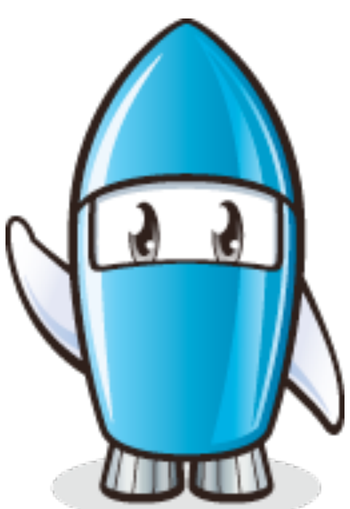
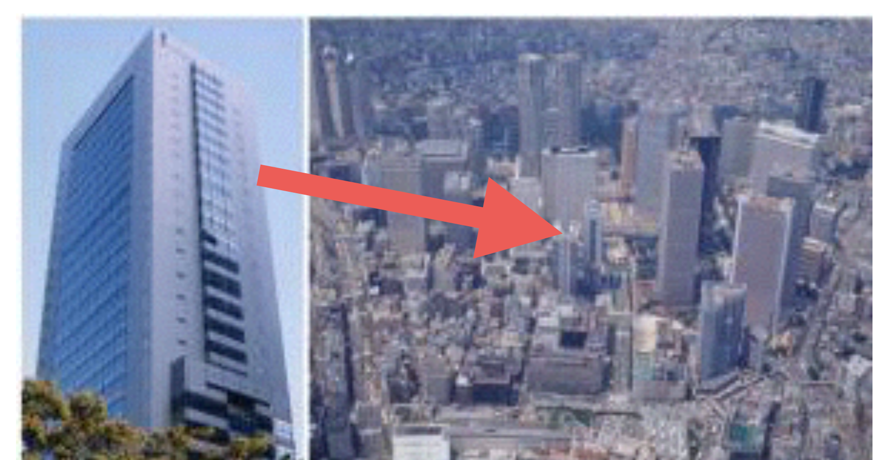
Beyond the SM phenomena and the extended Higgs sector based on the SUSY gauge theory with confinement

Tetsuo SHINDOU (Kogakuin University)

- S. Kanemura, E. Senaha, T.S., T. Yamada, JHEP1305,066
- S. Kanemura, N. Machida, T.S., T. Yamada, PRD89,013005
- S. Kanemura, N. Machida, T.S., PLB738, 178





15/2/2015, HPNP2015@Univ. of Toyama

Physics beyond the SM

A new particle is discovered

&

Its properties are consistent with a SM Higgs boson

↓

The SM seems to be established

However, it's not the end of the story

We still require the NP beyond the SM

- Baryon asymmetry of the Universe?
- What's the Dark Matter?
- Origin of tiny neutrino mass?
- Charge quantisation? ⟵ Unified theory ? (Hierarchy problem)
- …

There should be NP!!

Scale of the NP?

How far is the new physics ?

- BAU : depending on the models
  - EWBG: TeV
  - Leptogenesis: ~10^9GeV
- DM : depending on the thermal history, properties of DM
  - WIMP: ~100GeV
  - WIMPzilla: 10^{16}GeV
- m_ν : depending on the models
  - Seesaw: keV~10^{15}GeV
  - Radiative mechanism:TeV
- Hierarchy problem : may be around TeV!

We don't have enough knowledge on the NP scale

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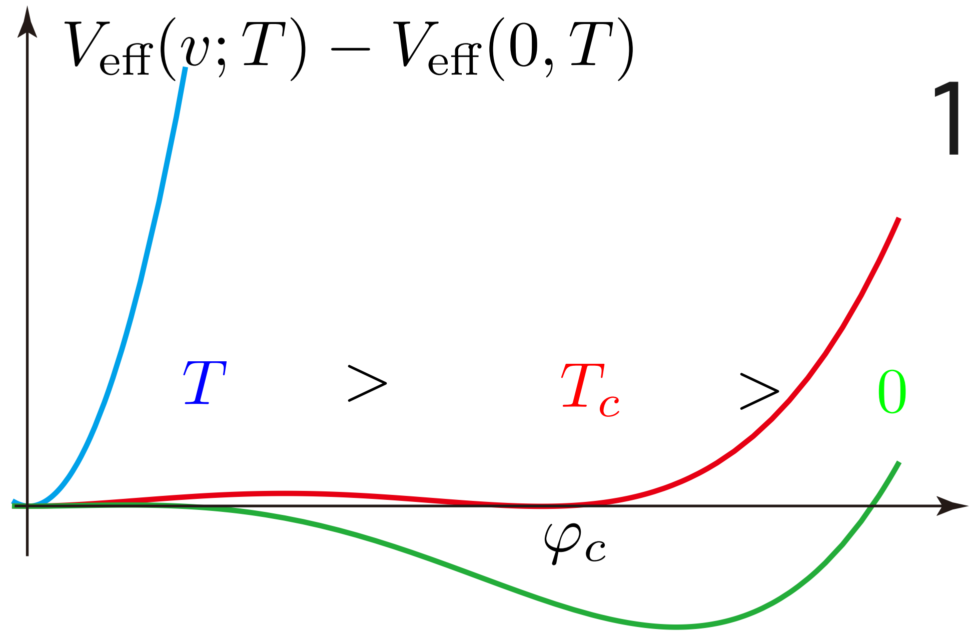
We don't have enough knowledge on the NP scale

In this talk, we focus on the solutions@TeV scale

Electroweak Baryogenesis

Nice review was given by E. Senaha

Electroweak Baryogenesis ⟷ essence of EWSB



1st order electroweak transition

+

Sphaleron

To avoid too strong washout

The strong enough first order EWPT is necessary → $\phi_c/T_c>1$

But the condition cannot be satisfied in the SM

Some extension is necessary.

e.g. extra boson loop can enhance the ϕ_c/T_c

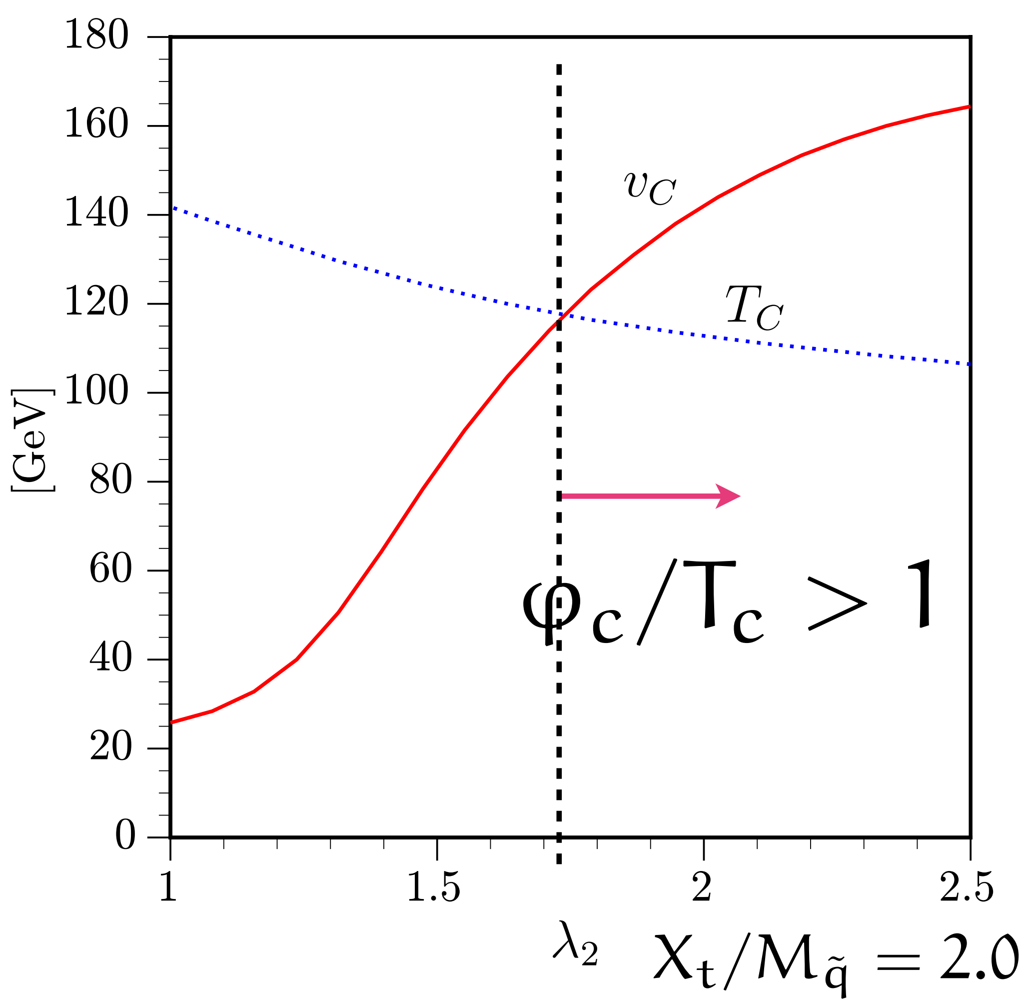
2HDM, rSM, …

A SUSY model for EWPT

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

In SUSY model with 4 Higgs doublets and 2 charged singlets,

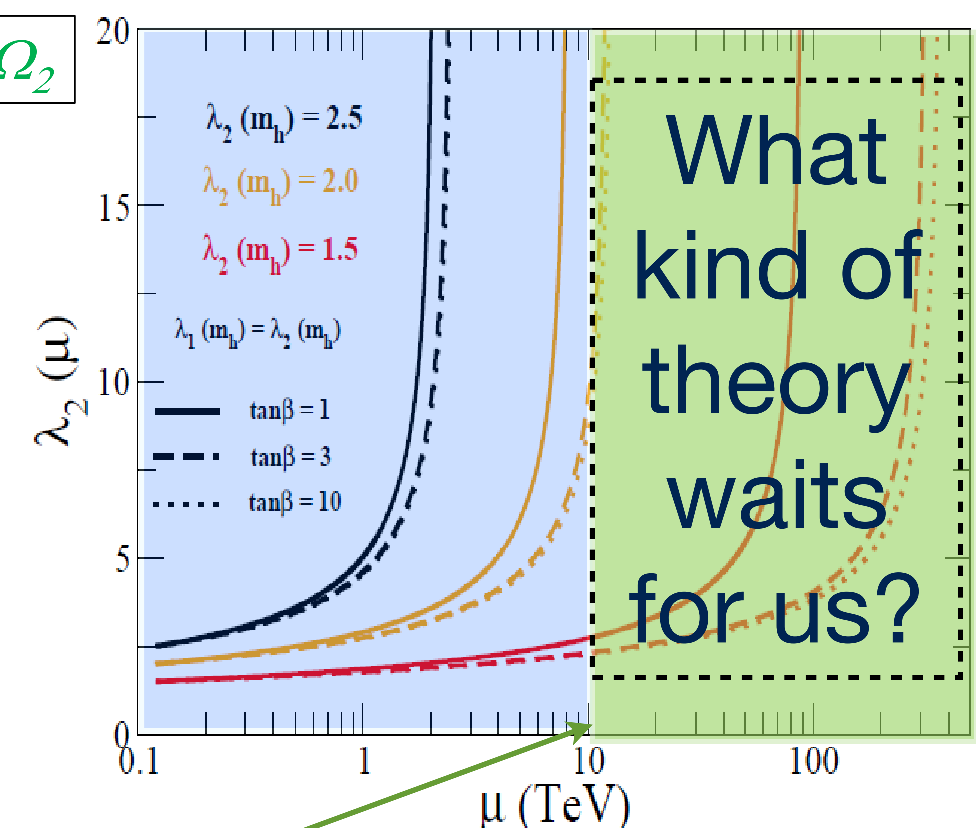
$$W = \boxed{\lambda_1 \Omega_1 H_1 \cdot H_3 + \lambda_2 \Omega_2 H_2 \cdot H_4} - \mu H_1 \cdot H_2 - \mu' H_3 \cdot H_4 - \mu_\Omega \Omega_1 \Omega_2$$



