UV Complete Model with a composite Higgs sector for Baryogenesis, DM, and neutrino masses

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

since 1887

10.07.2017 Bled 2017 workshop@Bled, Slovenia

In the physics group: 5 faculties (incl. me)

- 2 Particle theorists
- 1 ILC experimentalist
- 2 Astrophysicists (Theorist & ALMA)

Please visit us!

Introduction

Physics beyond the SM

The Higgs boson was discovered (2012)

&

Its properties are consistent with a SM Higgs boson

↓

$\boxed{\text{The SM seems to be established}}$

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)
- Some excess might be found (muon g-2, …)
- …

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- …

How to solve problems

Many ideas have been proposed in literature

- **BAU**
  Electroweak Baryogenesis, Leptogenesis …
- **m_ν**
  Seesaw mechanism, Radiative mass generation,
  Tiny VEV of extra Higgs, …
- **DM**
  Some new symmetry to protect DM decay, …

How to solve problems

A popular choice is

- **BAU**
  Electroweak Baryogenesis, Leptogenesis …
- **m_ν**
  Seesaw mechanism, Radiative mass generation, Tiny VEV of extra Higgs, …
- **DM**
  Some new symmetry to protect DM decay, …

Such a model can be embedded to traditional SUSY GUT scenarios

μ

SUSY GUT

MSSM+RHN

MSSM with R_p

How to solve problems

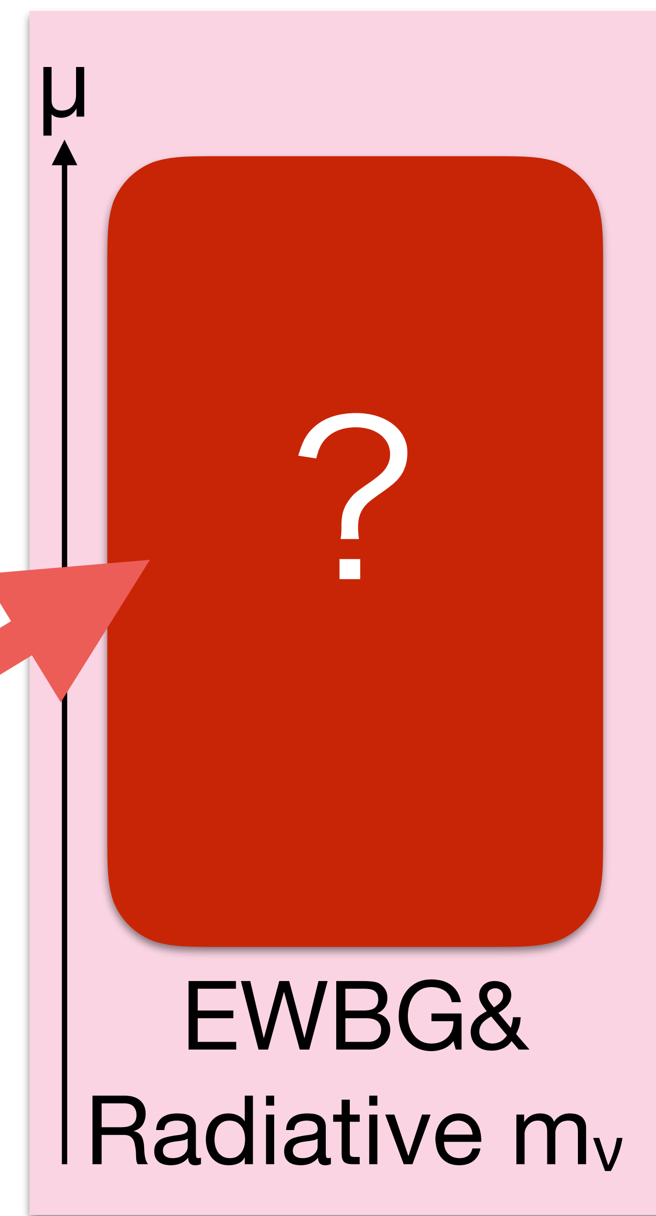
It is worth while considering TeV scale solutions

- **BAU**
  Electroweak Baryogenesis, Leptogenesis …

- **m_ν**
  Seesaw mechanism, Radiative mass generation, Tiny VEV of extra Higgs, …

- **DM**
  Some new symmetry to protect DM decay, …

What kind of fundamental theory will be there?

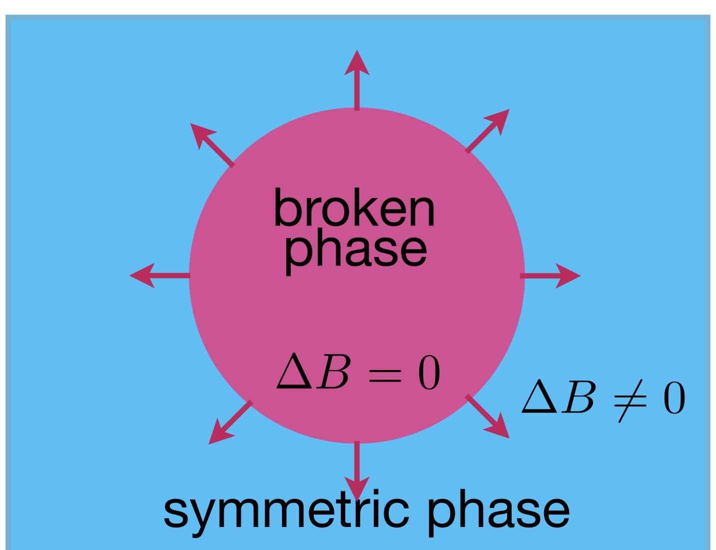


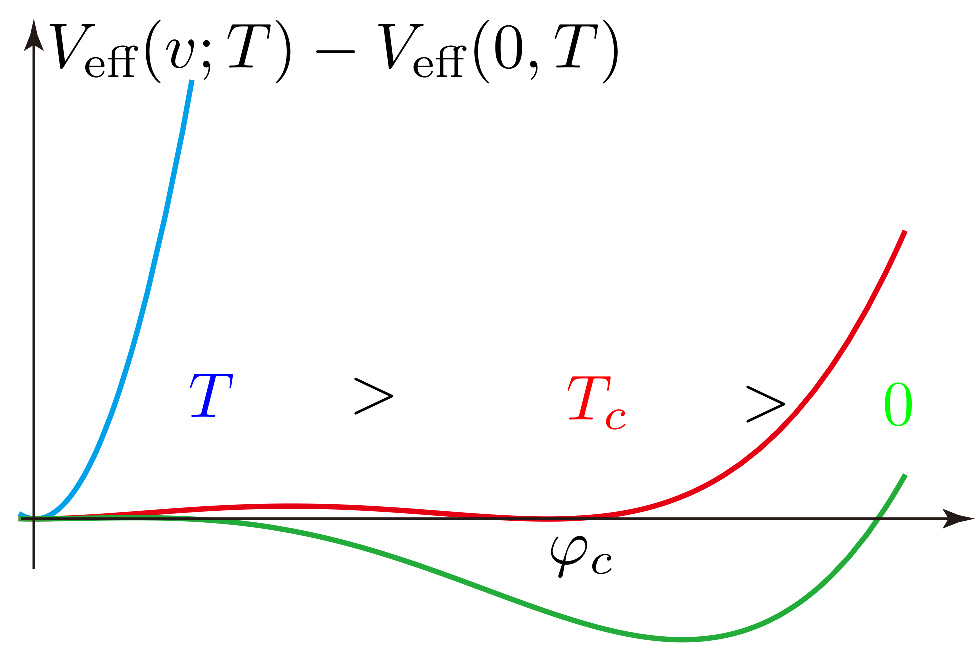
Electroweak Baryogenesis

Kuzmin, Rubakov, Shaposhnikov, PLB155,36

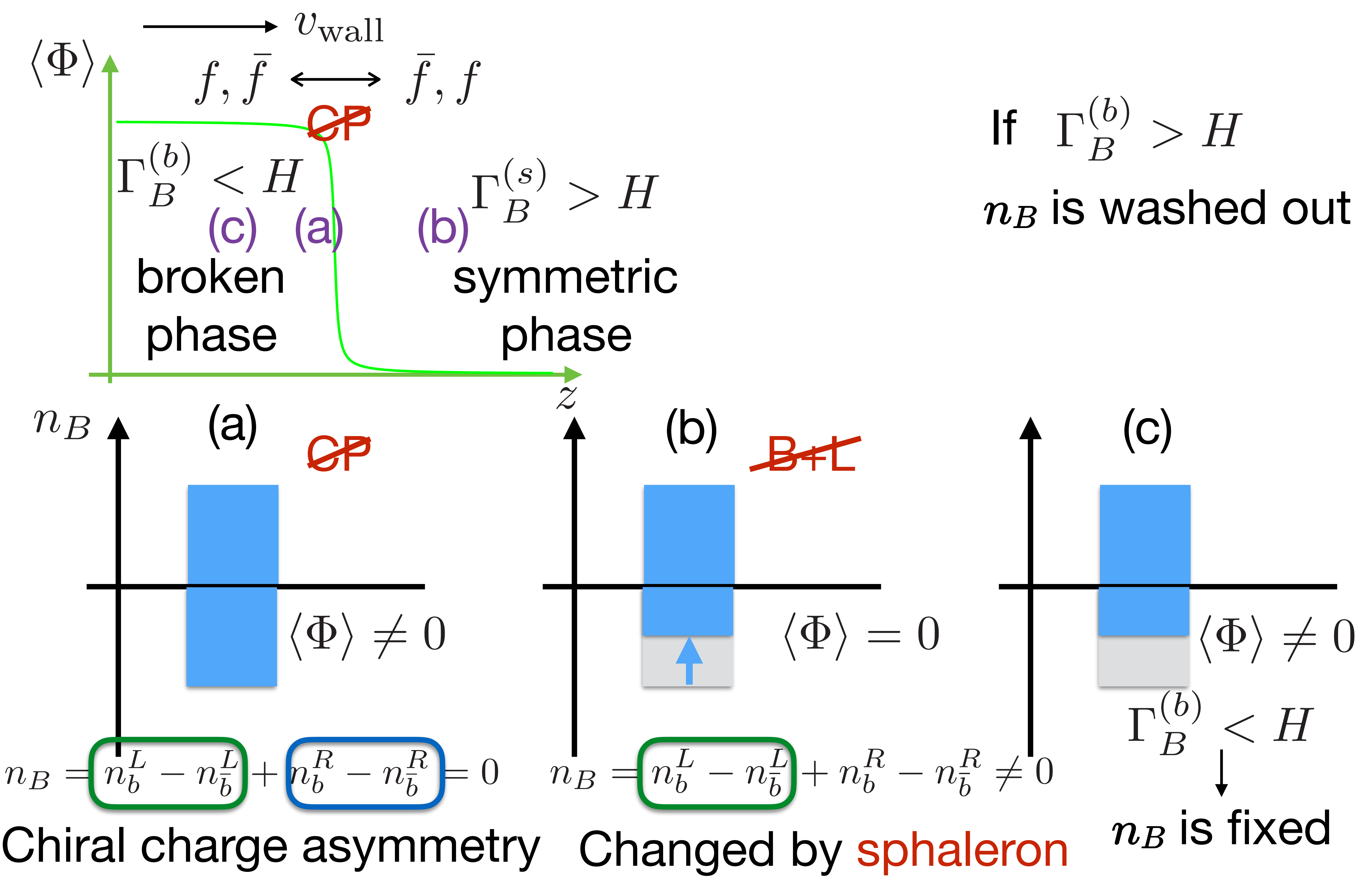
How to satisfy the Sakharov's conditions?

