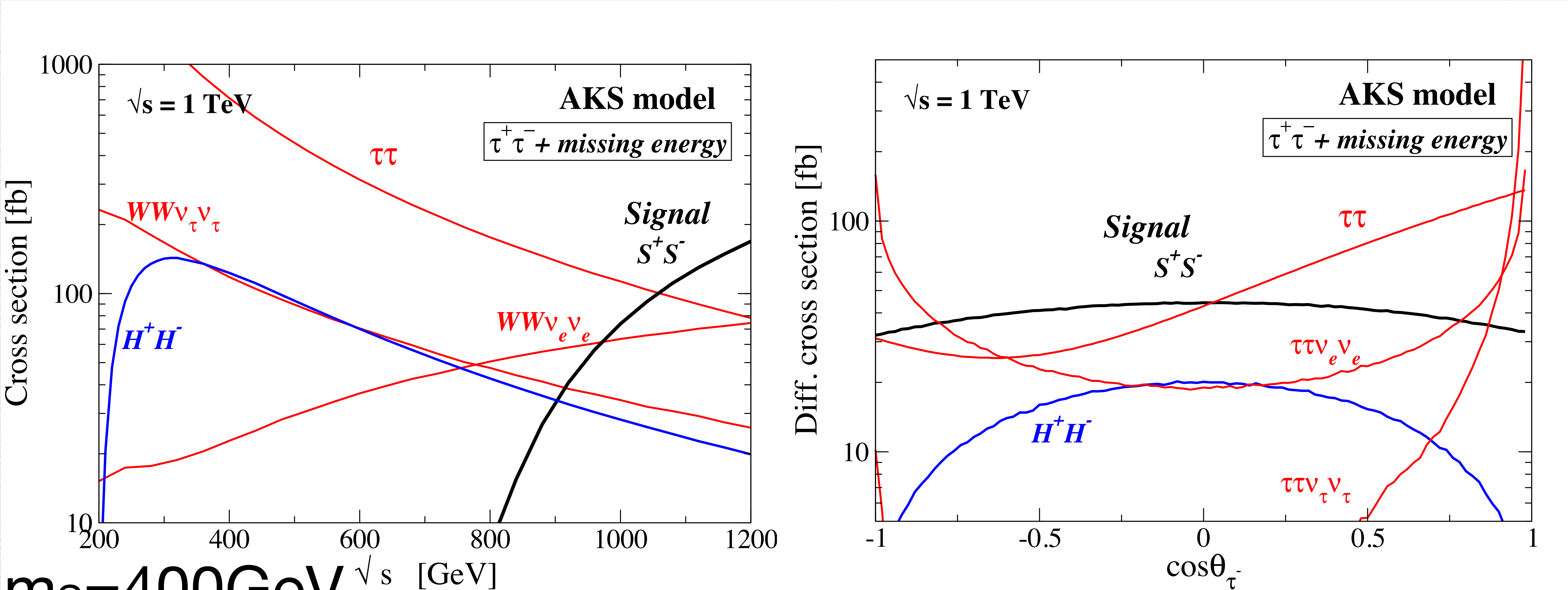
E_{had}

The masses can be precisely determined

Singlet-like scalar @ ILC

Aoki&Kanemura, PLB689,28.

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

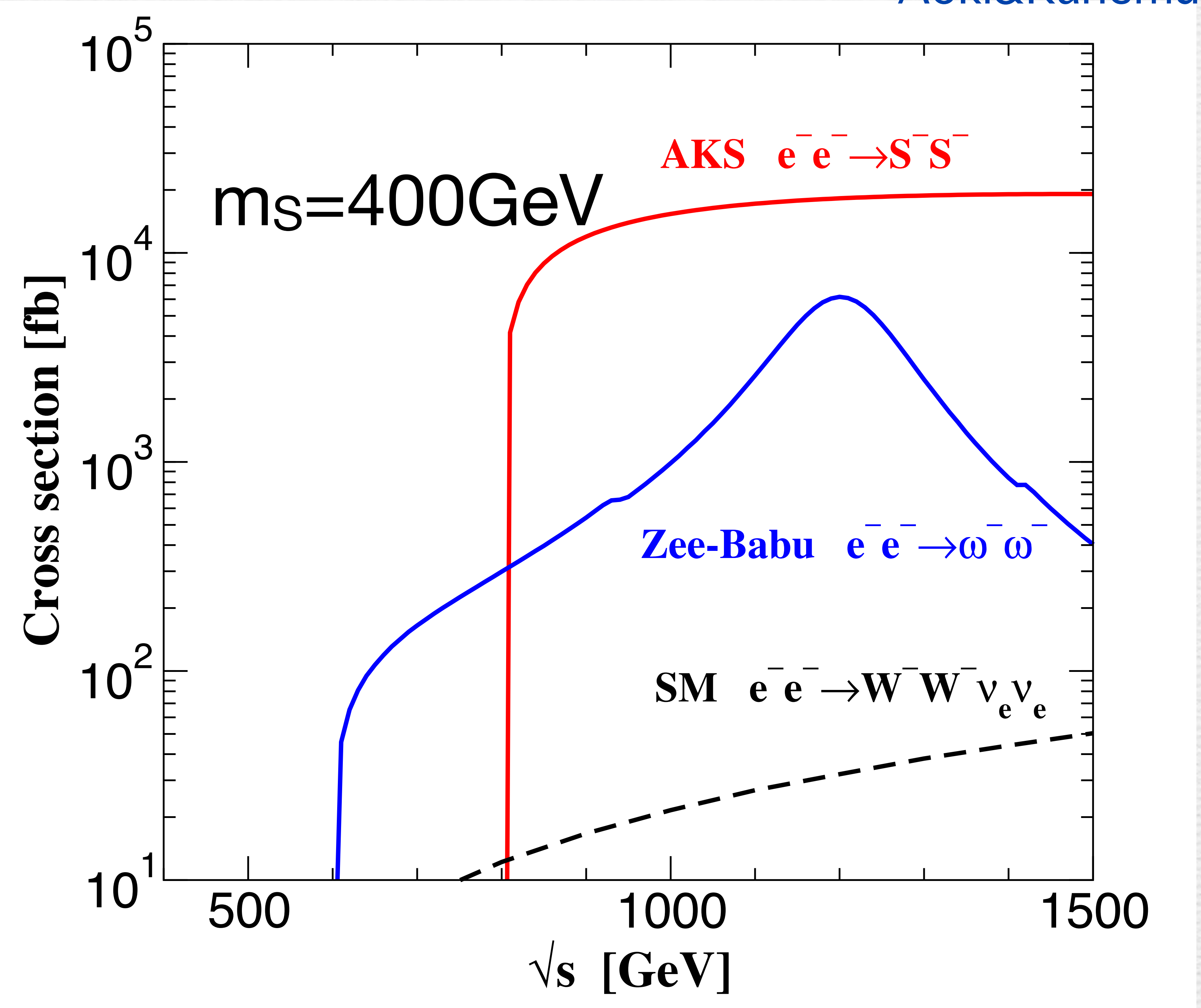


m_S=400GeV

A signal can be seen at the ILC@1TeV

Singlet-like scalar @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

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

Rich fields may wait for us just above the TeV scale

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→ E

large top Yukawa coupling

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

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

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 Z2 odd new fields

$$W = \lambda \Phi_{u,d} \Phi_1' \Phi_2'$$ → $$\Delta V = |\lambda|^2 h^2 \varphi_{1,2}'^{\dagger} \varphi_{1,2}'$$

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 $\sim\lambda v$

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