Landau pole appears at the scale much lower than the Planck scale

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

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

Neutrino mass&DM

Good reviews were given by E. Ma, S. Nasri, and H. Sugiyama

As a mechanism for neutrino mass generation@TeV,

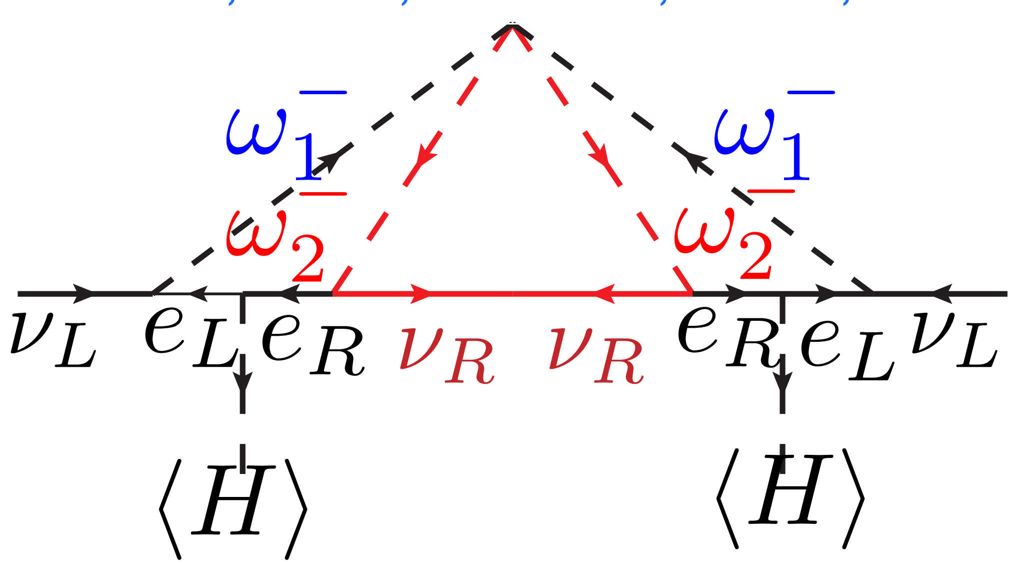
radiative seesaw scenarios

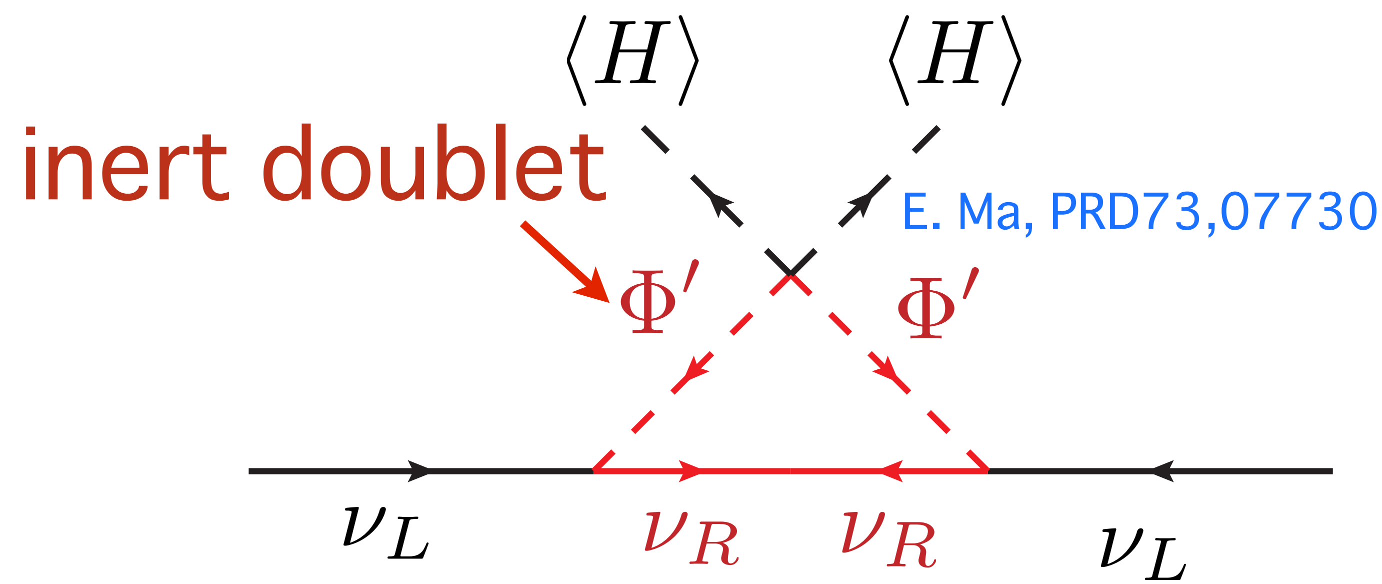
↓

Loop diagrams with RHN give tiny neutrino mass

Z_2-odd ← To avoid tree level contribution

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





Lightest Z_2-odd neutral particle can be a DM

New scalars are introduced in this class of models

Can such extra scalars enhance the 1st order EWPT?

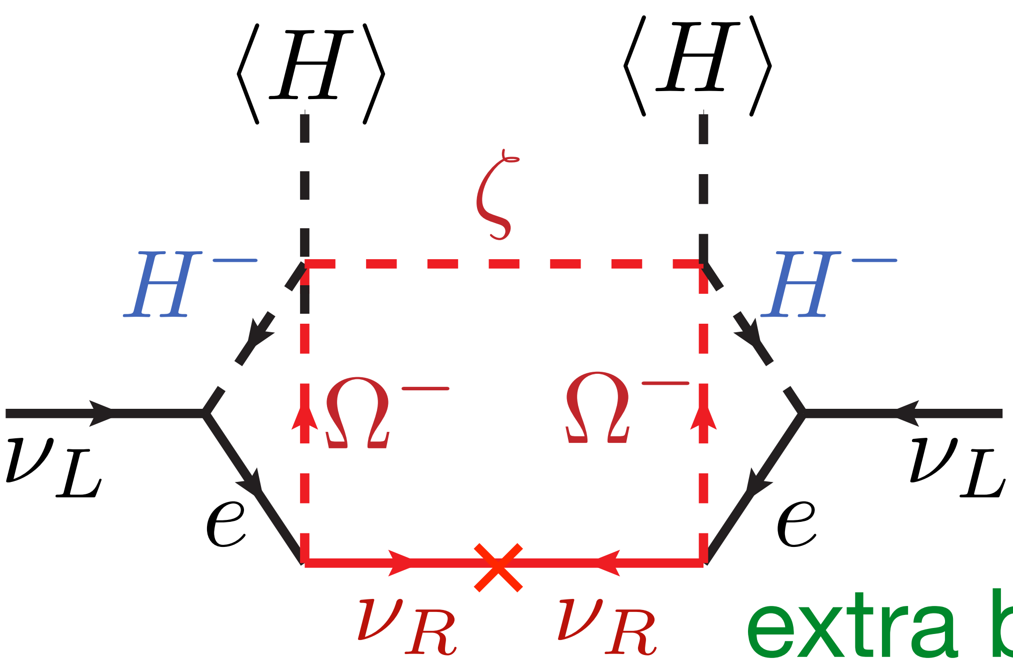
AKS model

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

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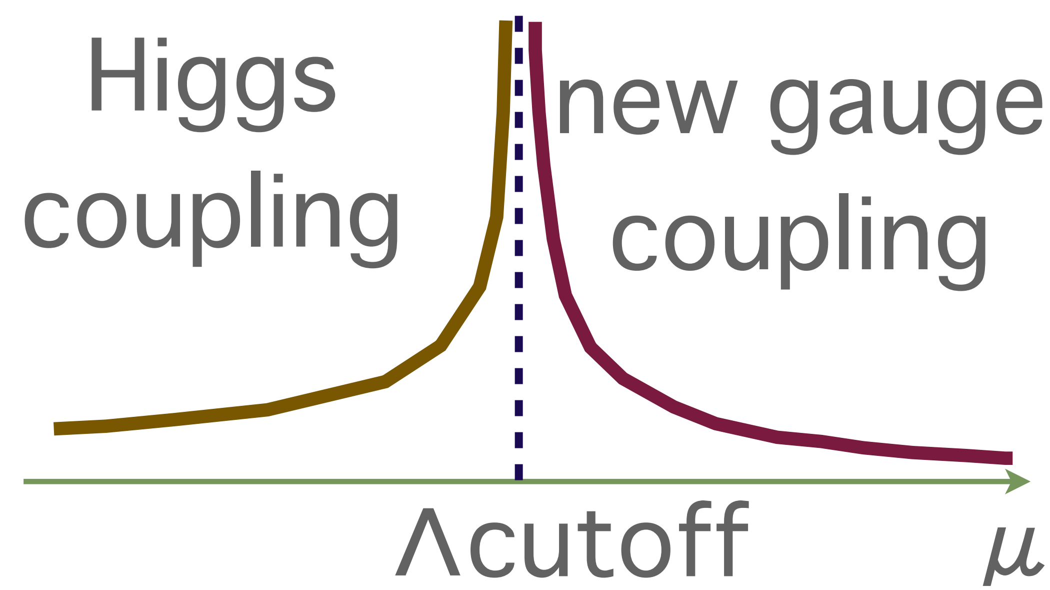
Our expectation:



Fundamental Theory?

- What is the fundamental theory of such a model?
  - Large coupling constant → Landau pole (cutoff)
  - What is the origin of strong Higgs force?
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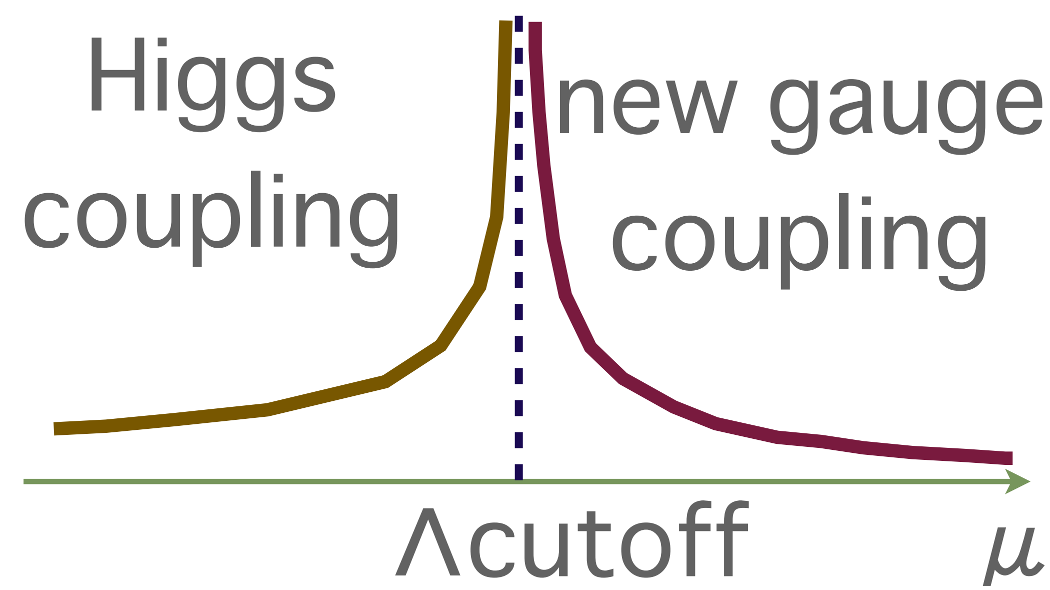
We have a nice candidate!
SUSY $SU(2)_H$ model

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!

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

RHN is introduced

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

We will introduce a Z_2 symmetry (unbroken)

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 neutrino is introduced as $SU(2)_H$ singlet field

In the low energy effective theory,

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

Higgs sector of the effective theory

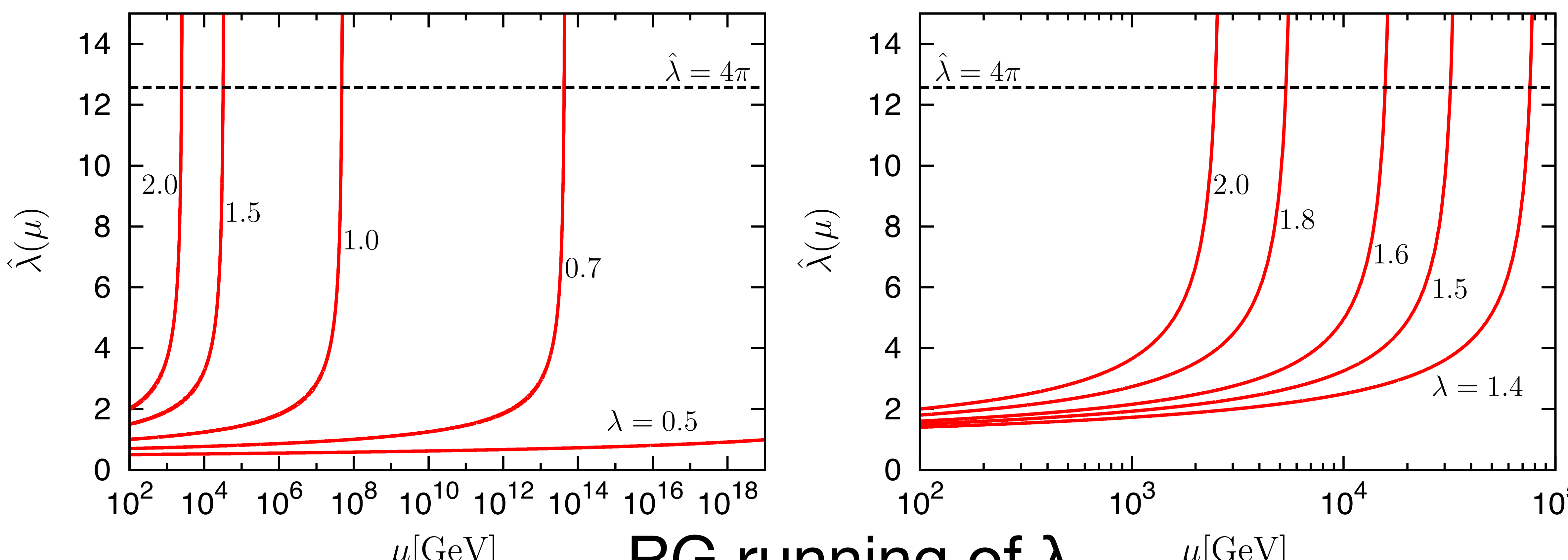
S.Kanemura,E. Senaha, T.S,T.Yamada,JHEP1305,066