- **B violation** : Sphaleron process ($\cancel{B+L}$ but with B-L)
- **C violation** : Chiral gauge interaction
- **CP violation:** KM phase and other complex phases in the BSM
- **Out of equilibrium:** 1st order EWPT(electroweak phase transition) with expanding bubble walls





Mechanism of EWBG



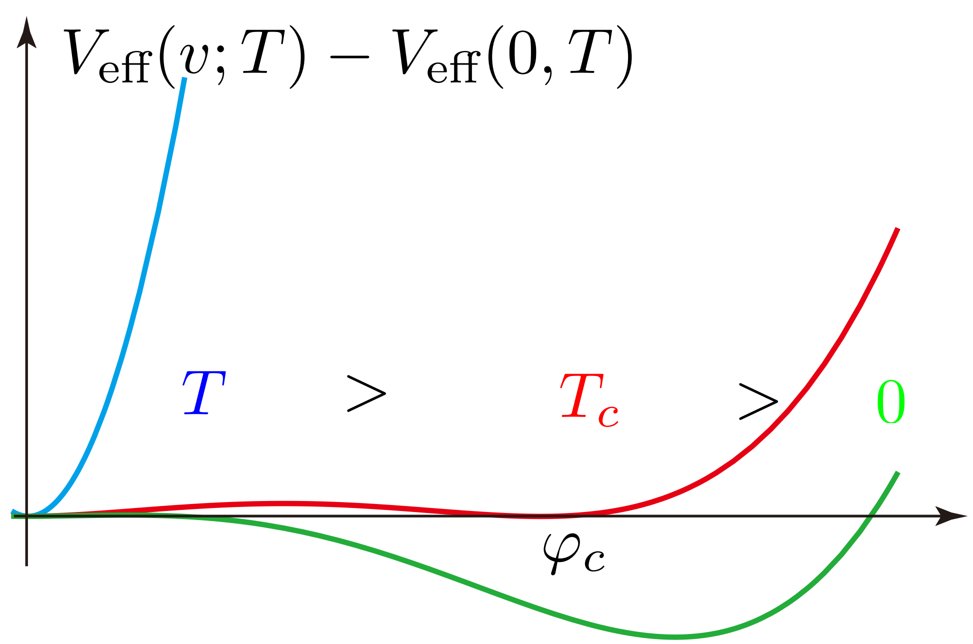
Strong 1st order EWPT

Strong 1st order EWPT is required
for the successful electroweak baryogenesis

$\Gamma_B^{(b)} < H$ is necessary to avoid washout

$$\Gamma_B^{(b)}(T) \simeq (\mathrm{prefactor})e^{-E_{\mathrm{sph}}/T} \qquad E_{\mathrm{sph}} \propto v(T)$$

We need large Higgs VEV after the EPWT



The condition can be roughly written as $\boxed{\phi_c/T_c>1}$

Electroweak Baryogenesis

Kuzmin, Rubakov, Shaposhnikov, PLB155,36

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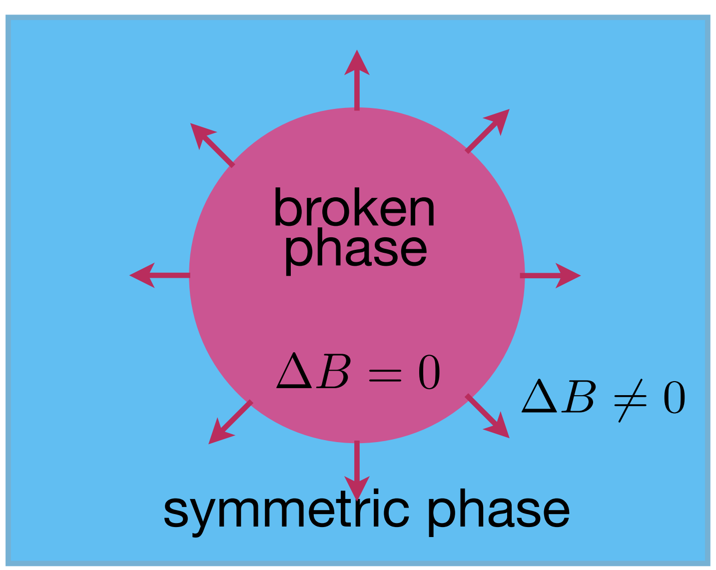


In this talk, we focus on the 1st order EWPT

EWPT 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

m_h=125GeV

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
- ...

To get strong 1st order EWPT

Strong 1st order EWPT requires extension of the SM

Extra boson loop can enhance ϕ_c/T_c

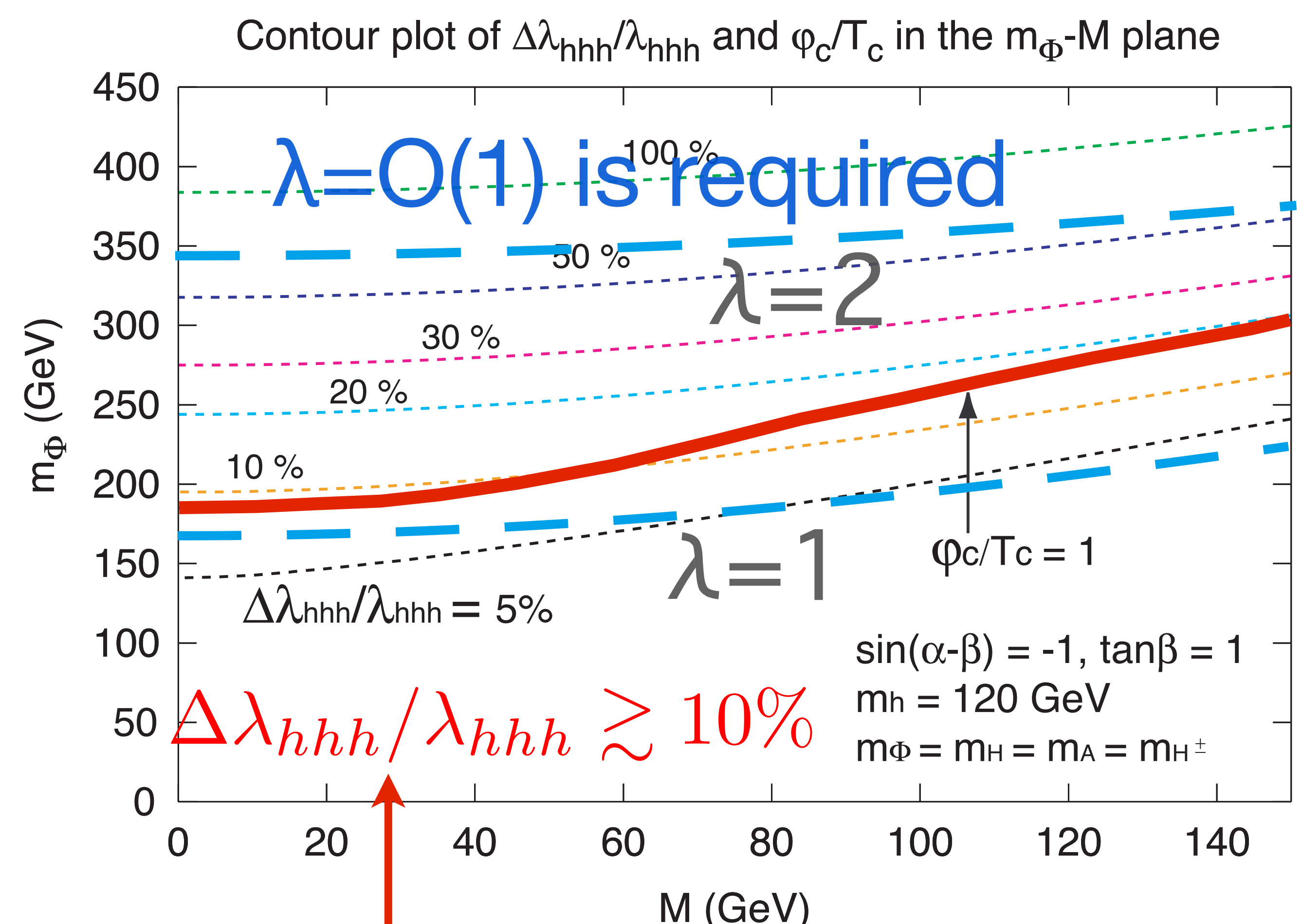
↓

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.

- The boson mass should be dominated by Higgs VEV
- Heavy mass (strong coupling with Higgs) is preferable

EWPT in the MSSM

Carena et al.,PLB380,81;⋯

Lighter stop loop can contribute

large top Yukawa coupling

enhance

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

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

where the maximal contribution case is considered;

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

For larger M_{TR}, the effect is smaller

Light stop is necessary $\longleftrightarrow$ $\left\{ \begin{array}{l} \text{No new coloured particles at LHC} \\ m_h\text{=125GeV} \end{array} \right.$

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

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

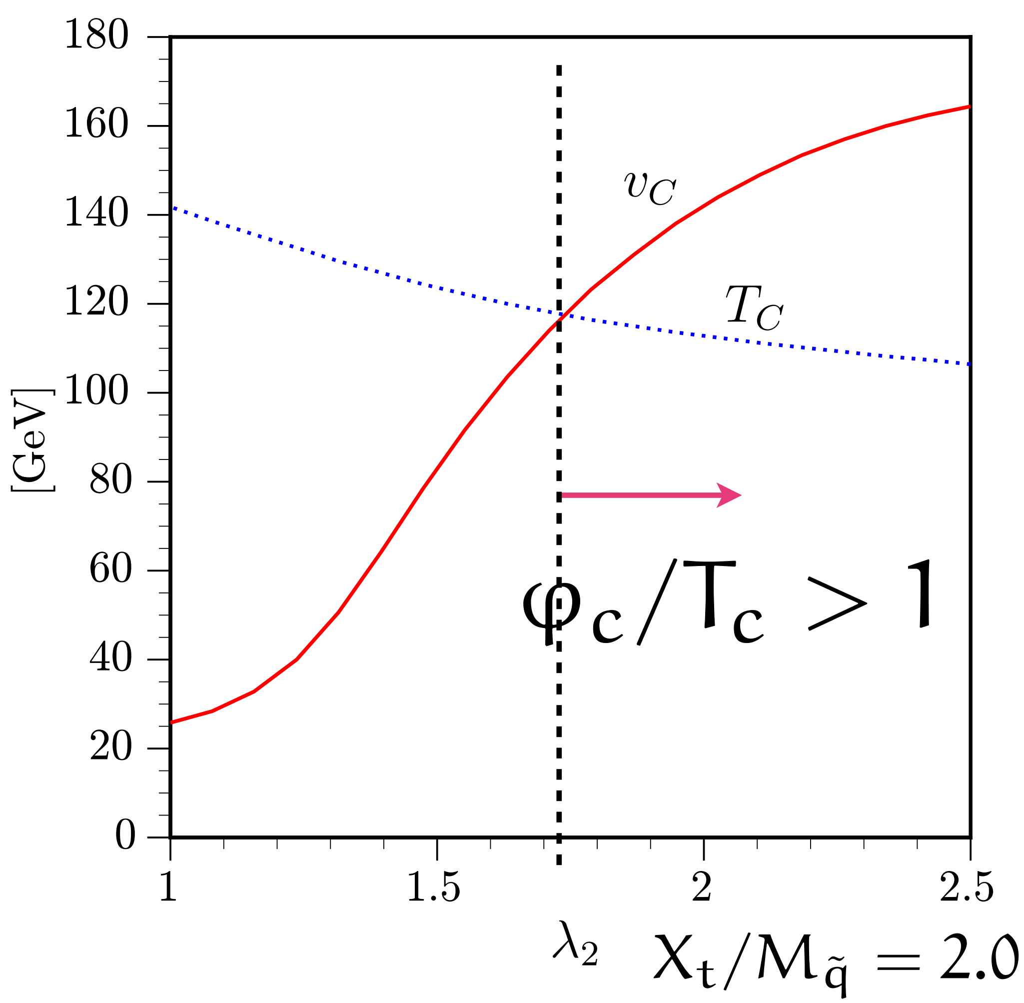
MSSM should be also modified at TeV scale for EWBG