$\lambda\langle n\rangle$ → μ

MSSM-like Higgs doublets → H_u, H_d

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

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



RG running of λ

$\lambda(\mu_{EW})>1.5 \rightarrow \Lambda_H < O(10)$TeV

1st order EWPT

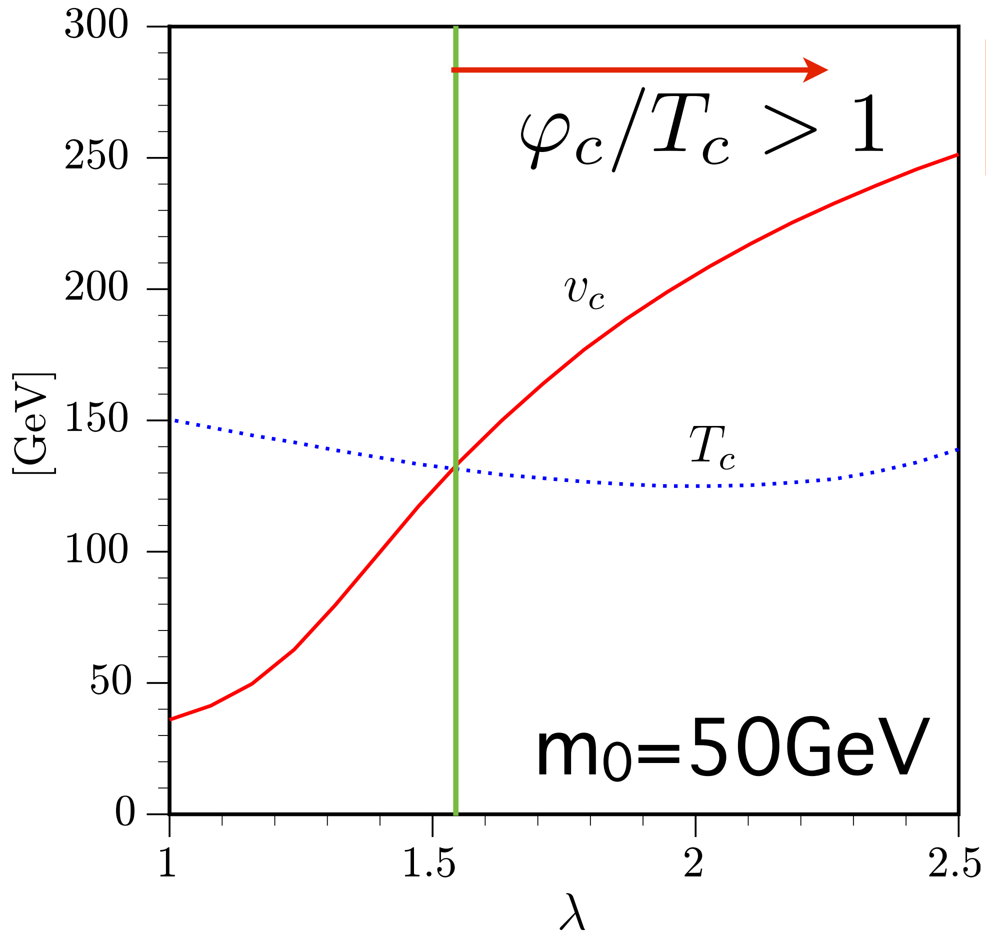
Benchmark:

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

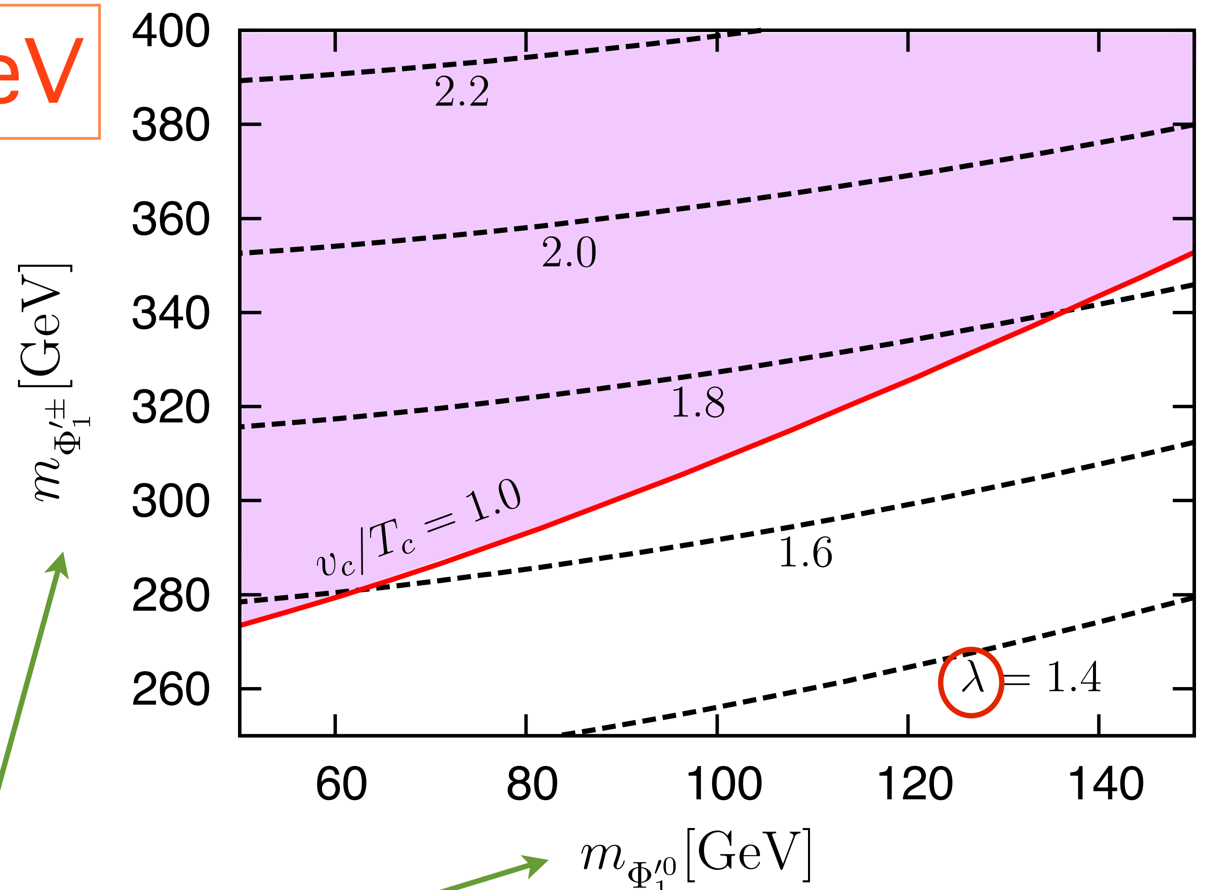
$$\tan\beta = 15, m_{H^+} = 350\text{GeV}, \mu = 200\text{GeV}, M_{\tilde{t}} = M_{\tilde{q}} = 2000\text{GeV}$$

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

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



mh=126GeV



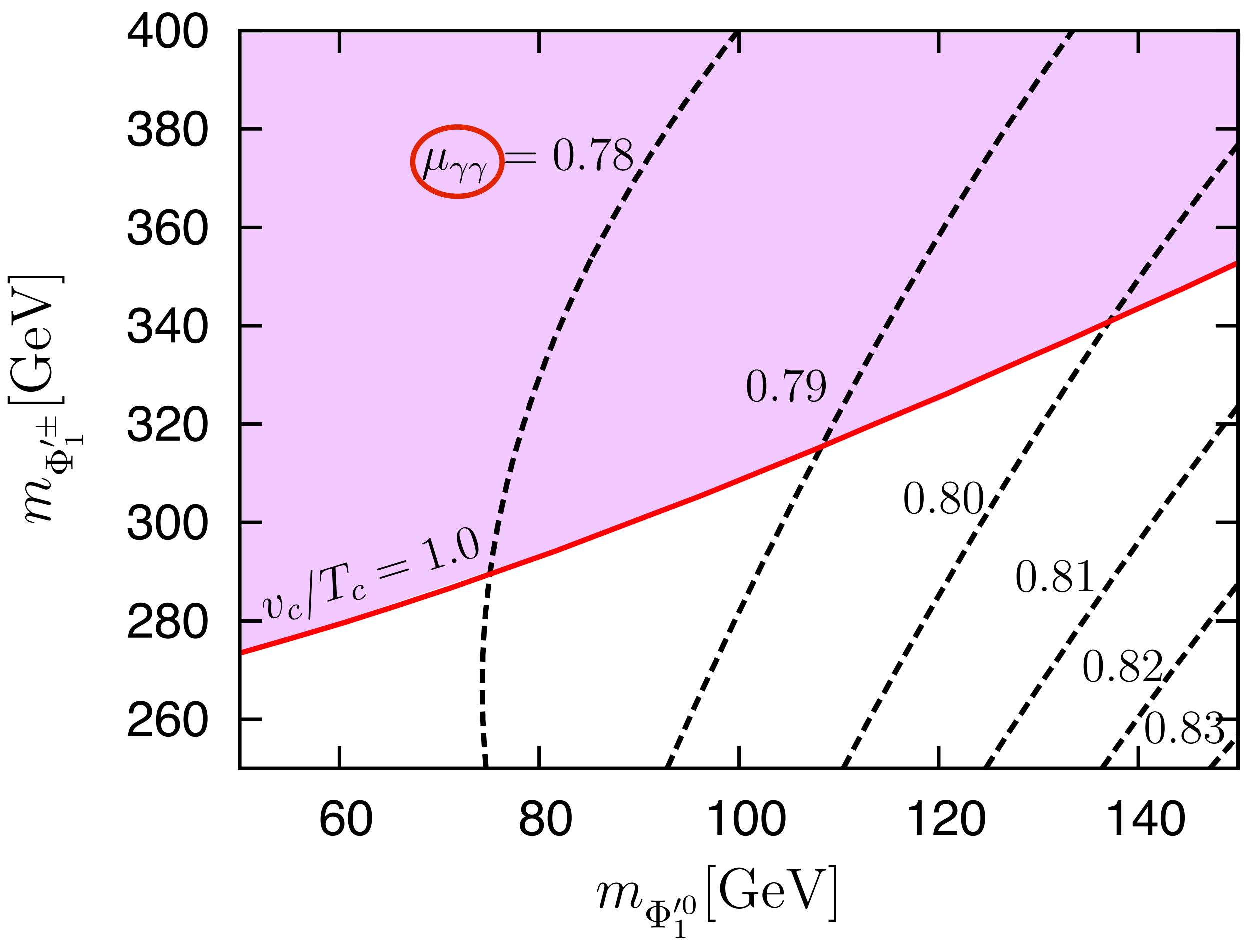
Lightest Z_2 odd masses

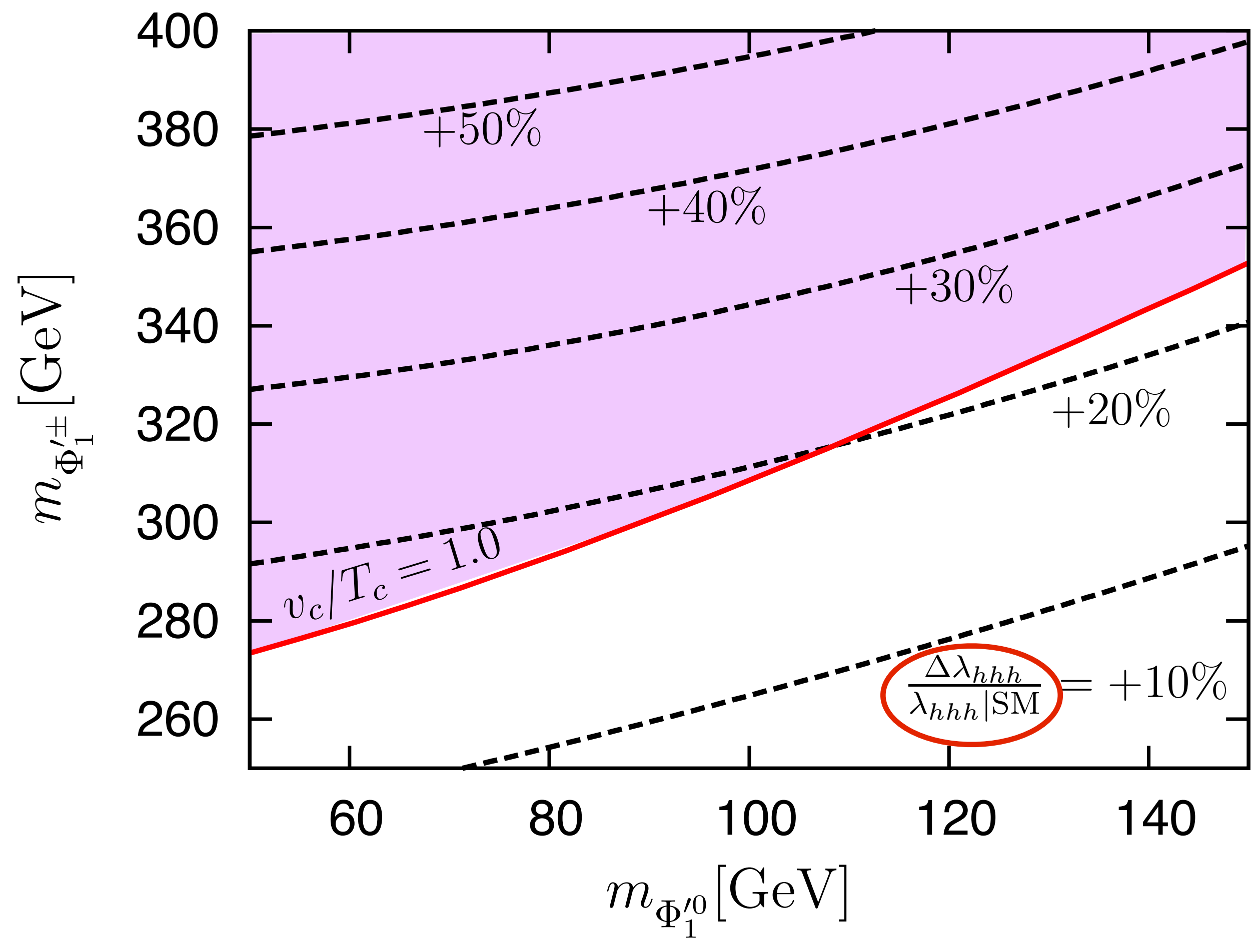
$\varphi_c/T_c > 1$ can be satisfied!!

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

1st order EWPT

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% smaller than the SM prediction in the region of $v_c/T_c>1$

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

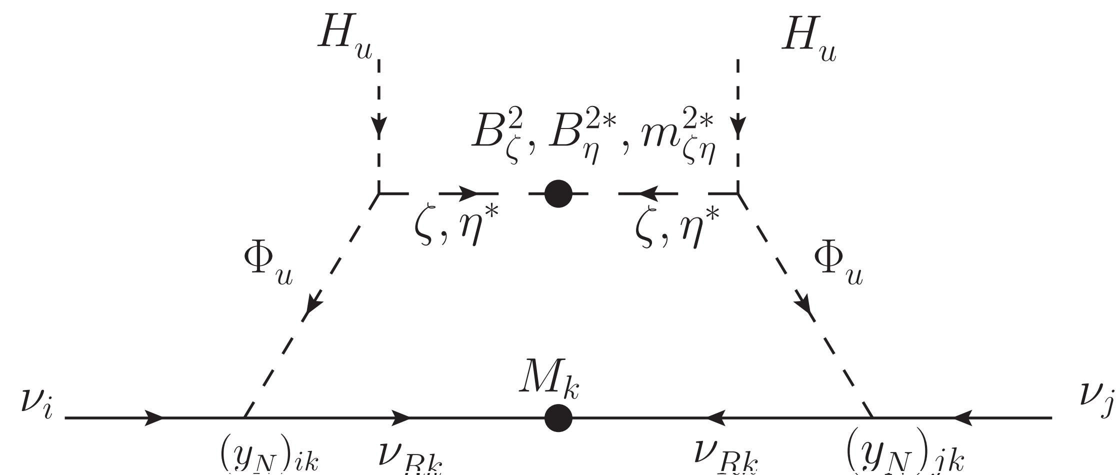
more than 20% deviation from the SM prediction

Neutrino Mass Generation

S.Kanemura, N. Machida, T.S, T.Yamada,PRD89,013005,
S. Kanemura, N. Machida, T.S.,

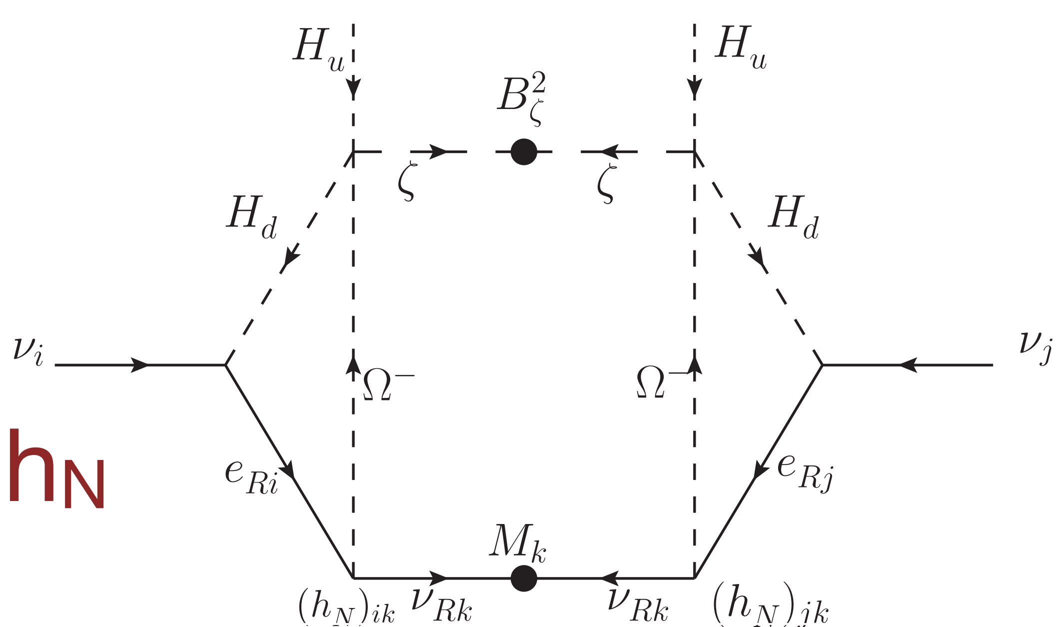
$$W_N = (y_N)_i N_i^c L_j \Phi_u + (h_N)_{ij} N_i^c E_j^c \Omega^- + \frac{M_i}{2} N_i^c N_i^c$$

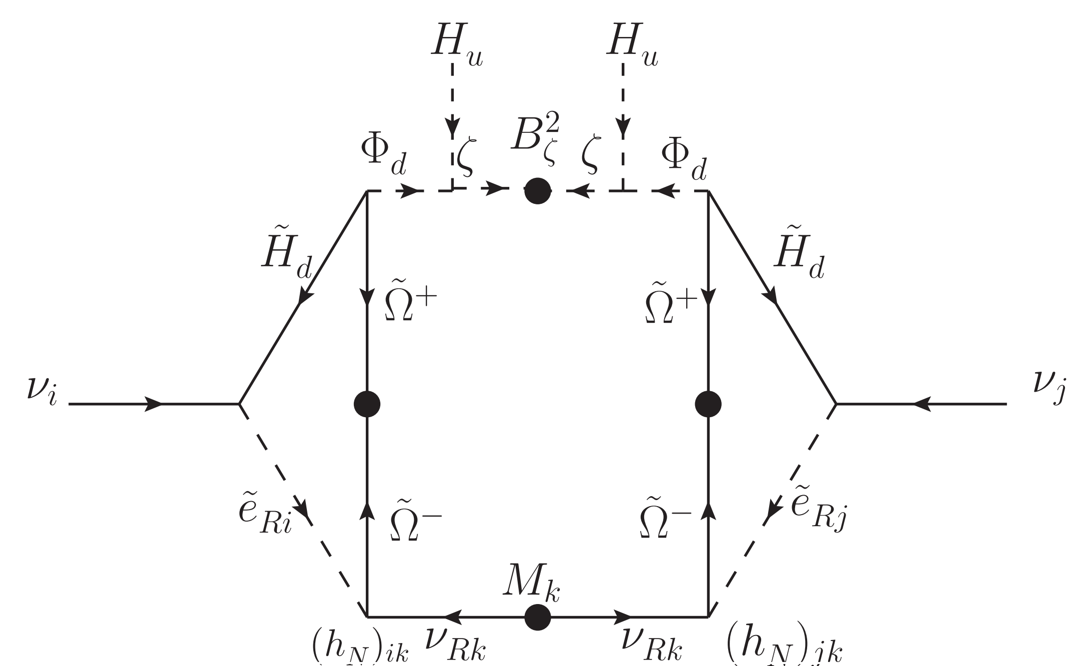
1-loop
driven by y_N



It corresponds to SUSY Ma model

3-loop
driven by h_N





They correspond to SUSY AKS model

Neutrino Mass Generation

S. Kanemura, N. Machida, T.S., PLB738, 178

Two different types of contributions are possible

Even if there is only one RHN,
two mass differences are reproduced!

For example,

1-loop contribution ⋯⋯⋯▶ $m_2^2 - m_1^2$ (solar)

3-loop contribution ⋯⋯⋯▶ $m_3^2 - m_2^2$ (atmospheric)

Dangerous LFV can be avoided by this choice

Dark Matter

In general, there are three DM candidates

Lightest Z_2-odd

Lightest R_p-odd

can be DM

$(R_p, Z_2)=(+,-),(-,-),(-,+)$

For example,

(+,-): Right-Handed Neutrino
(-, -): Right-Handed Sneutrino
(-,+): MSSM neutralino

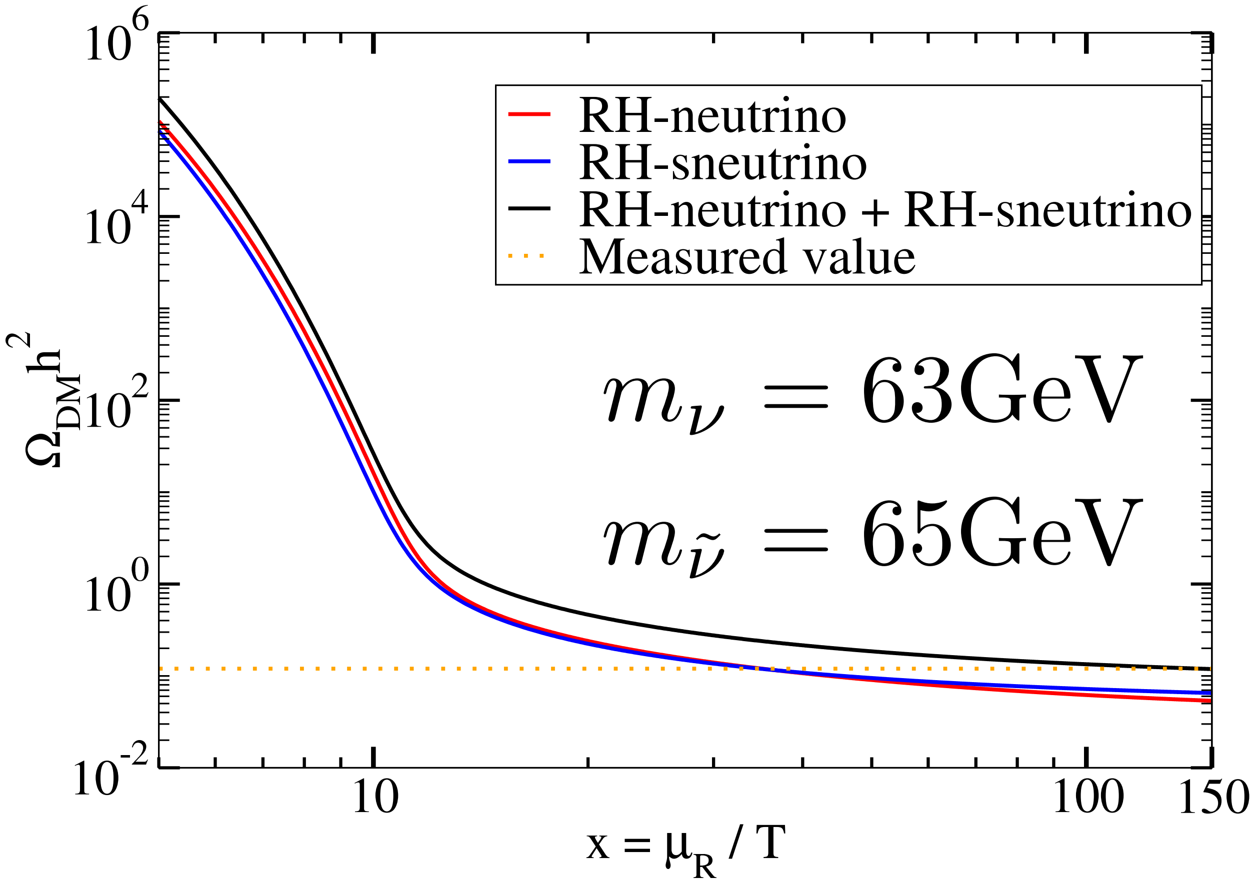
If $m_{\tilde{\chi}^0} > m_\nu + m_{\tilde{\nu}}$, only RHN and RHsN can be DM