SUSY Example for EWPT

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

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

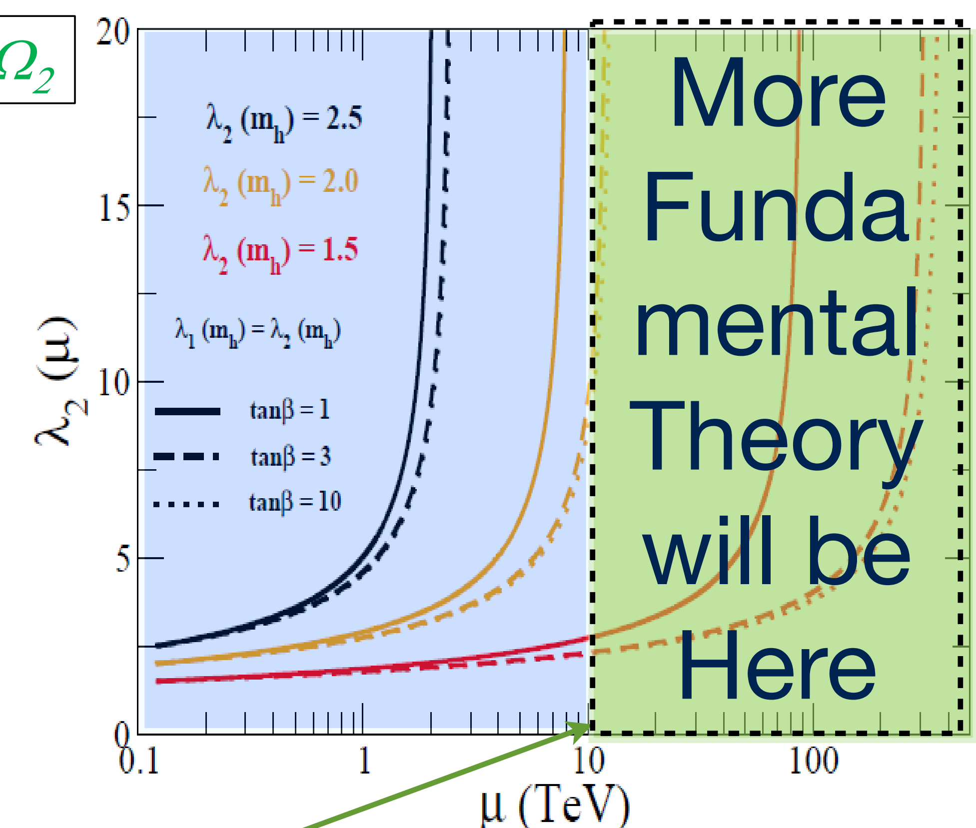
$$W = \boxed{\lambda_1 \Omega_1 H_1 \cdot H_3 + \lambda_2 \Omega_2 H_2 \cdot H_4} - \mu H_1 \cdot H_2 - \mu' H_3 \cdot H_4 - \mu_\Omega \Omega_1 \Omega_2$$



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

Tiny neutrino mass

The Majorana neutrino case

$$\frac{c_{ij}}{M}(\bar{\ell}^c_{Li}\cdot\Phi)(\ell_{Lj}\cdot\Phi)$$

$$\Downarrow$$

$$(m_\nu)_{ij}\bar{\nu}^c_i\bar{\nu}_j$$

For tiny neutrino mass,

- Large M

  or is necessary

- Small c

Seesaw model (SM+RN)

Heavy RN mass M gives strong suppression

$c_{ij} \sim 0.01^2$ & $M \sim 10^{10}\ \mathrm{GeV}$ $\longrightarrow$ $m_\nu \sim 0.1\ \mathrm{eV}$

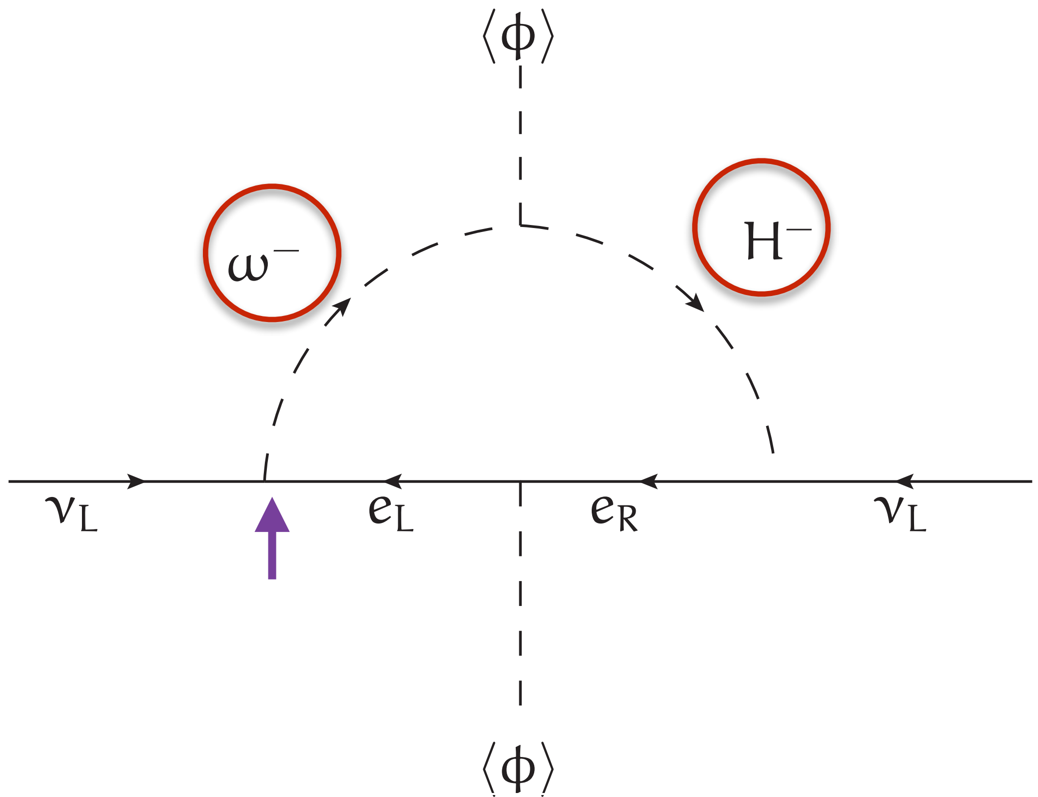
Loop induced case

n-loop contribution: $c_{ij} = \mathcal{O}\left(\frac{f^{2n}}{(16\pi^2)^n}\right)$

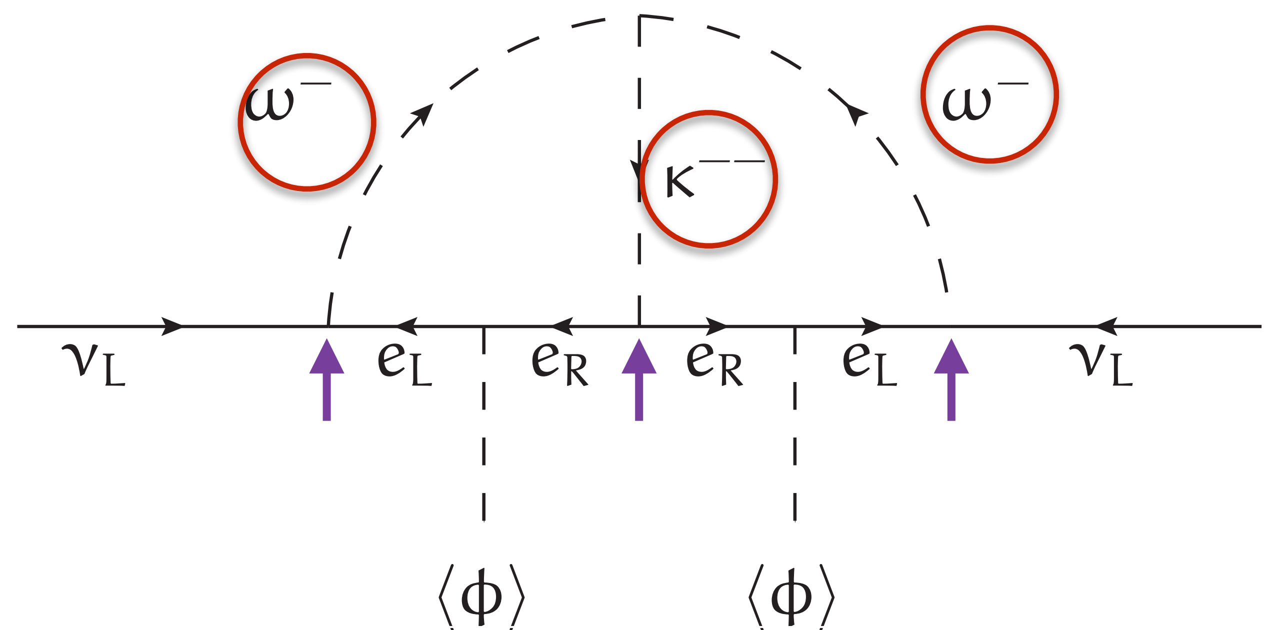
$f \sim 0.01$ & $M \sim 1\ \mathrm{TeV}$ & $n = 2$ $\longrightarrow$ $m_\nu \sim 0.1\ \mathrm{eV}$

Concrete examples

A.Zee, PLB93, 389; PLB161,141



A. Zee, NPB264,99; K.S. Babu, PLB203,132



New scalars are introduced

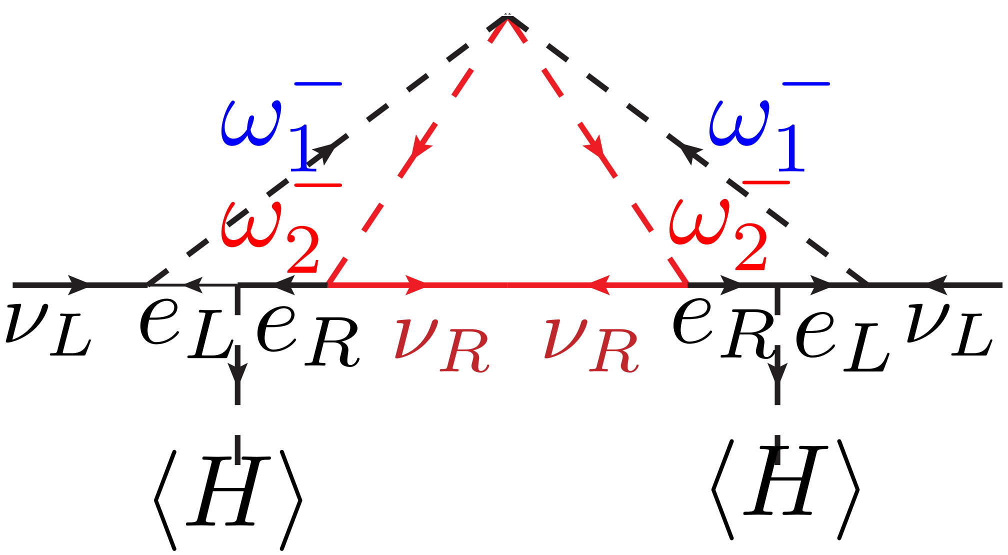
In these models, coupling violates the lepton number

Radiative Seesaw

Model with RHN provides DM candidate

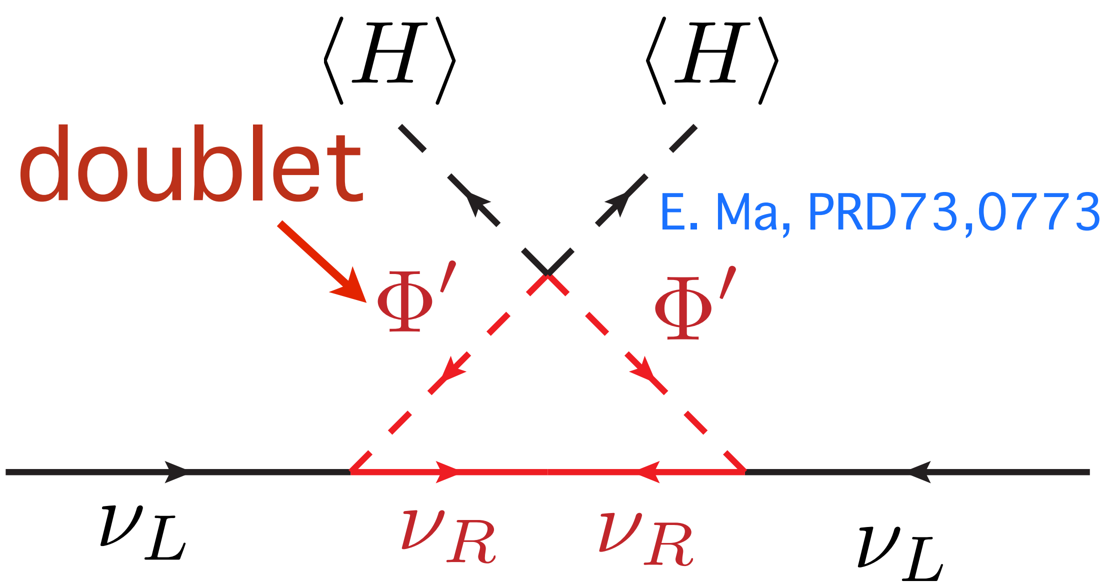
Z_2-odd ← To avoid tree level contribution

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

New scalars are introduced in this class of models

Can such extra scalars enhance the 1st order EWPT?