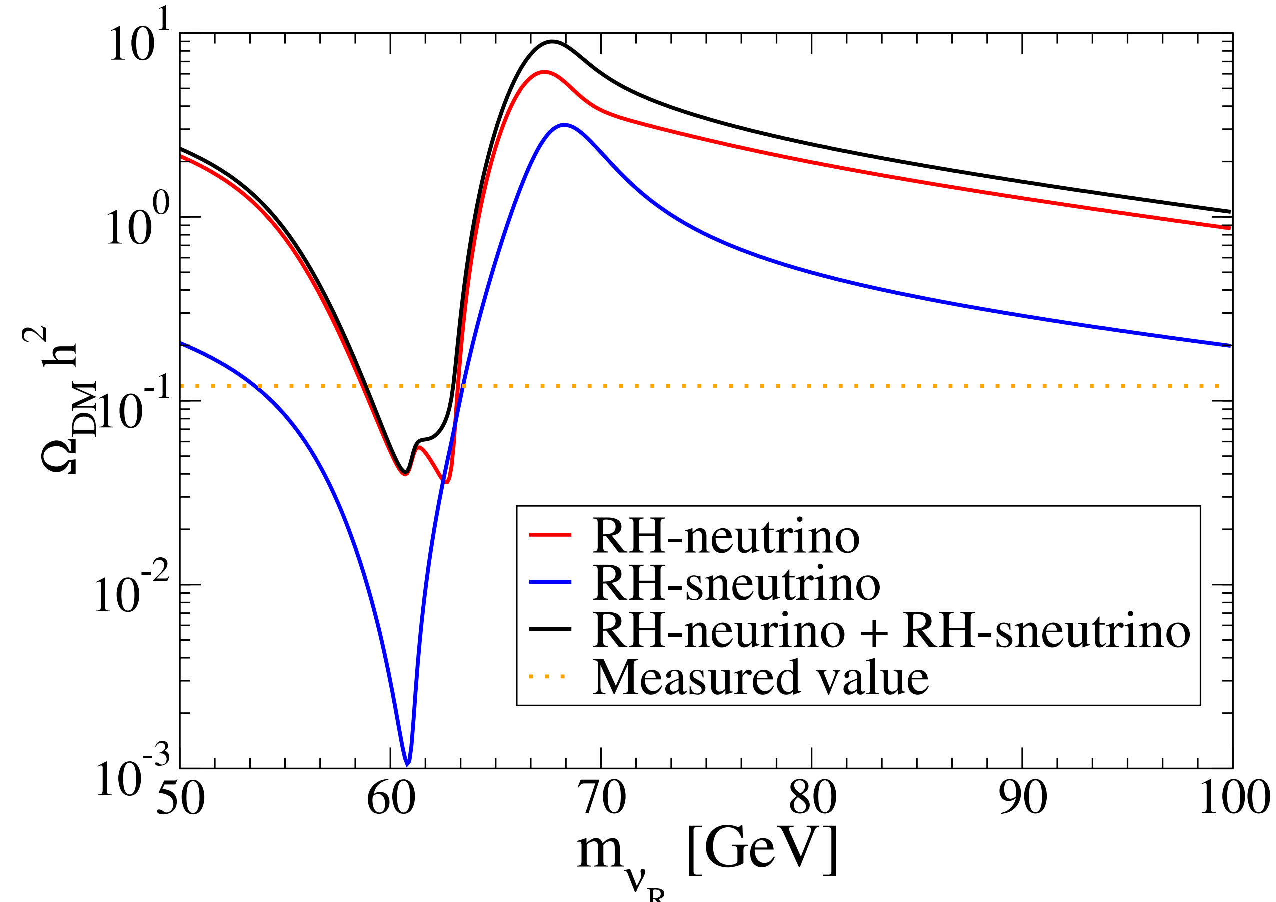
$\nu + \nu \to \mathrm{SM} + \mathrm{SM}$ $\tilde{\nu} + \tilde{\nu} \to \mathrm{SM} + \mathrm{SM}$ $\tilde{\nu} + \tilde{\nu} \leftrightarrow \nu + \nu$

conversion process

Dark Matter

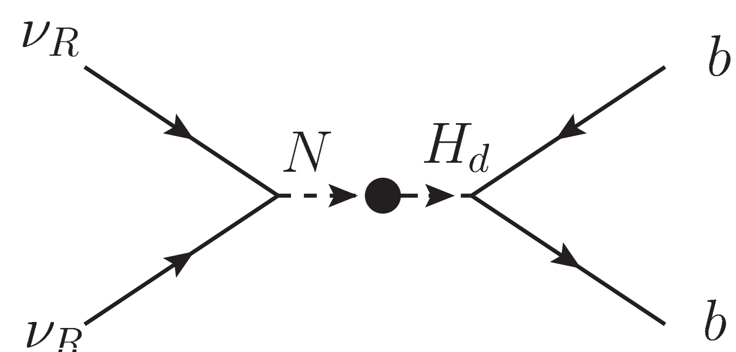
S. Kanemura, N. Machida, T.S., PLB738, 178





$$m_{\tilde{\nu}} = m_\nu + 2\text{GeV}$$

It's a kind of Higgs portal DM



Benchmark Scenario

S. Kanemura, N. Machida, T.S., PLB738, 178

λ, $\tan\beta$, and μ-terms
$\lambda = 1.8$ ($\Lambda_H = 5$ TeV) $\quad \tan\beta = 15 \quad \mu = 250$ GeV $\quad \mu_\Phi = 550$ GeV $\quad \mu_\Omega = -550$ GeV

Z_2-even Higgs sector
$m_h = 126$ GeV $\quad m_{H^\pm} = 990$ GeV $\quad m_N^2 = (1050 \text{ GeV})^2 \quad A_N = 2900$ GeV

Z_2-odd Higgs sector
$\bar{m}^2_{\Phi_u} = \bar{m}^2_{\Omega_-} = (175 \text{ GeV})^2 \quad \bar{m}^2_{\Phi_d} = \bar{m}^2_{\Omega_+} = \bar{m}^2_\zeta = (1500 \text{ GeV})^2 \quad \bar{m}^2_\eta = (2000 \text{ GeV})^2$
$B_\Phi = B_\Omega = A_\zeta = A_\eta = A_{\Omega^+} = A_{\Omega^-} = m^2_{\zeta\eta} = 0 \quad B^2_\zeta = (1400 \text{ GeV})^2 \quad B^2_\eta = (700 \text{ GeV})^2$

RH neutrino and RH sneutrino sector
$m_{\nu_R} = 63$ GeV $\quad m_{\tilde{\nu}_R} = 65$ GeV $\quad \kappa = 0.9$
$y_N = (3.28i, 6.70i, 1.72i) \times 10^{-6} \quad h_N = (0, 0.227, 0.0204)$

Other SUSY SM parameters
$m_{\tilde{W}} = 500$ GeV $\quad m_{\tilde{q}} = m_{\tilde{\ell}} = 5$ TeV

↓

Non-decoupling effects
$\varphi_c/T_c = 1.3 \quad \lambda_{hhh}/\lambda_{hhh}\|_{\text{SM}} = 1.2 \quad \text{B}(h \to \gamma\gamma)/\text{B}(h \to \gamma\gamma)\|_{\text{SM}} = 0.78$

Neutrino masses and the mixing angles
$(m_1, m_2, m_3) = (0, 0.0084 \text{ eV}, 0.0050 \text{ eV}) \quad \sin^2\theta_{12} = 0.32 \quad \sin^2\theta_{23} = 0.50 \quad \|\sin\theta_{13}\| = 0.14$

LFV processes
$\text{B}(\mu \to e\gamma) = 3.6 \times 10^{-13} \quad \text{B}(\mu \to eee) = 5.6 \times 10^{-16}$

Relic abundance of the DM
$\Omega_{\nu_R} h^2 = 0.055 \quad \Omega_{\tilde{\nu}_R} h^2 = 0.065 \quad \Omega_{\text{DM}} h^2 = \Omega_{\nu_R} h^2 + \Omega_{\tilde{\nu}_R} h^2 = 0.12$

Spin-independent DM-proton scattering cross sections
$\sigma^{\text{SI}}_{\nu_R} = 3.1 \times 10^{-46} \text{ cm}^2 \quad \sigma^{\text{SI}}_{\tilde{\nu}_R} = 7.7 \times 10^{-47} \text{ cm}^2 \quad \sigma^{\text{SI}}_{\text{DM}} = 1.1 \times 10^{-46} \text{ cm}^2$