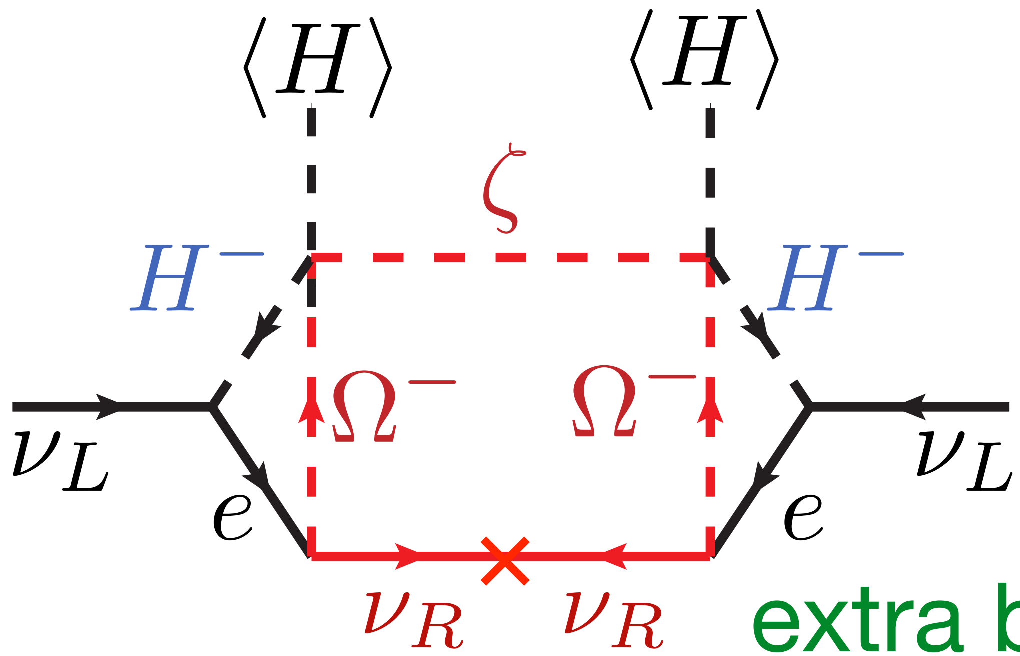
AKS model

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

$\longrightarrow$ neutrino mass

extra boson loop $\rightarrow$ strong 1st order EWPT

As a phenomenological model, this is quite interesting

But ...

Many extra scalars $\longrightarrow$ What is the origin of them?

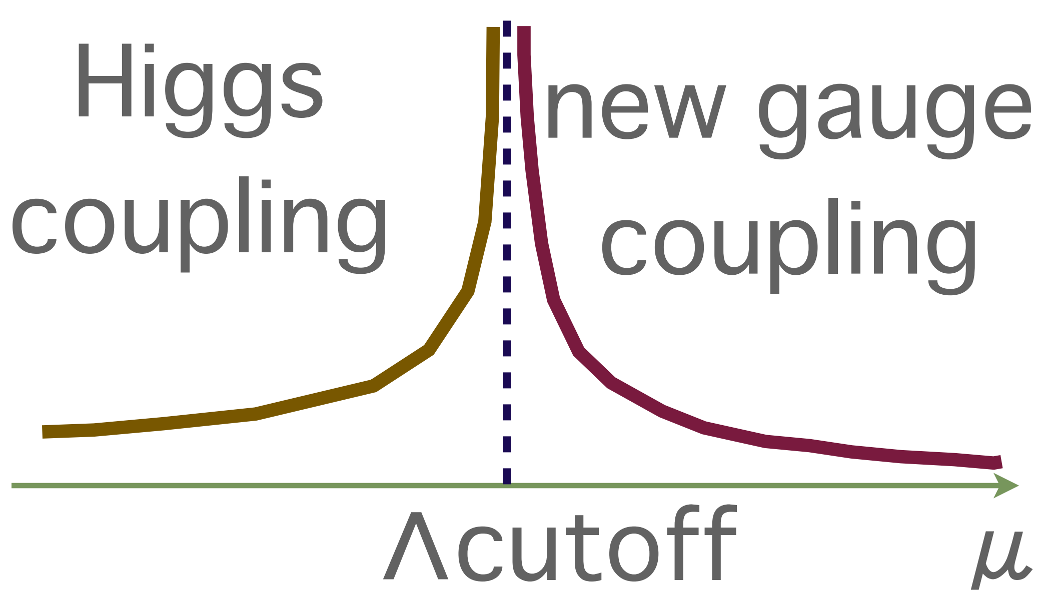
Large couplings $\longrightarrow$ Landau pole at low energy scale

The fundamental picture is different from GUT over grand desert

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 ?

Our expectation:



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

$SU(2)_H$ model

SUSY SU(2)$_H$ model

SUSY SU(N$_c$) : $\boxed{N_f = N_c + 1 \Rightarrow \text{confinement}}$ 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!

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	$-1/2$

nMSSM-like

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

Higgs sector of the effective theory

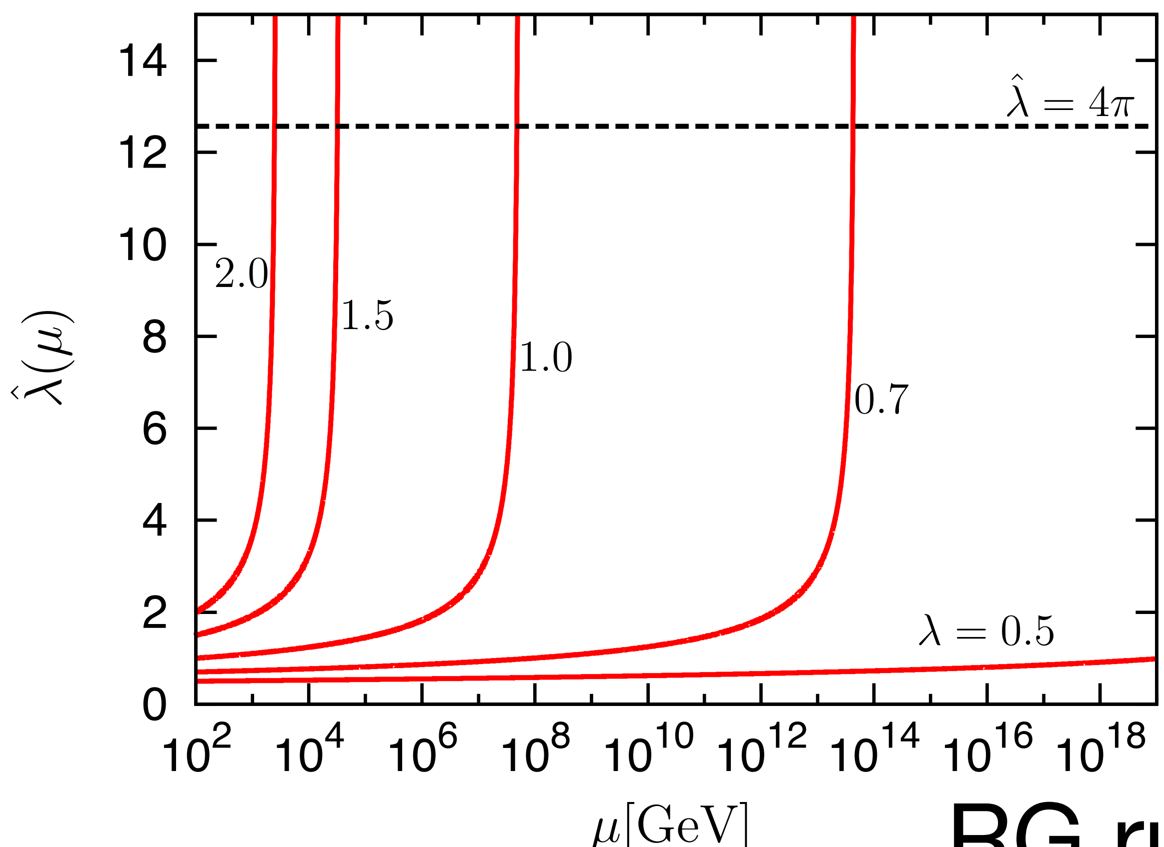
S.Kanemura,E. Senaha, T.S,T.Yamada,JHEP1305,066