EWPT

Neutrino mass&mixing

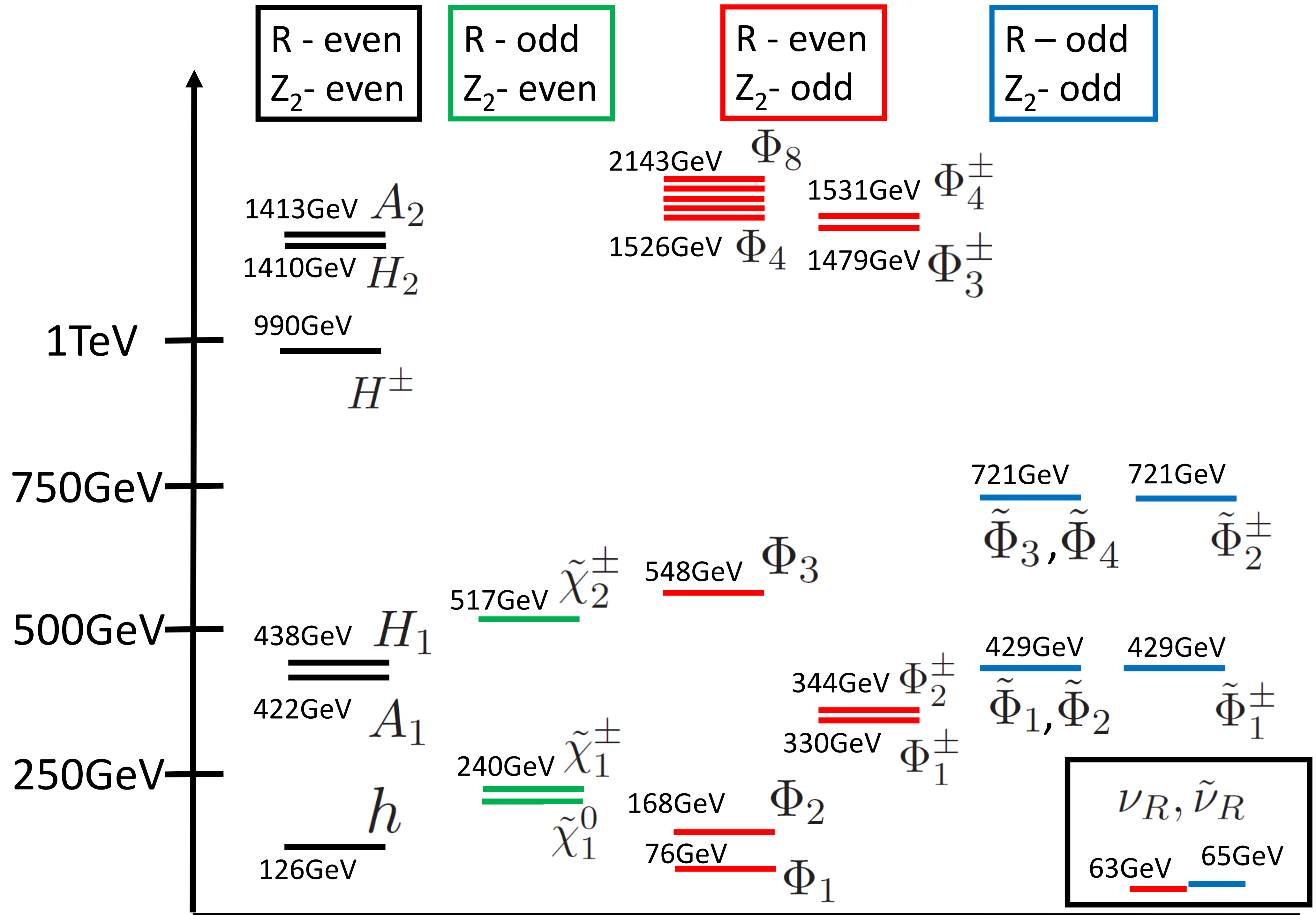
LFV

Relic abundance of DM

Direct detection of DM

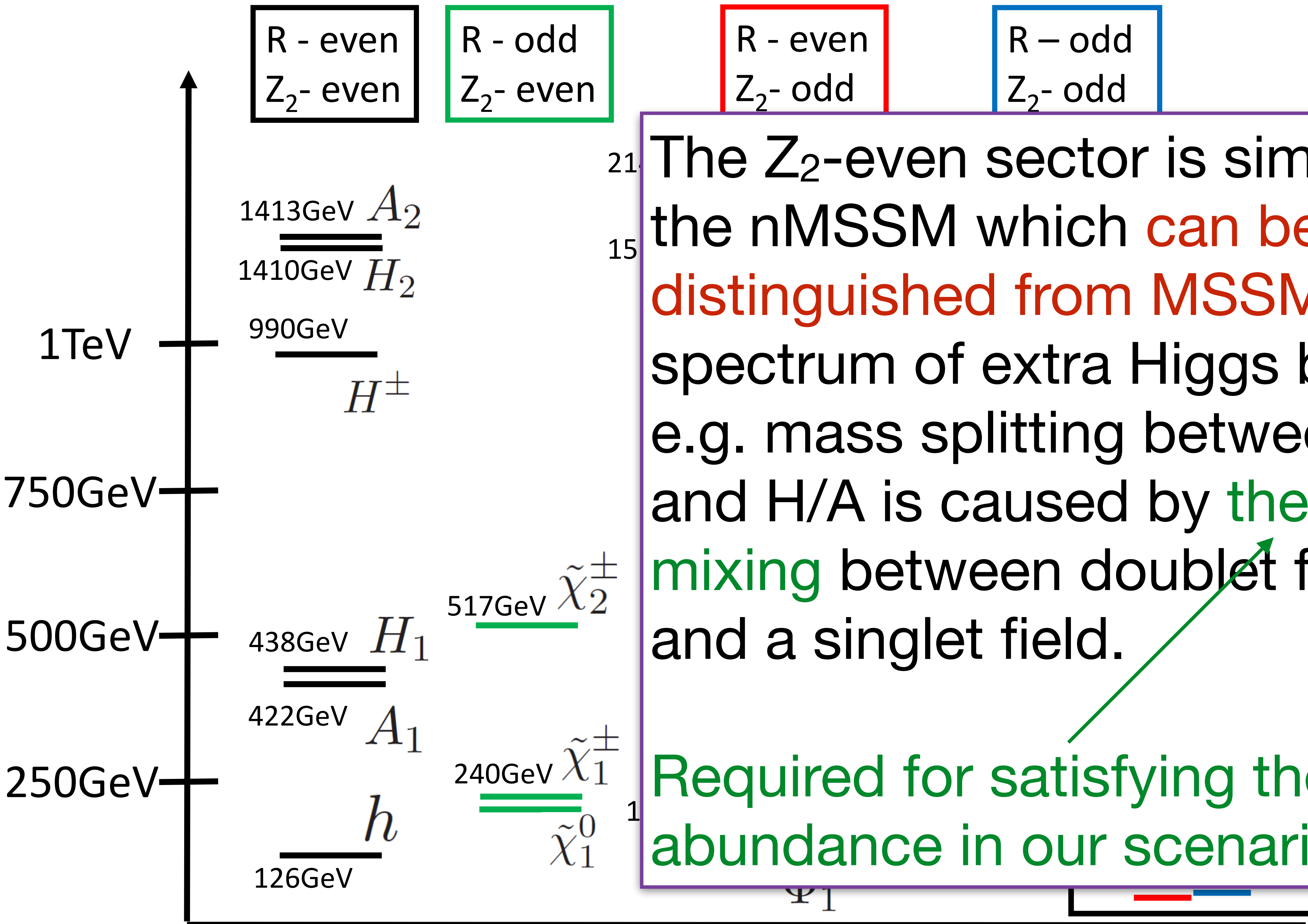
Spectrum at Benchmark point

S. Kanemura, N. Machida, T.S., PLB738, 178



Spectrum at Benchmark point

S. Kanemura, N. Machida, T.S., PLB738, 178



The Z_2-even sector is similar to the nMSSM which can be distinguished from MSSM by the spectrum of extra Higgs bosons. e.g. mass splitting between H^+ and H/A is caused by the large mixing between doublet fields and a singlet field.

Required for satisfying the DM abundance in our scenario

Finger printing

S. Kanemura, N. Machida, T.S., PLB738, 178

In our model, the Higgs couplings are affected

By precise measurement of the Higgs couplings, one can distinguish our scenario from nMSSM

κ_W	κ_Z	κ_u	κ_d	κ_ℓ	κ_γ	$\lambda_{hhh}/\lambda_{hhh}^{\rm SM}$
0.990	0.990	0.990	0.978	0.978	0.88	1.2

They are significantly affected by the loop of Z_2 odd particles

Spectrum at Benchmark point

S. Kanemura, N. Machida, T.S., PLB738, 178

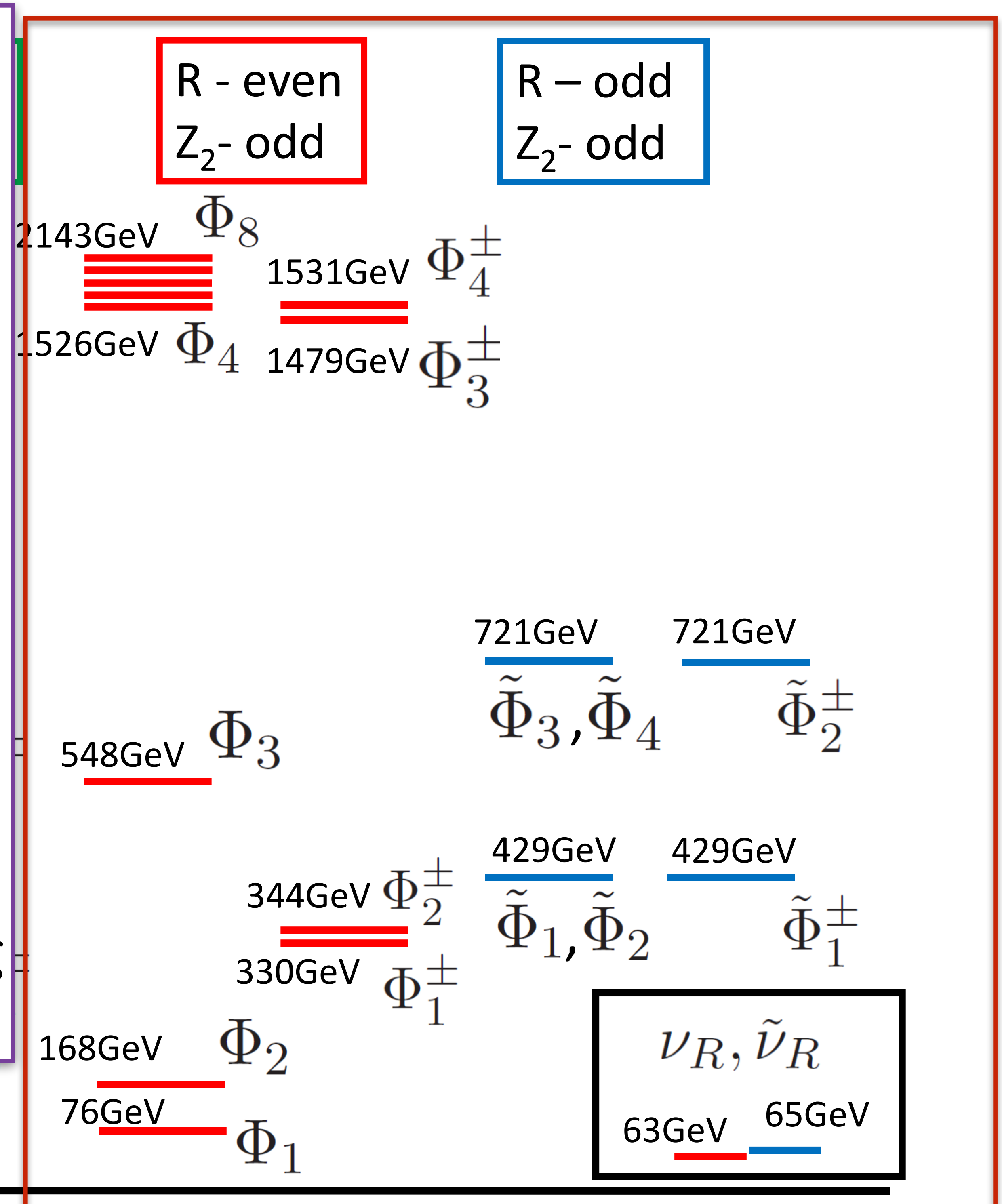
Inert doublet search at ILC can provide a strong hint on the Z_2 odd sector.
e.g.

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

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

Inert charged-singlet search is also useful to explore the Z_2-odd sector

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



Rich phenomenology!!

Summary

- It is quite interesting, NP in the Higgs sector provides solutions for baryogenesis, neutrino mass, DM.
  - Electroweak baryogenesis, radiative generation of neutrino mass, DM
  - 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's very different from GUT beyond the grand desert

Back up

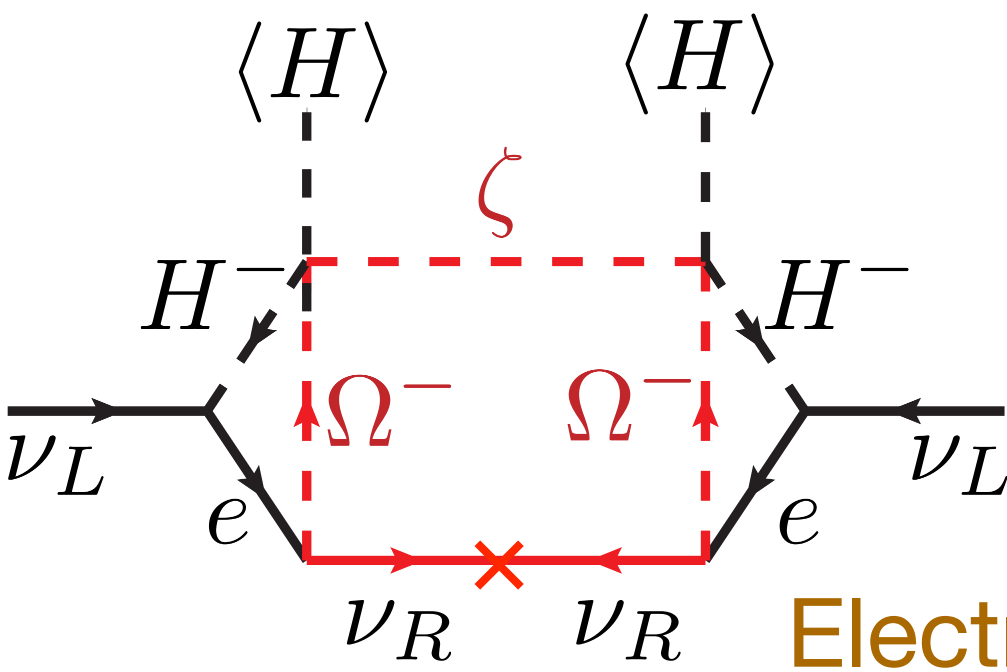
Fields in radiative seesaw model

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!!

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!