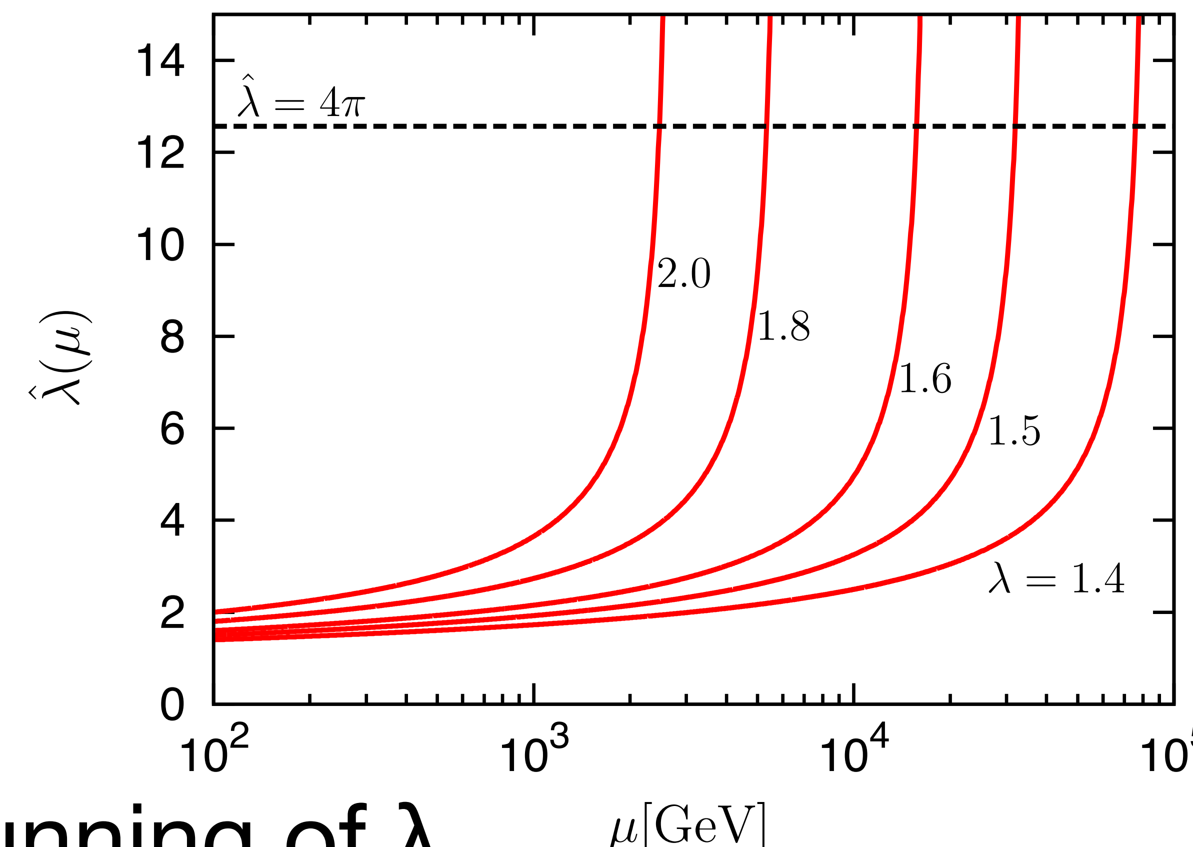
$\lambda\langle n\rangle$

MSSM-like Higgs doublets

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

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





RG running of λ

1st order EWPT

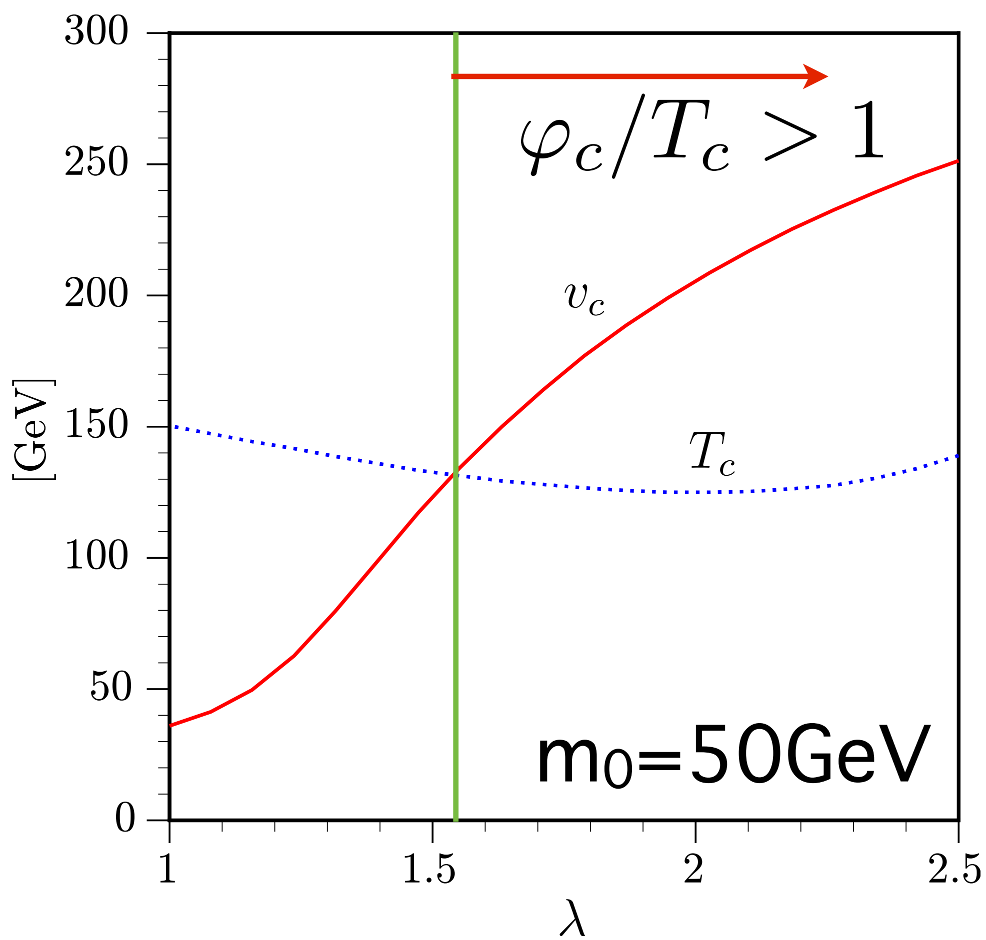
Benchmark:

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

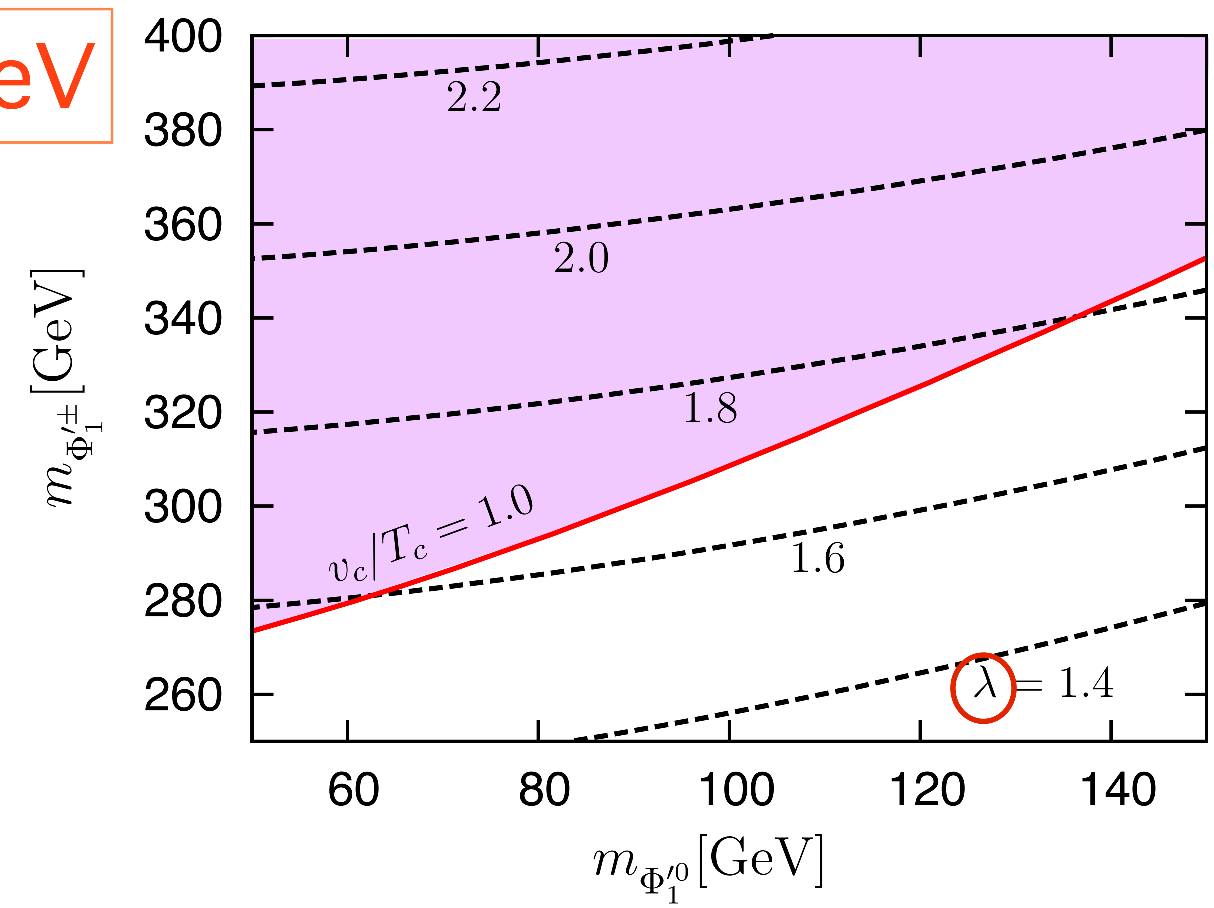
$\tan\beta = 15, m_{H^+} = 350\text{GeV}, \mu = 200\text{GeV}, M_{\tilde{t}} = M_{\tilde{q}} = 2000\text{GeV}$

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

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



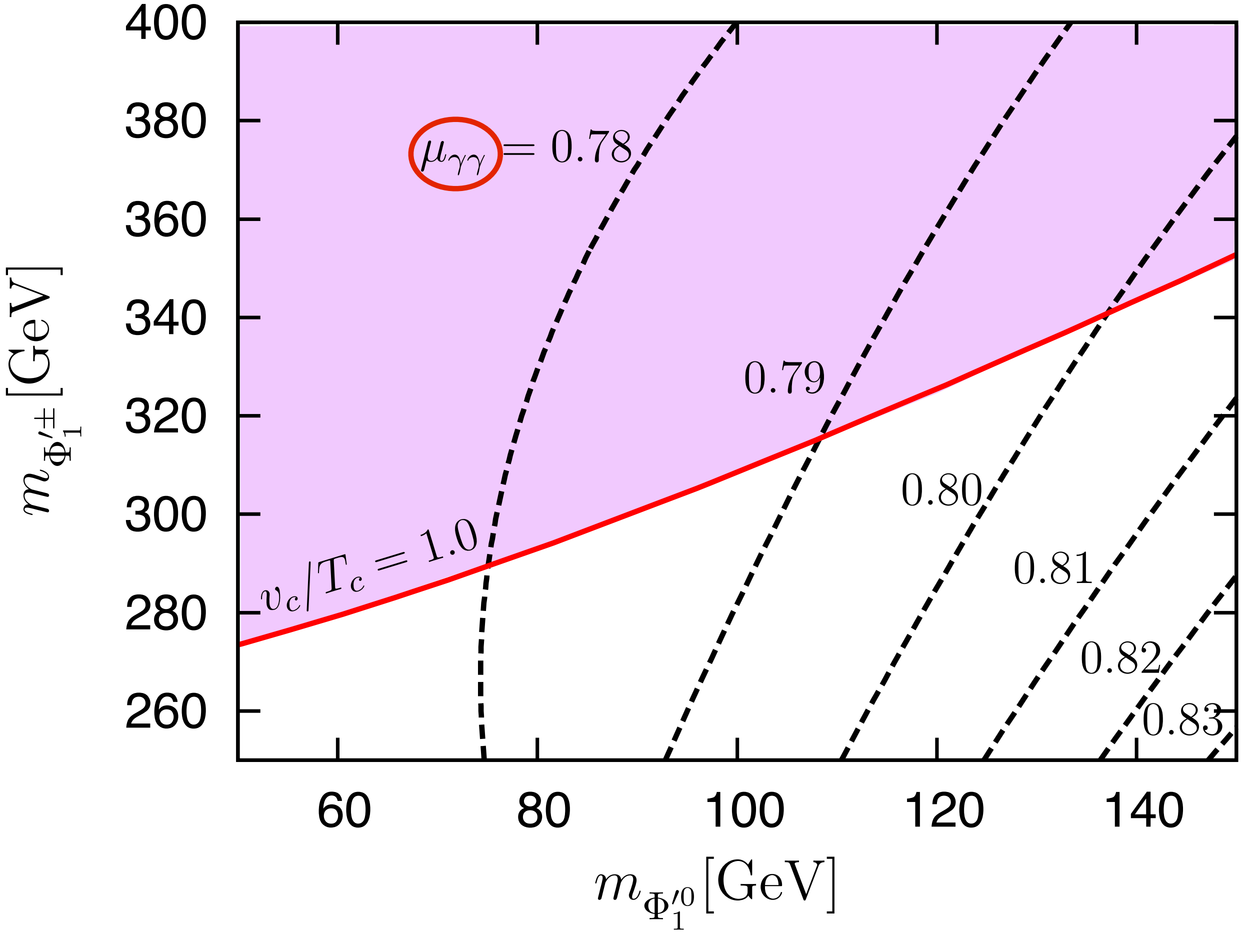
m_h=126GeV

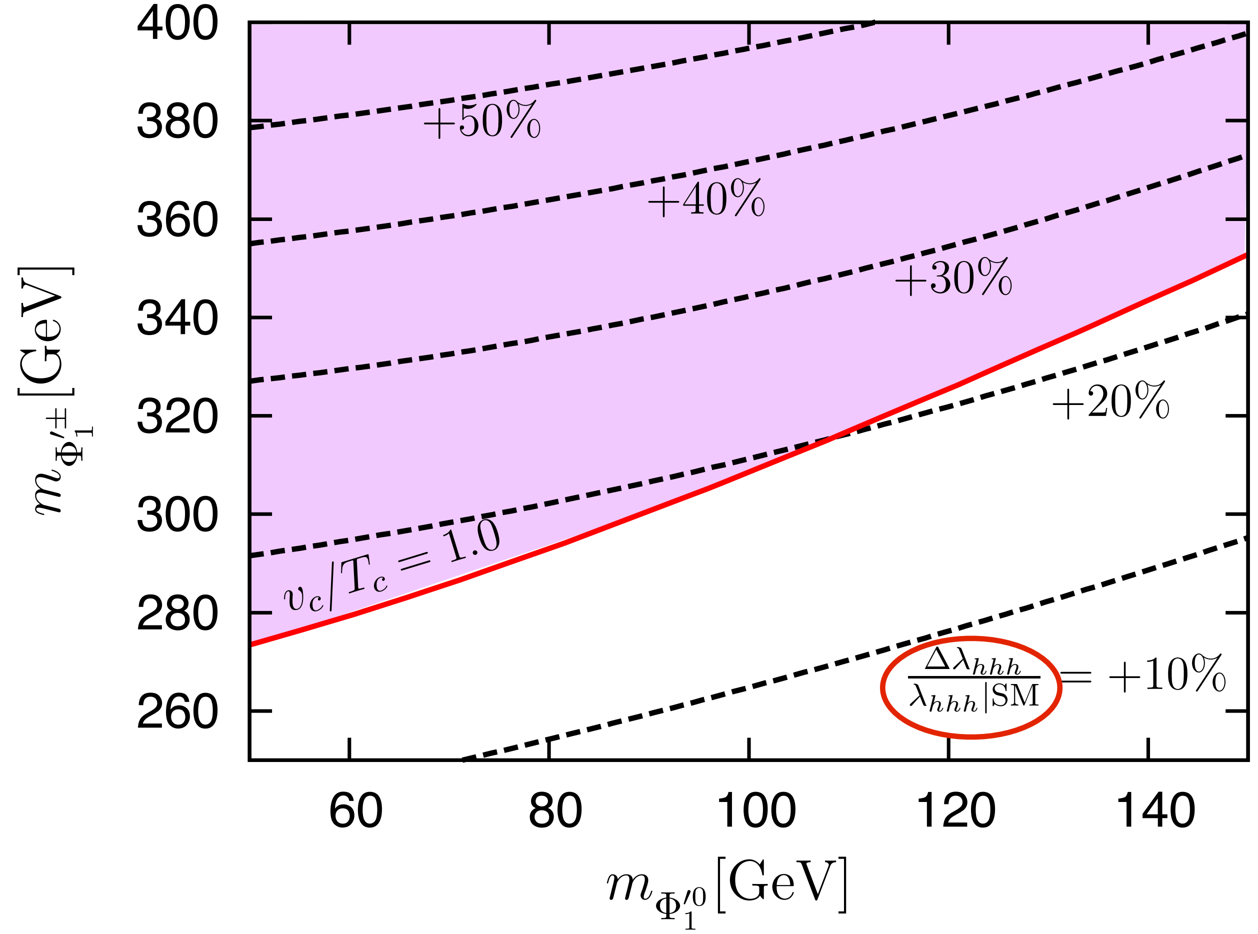


$\varphi_c/T_c > 1$ can be satisfied!! → $\varphi_c/T_c > 1 \Longrightarrow \lambda \gtrsim 1.5 \quad (\Lambda_H \lesssim 20\text{TeV})$