To get strong 1st order EWPT

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=125GeV

conflict with LHC data

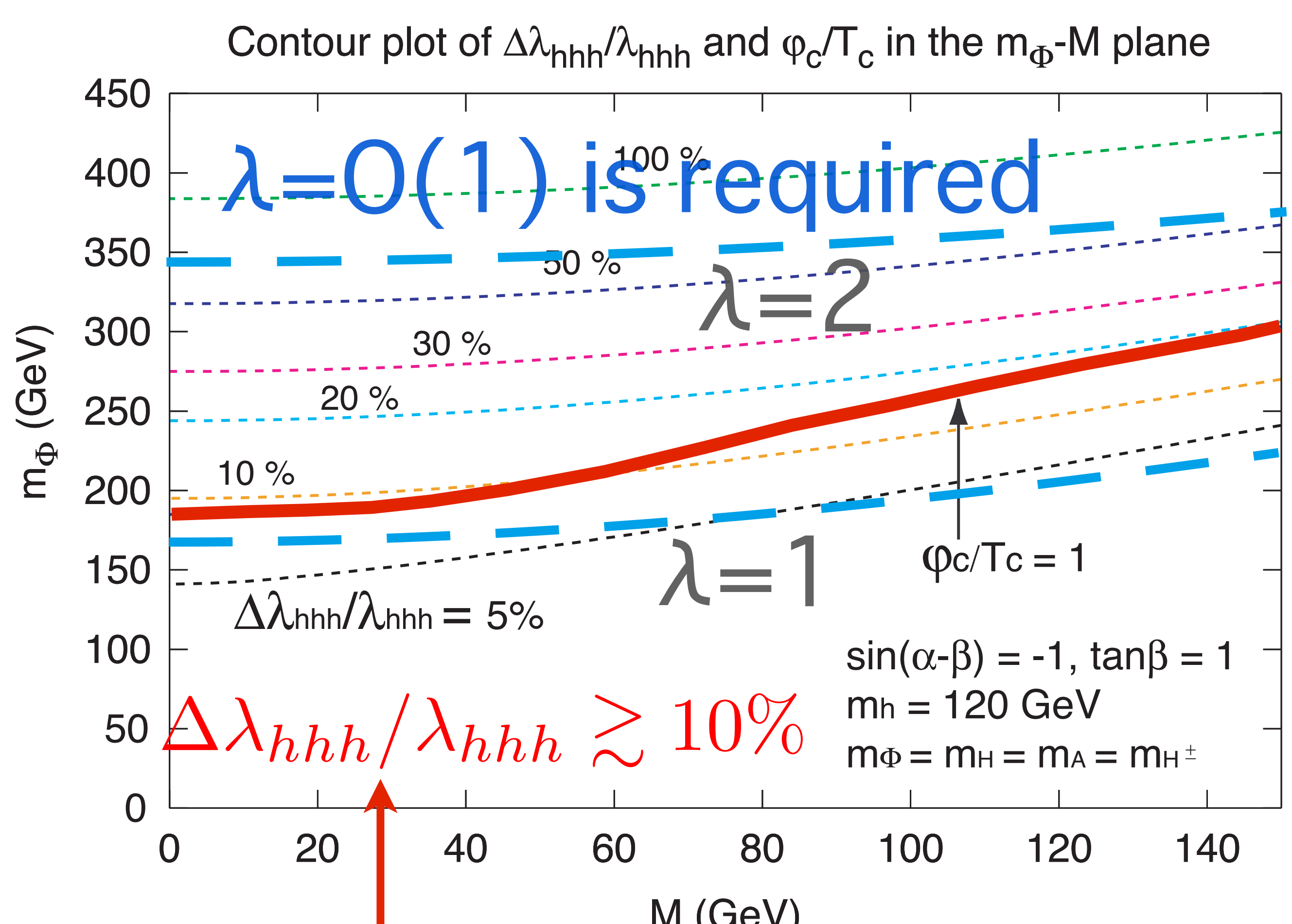
Extra boson loop can enhance ϕ_c/T_c

Extended Higgs sector!
e.g. 2HDM

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

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

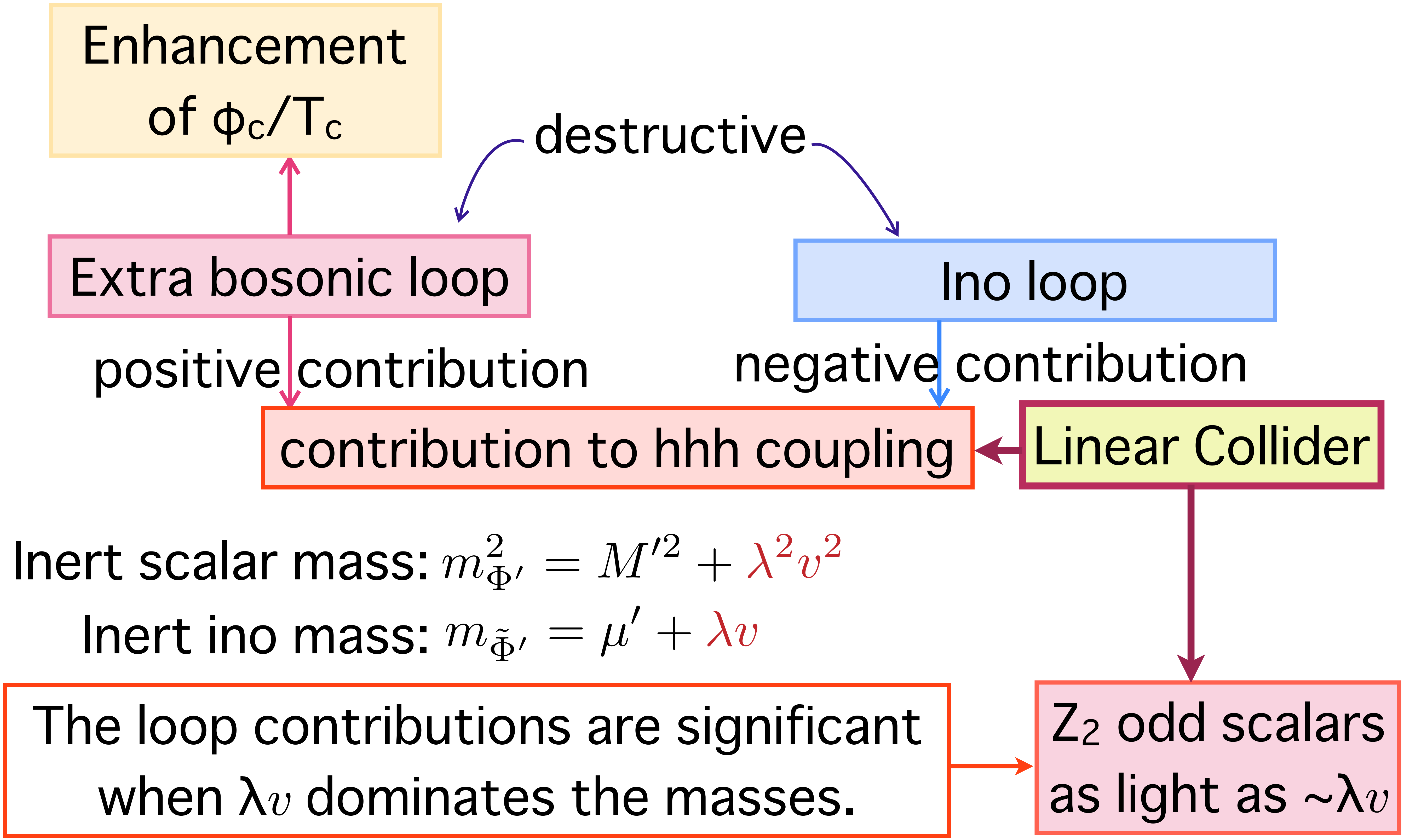
Extra Higgs bosons as H,A H±



Kanemura, Okada, Senaha,PLB606,361

Testable@Collider exp.

Tests of the scenario



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

Sensitivity for finger printing

Higgs WG report on snowmass 2013, arXiv:1310.8361

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

Exploring the Z_2 odd sector

Our model is characterized by the Z_2 odd sector

↓

Z_2-odd particle search is important

colorless → ILC

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.

Singlet-like charged particle Ω^+

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

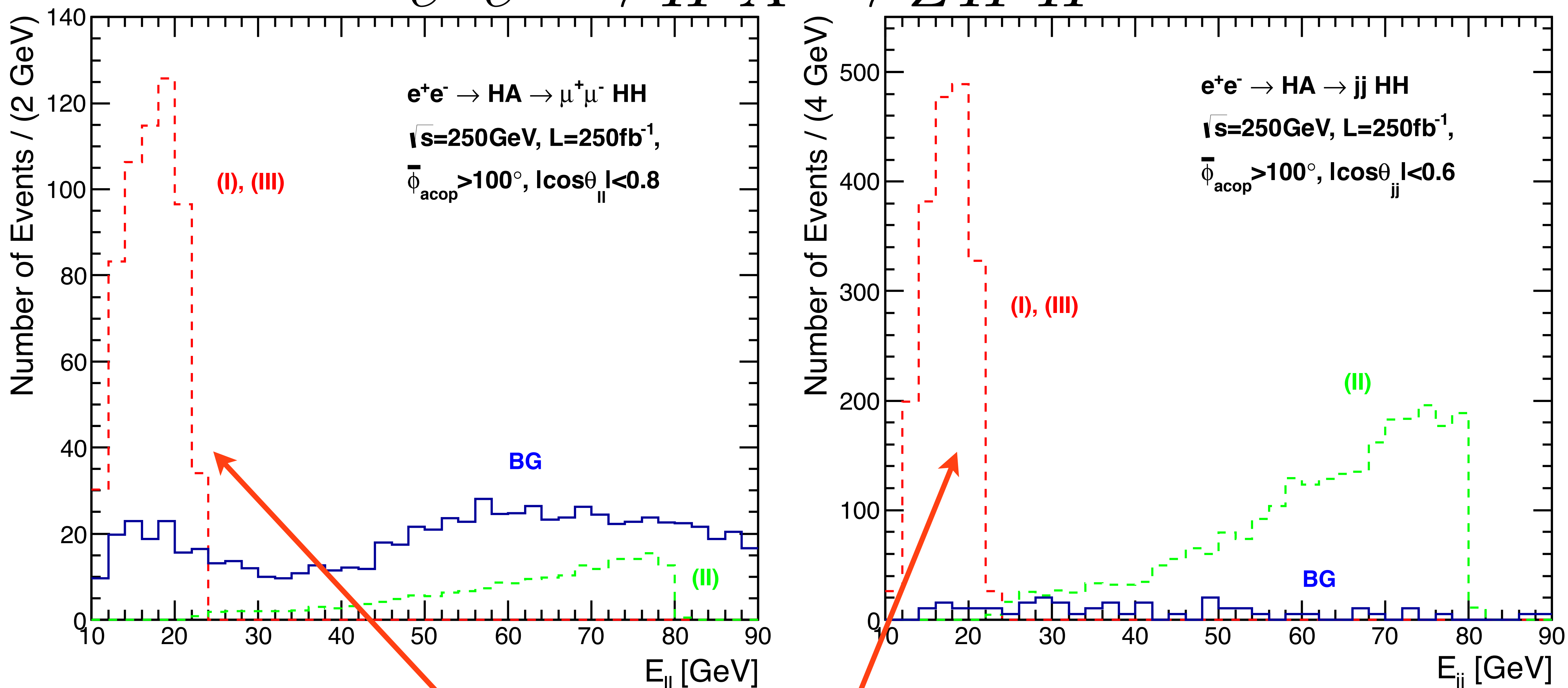
$$e^-e^- \to \Omega_1^-\Omega_1^-$$ ← Strong evidence of the model

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

Light inert doublet @ ILC

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

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

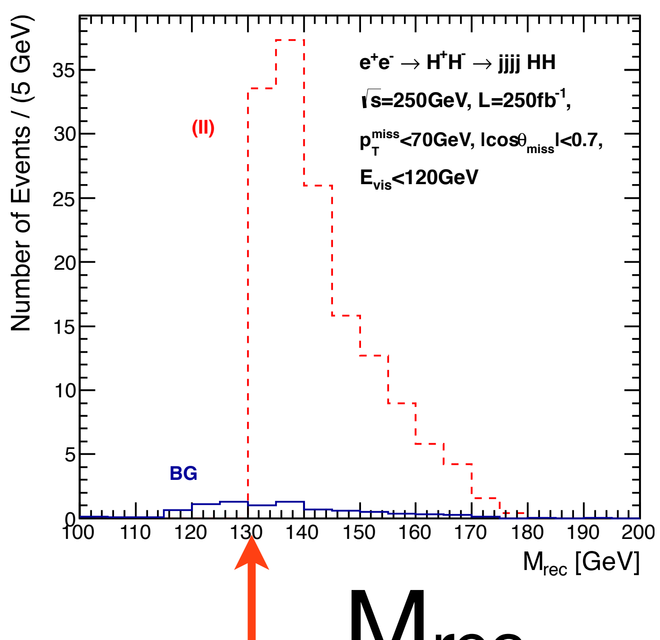


$$m_{H'} = 65\text{GeV}$$
$$m_{A'} = 73\text{GeV}$$
$$m_{H^{\pm\prime}} = 120\text{GeV}$$