1st order EWPT

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





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

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

~20% smaller than the SM prediction in the region of $v_c/T_c>1$

more than 20% deviation from the SM prediction

RHN is introduced

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

We will introduce a Z_2 symmetry (unbroken)

nMSSM-like

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	$+1/2$	+
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$N = H_{56}, N_\Phi = H_{34}, N_\Omega = H_{12}$	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,

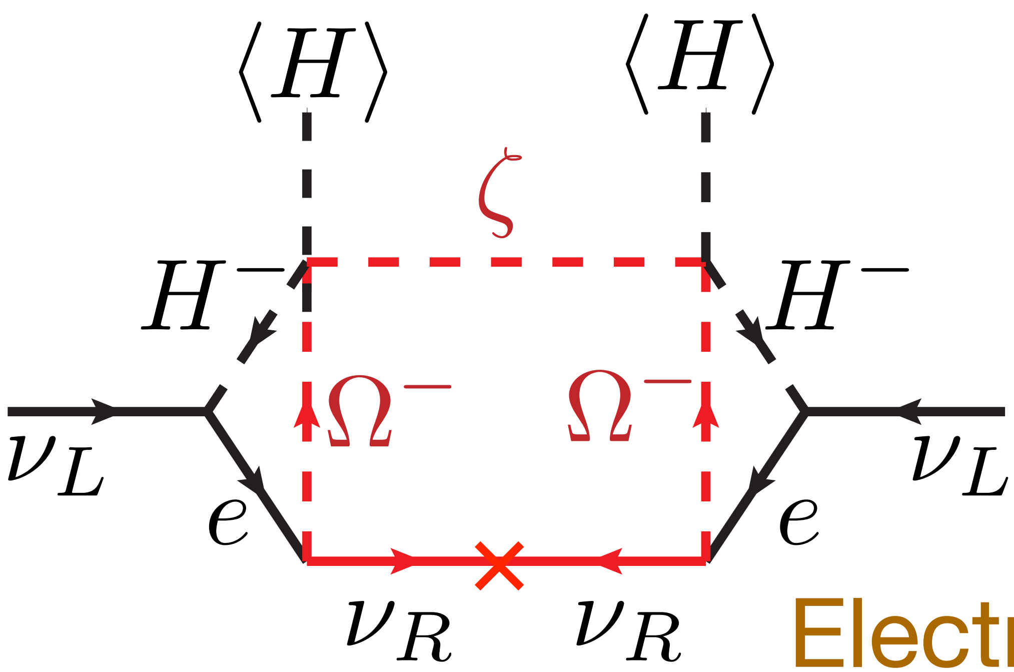
$$W_N = (y_N)_i N_i^c L_j \Phi_u + (h_N)_{ij} N_i^c E_j^c \Omega^- + \frac{M_i}{2} N_i^c N_i^c$$

Fields in radiative seesaw model

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

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

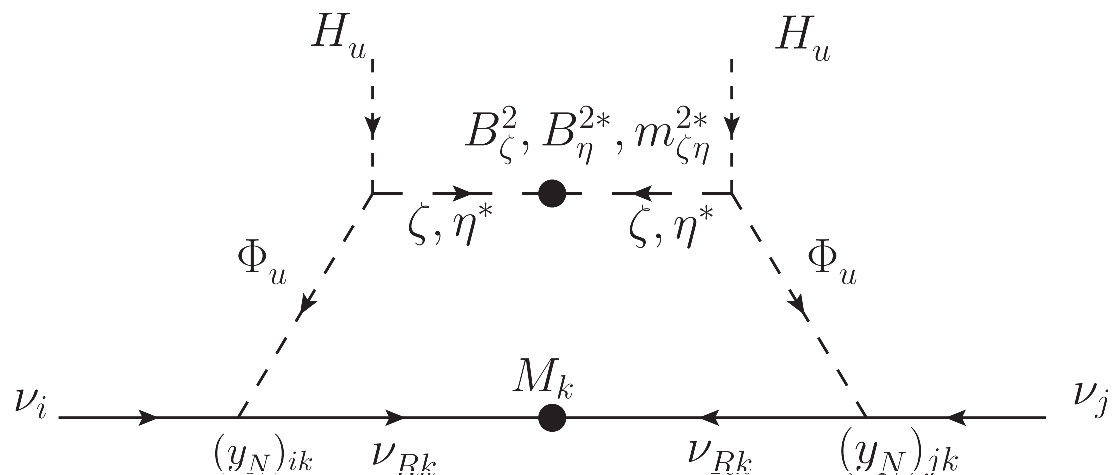
SU(2)$_H$ model automatically provides all the fields in the Higgs sector!!

Neutrino Mass Generation

S.Kanemura, N. Machida, T.S, T.Yamada,PRD89,013005,
S. Kanemura, N. Machida, T.S., PLB738, 178

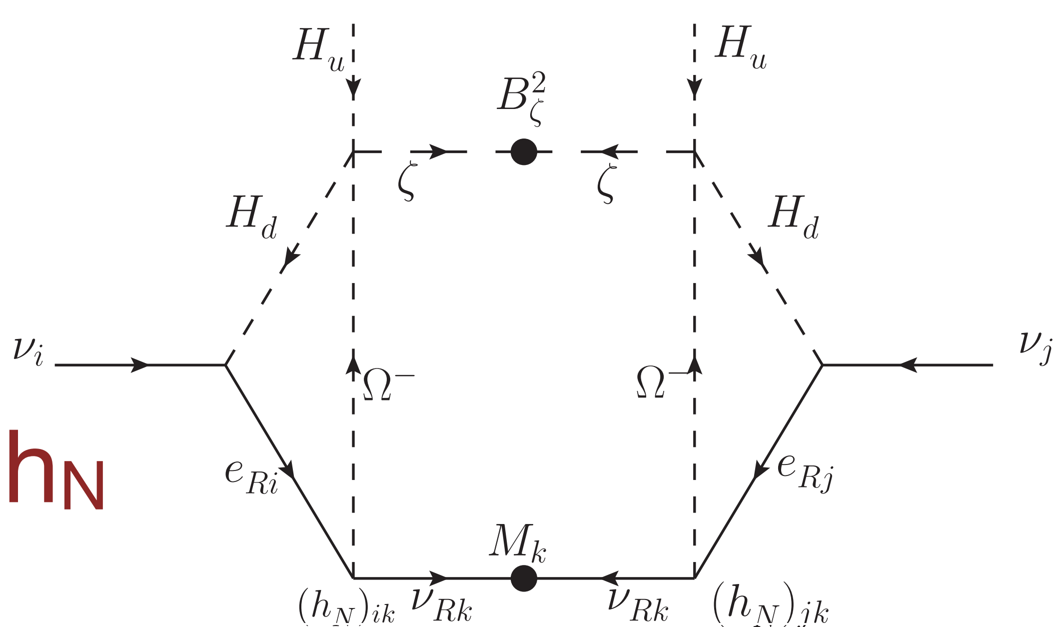
$$W_N = (y_N)_i N_i^c L_j \Phi_u + (h_N)_{ij} N_i^c E_j^c \Omega^- + \frac{M_i}{2} N_i^c N_i^c$$

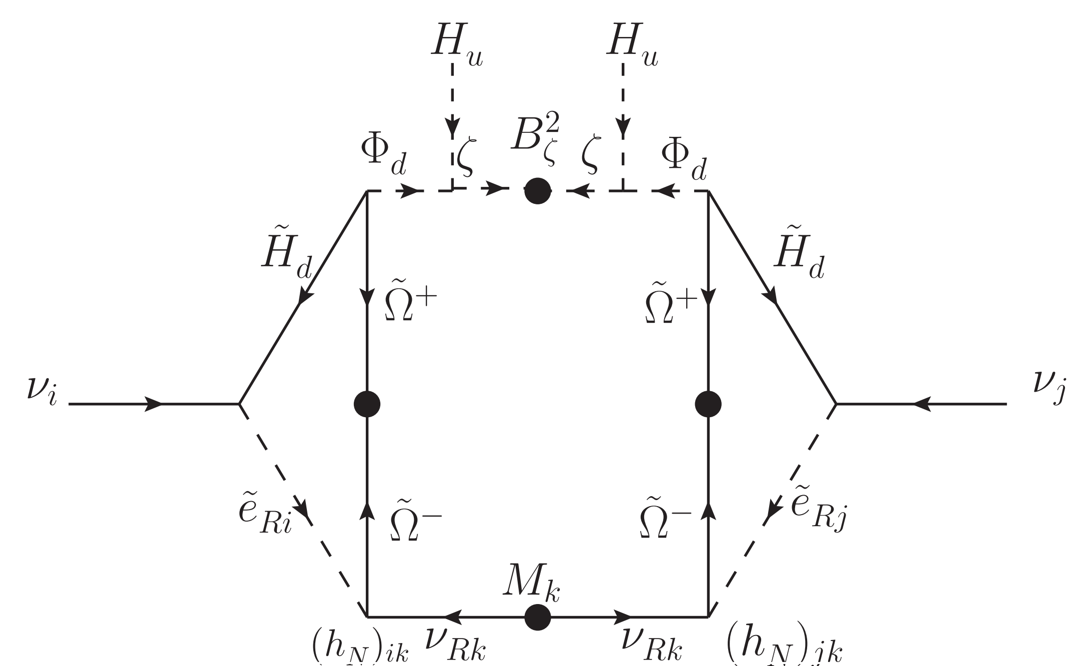
1-loop
driven by y_N



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

There are two different types of contributions

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

For example,

1-loop contribution $\cdots\cdots\cdots\cdots\blacktriangleright$ $m_2^2 - m_1^2$ (solar)

3-loop contribution $\cdots\cdots\cdots\cdots\blacktriangleright$ $m_3^2 - m_2^2$ (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

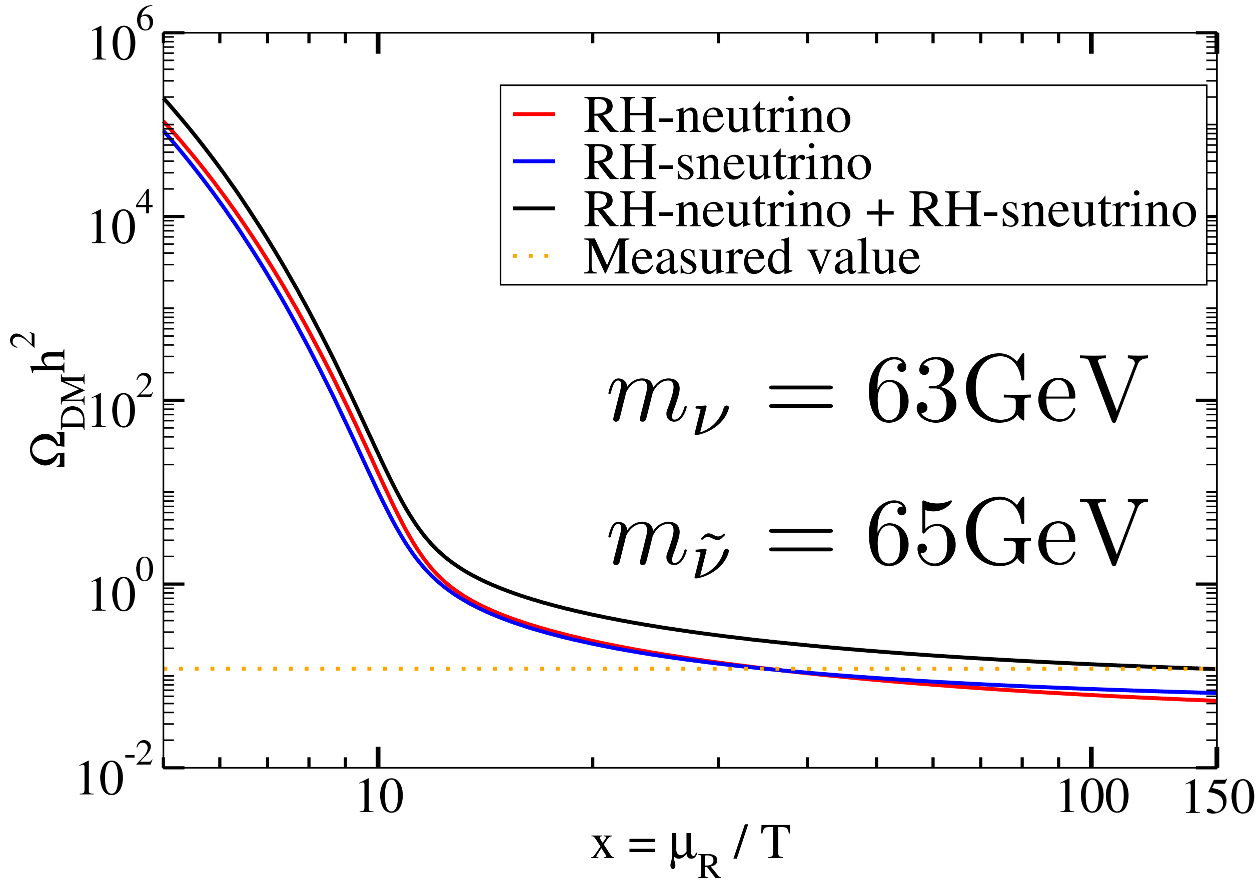
$\nu + \nu \to \mathrm{SM} + \mathrm{SM}$ $\quad \tilde{\nu} + \tilde{\nu} \to \mathrm{SM} + \mathrm{SM}$ $\quad \tilde{\nu} + \tilde{\nu} \leftrightarrow \nu + \nu$

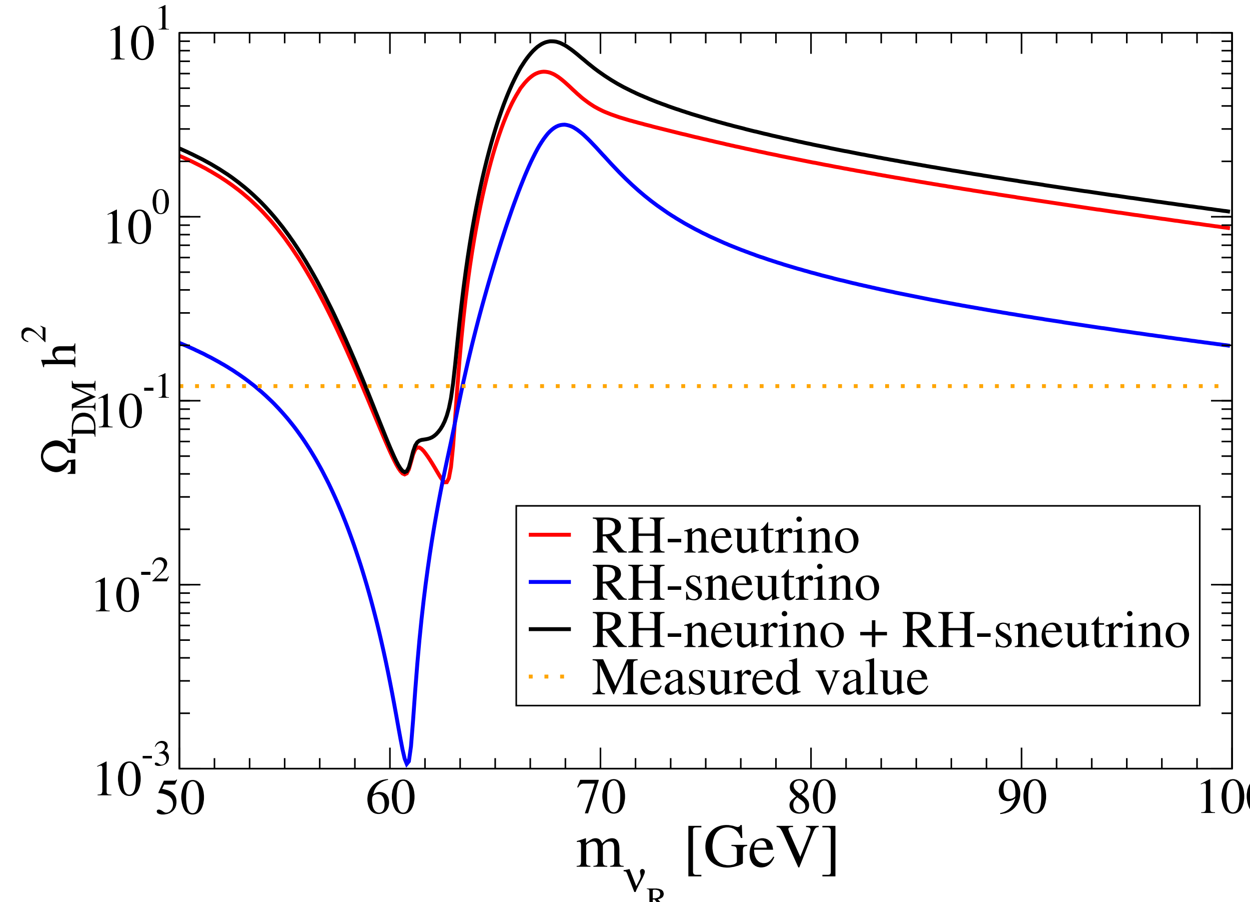
conversion process

As for the DM, multi-component DM scenario is realized

Dark Matter

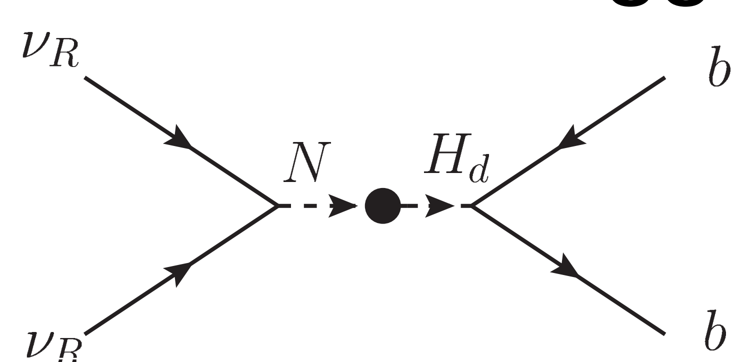
S. Kanemura, N. Machida, T.S., PLB738, 178





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

It's a kind of extended 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
$\varphi_c/T_c = 1.3 \quad \lambda_{hhh}/\lambda_{hhh}\vert_{\rm SM} = 1.2 \quad {\rm B}(h \to \gamma\gamma)/{\rm B}(h \to \gamma\gamma)\vert_{\rm SM} = 0.78$
Neutrino masses and the mixing angles
$(m_1, m_2, m_3) = (0, 0.0084\text{ eV}, 0.0050\text{ eV}) \quad \sin^2\theta_{12} = 0.32 \quad \sin^2\theta_{23} = 0.50 \quad \vert\sin\theta_{13}\vert = 0.14$
LFV processes
${\rm B}(\mu \to e\gamma) = 3.6 \times 10^{-13} \quad {\rm B}(\mu \to eee) = 5.6 \times 10^{-16}$
Relic abundance of the DM
$\Omega_{\nu_R}h^2 = 0.055 \quad \Omega_{\tilde{\nu}_R}h^2 = 0.065 \quad \Omega_{\rm DM}h^2 = \Omega_{\nu_R}h^2 + \Omega_{\tilde{\nu}_R}h^2 = 0.12$
Spin-independent DM-proton scattering cross sections
$\sigma^{\rm SI}_{\nu_R} = 3.1 \times 10^{-46}\text{ cm}^2 \quad \sigma^{\rm SI}_{\tilde{\nu}_R} = 7.7 \times 10^{-47}\text{ cm}^2 \quad \sigma^{\rm SI}_{\rm DM} = 1.1 \times 10^{-46}\text{ cm}^2$