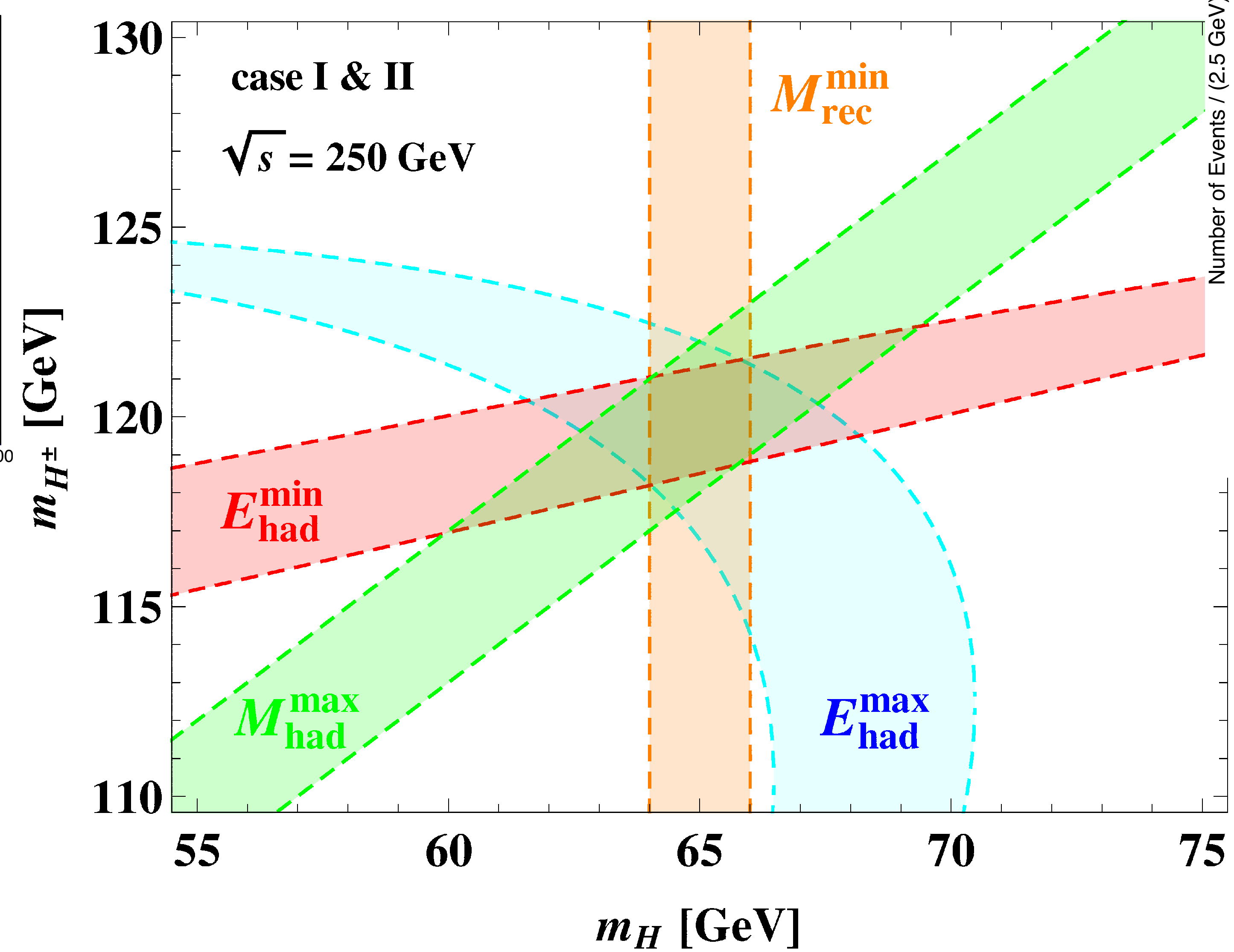
Light inert doublet @ ILC

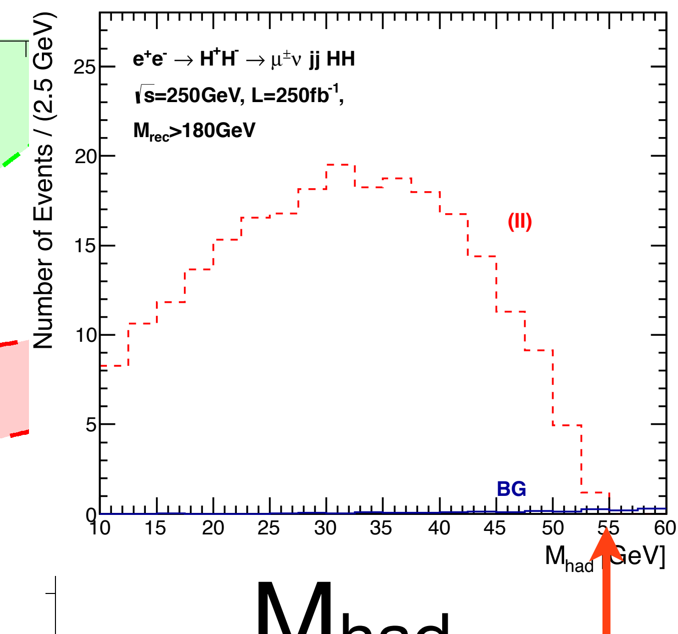
M. Aoki, S. Kanemura and H. Yokoya, PLB725,302.

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

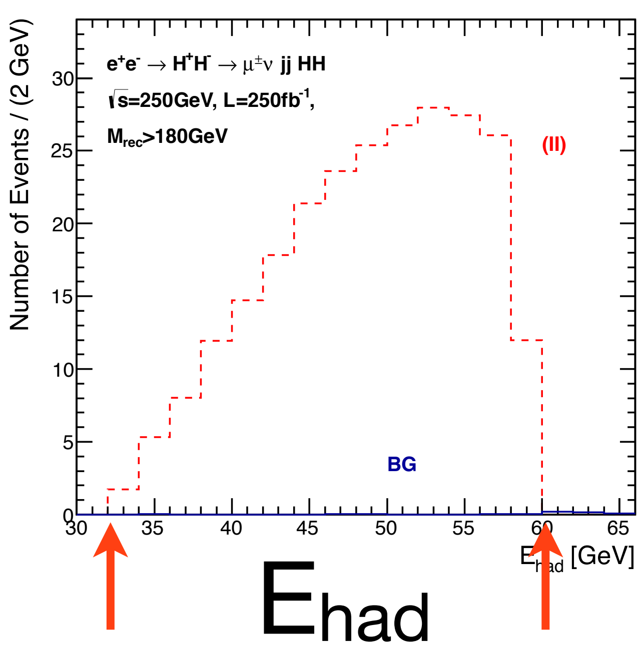


M_{rec}





M_{had}



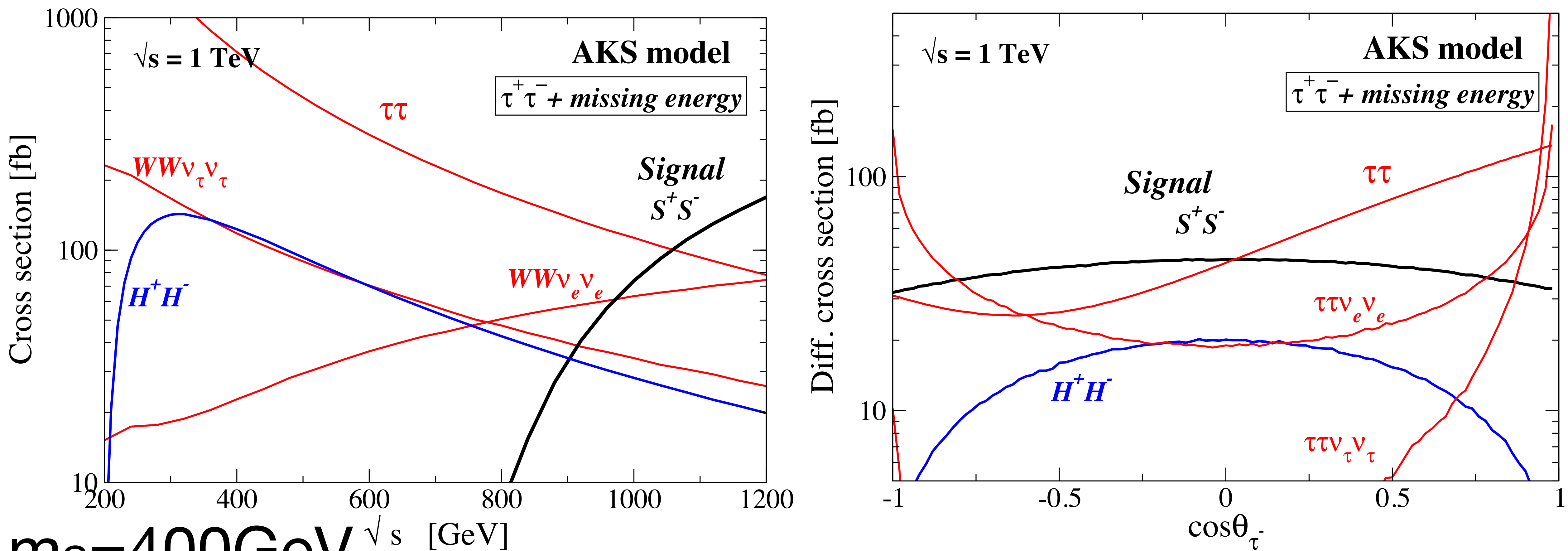
E_{had}

The masses can be precisely determined

Singlet like scalar @ILC

Aoki&Kanemura, PLB689,28.

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

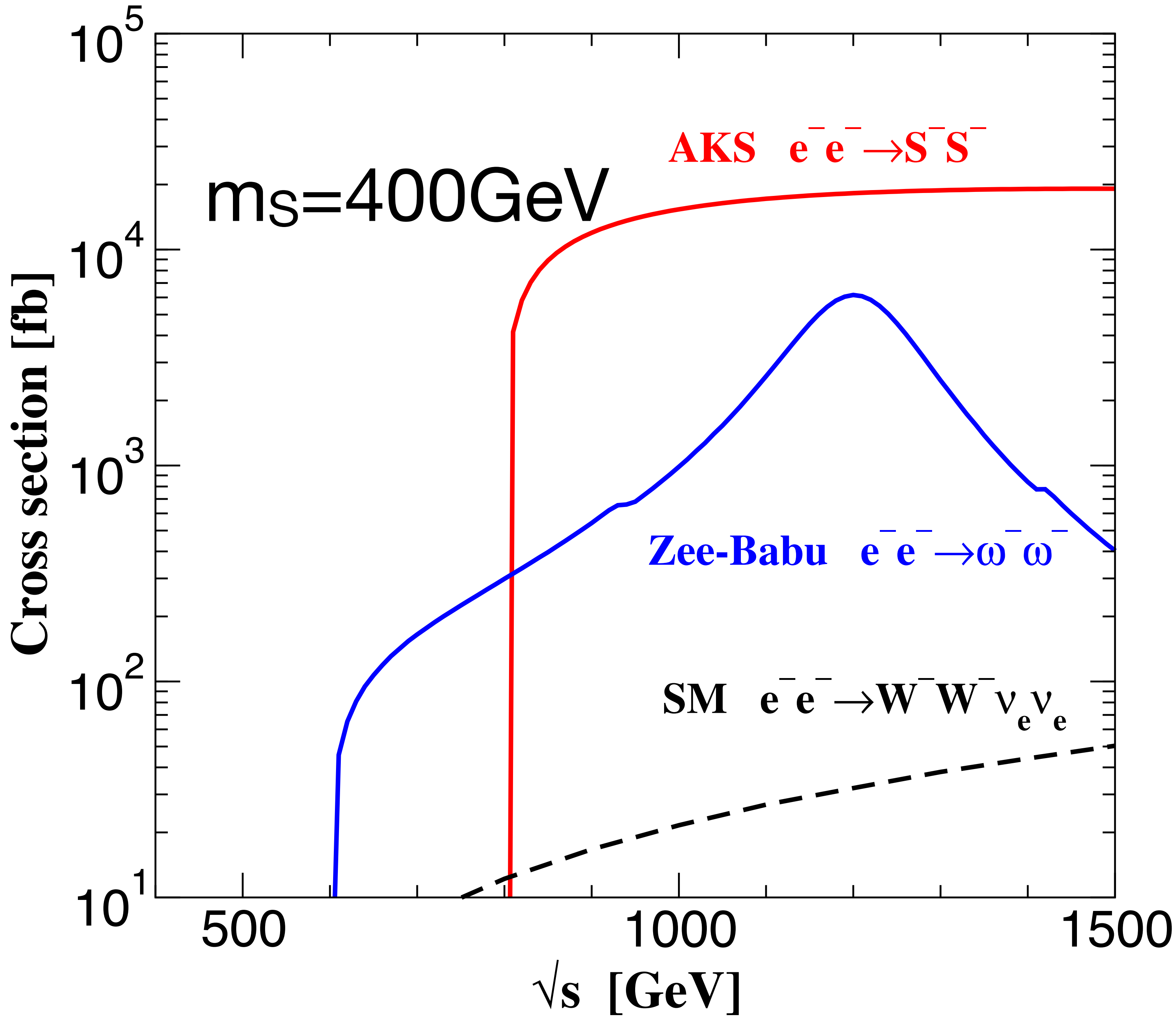


m_S=400GeV

A signal can be seen at the ILC@1TeV

Singlet like scalar @e⁻e⁻ collider

Aoki&Kanemura, PLB689,28.



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