EWPT

Neutrino mass&mixing

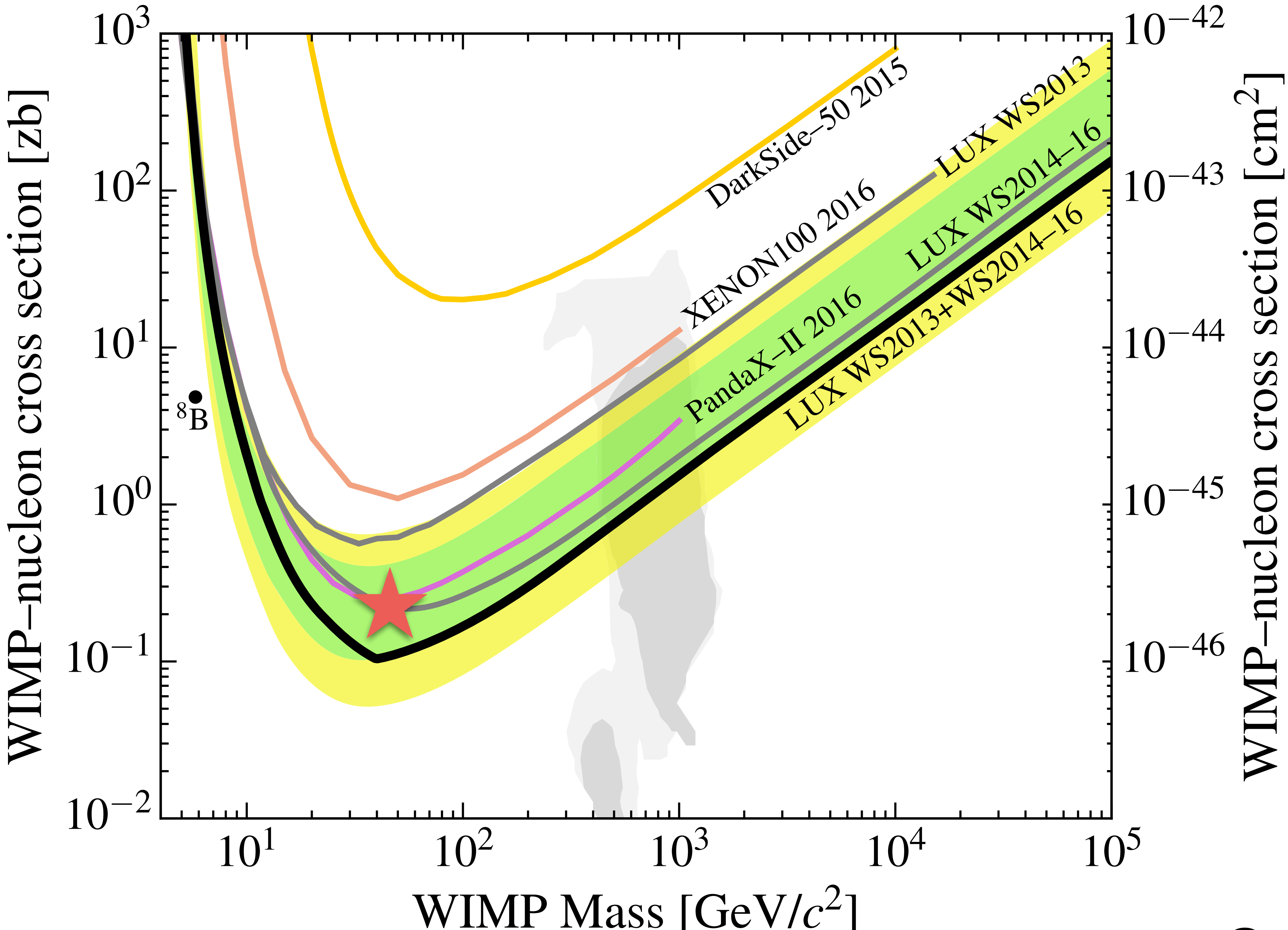
LFV

Relic abundance of DM

Direct detection of DM

New constraint from LUX

LUX, Phys.Rev.Lett. 118 (2017), 021303

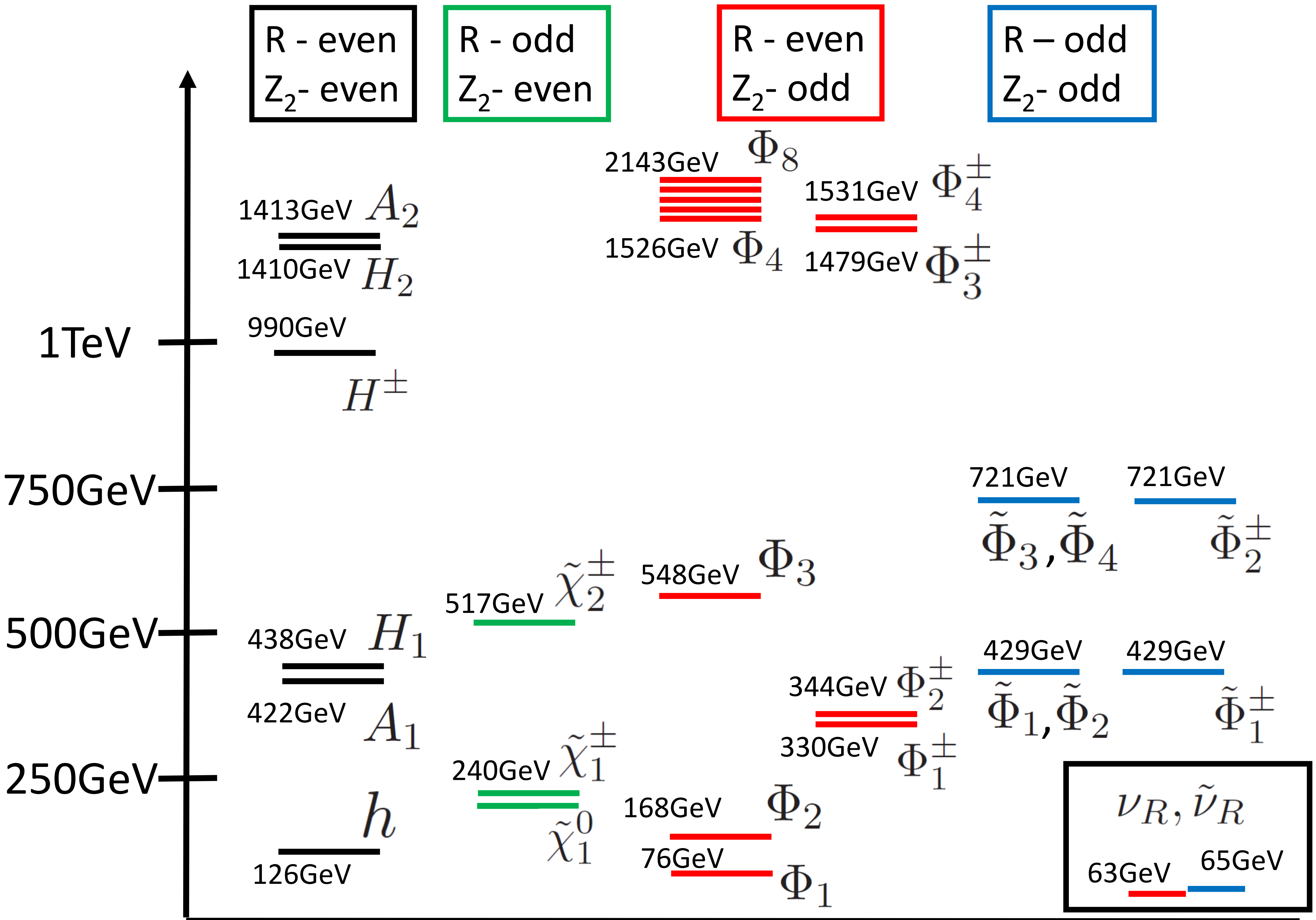


Oct. 2016

Comments on collider phenomenology

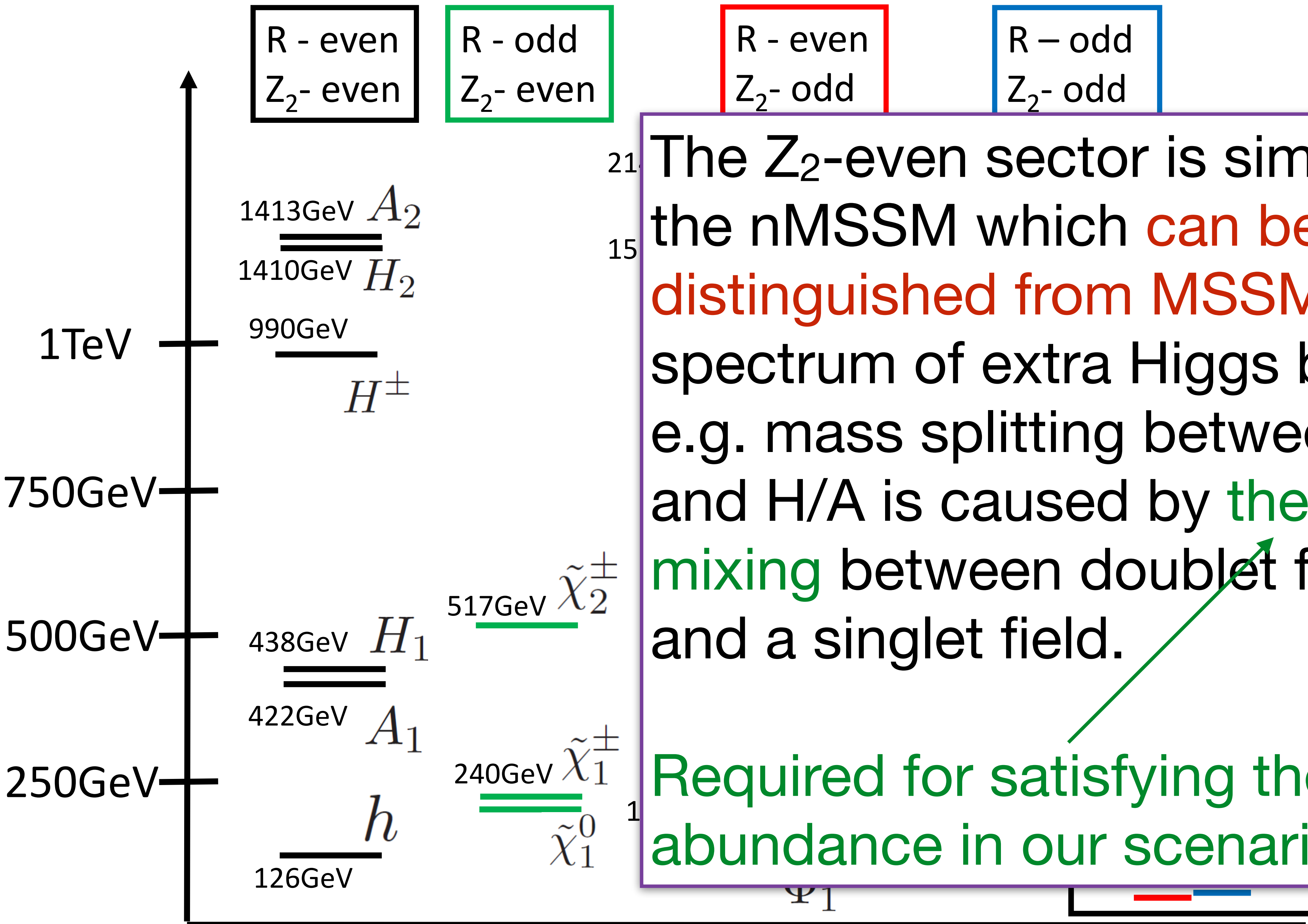
Spectrum at Benchmark point

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

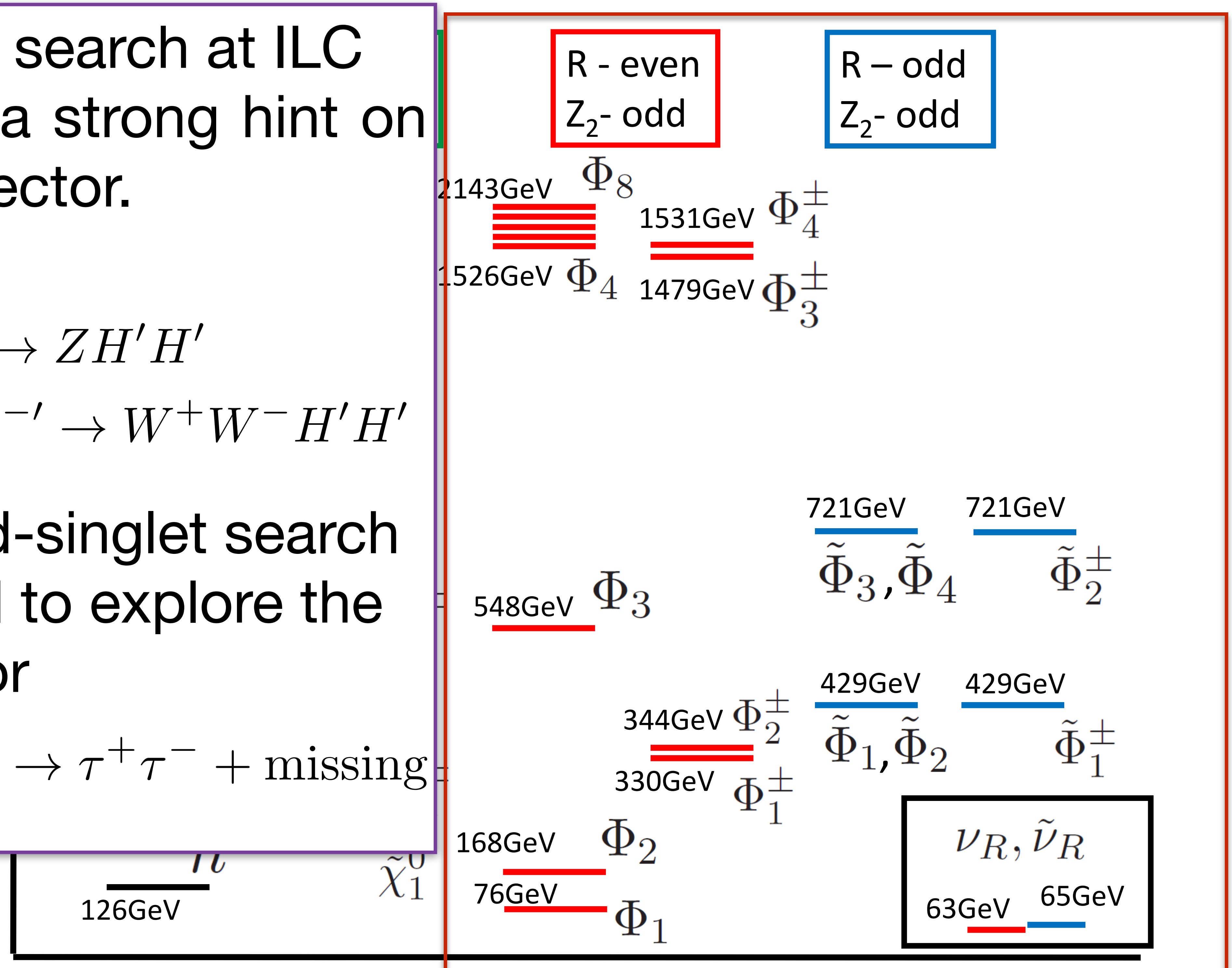
Inert doublet search at ILC can provide a strong hint on the Z_2 odd sector.
e.g.

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

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

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!!

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.

Summary

- We have considered a set of solutions to three problems in SM, Electroweak Baryogengesis (1st order EWPT), Radiative neutrino mass, and Dark Matter

- We succeeded to provide a candidate of fundamental theory of such models: SUSY $SU(2)_H$ with RHN

We should look for a new benchmark point…

- The fundamental picture is quite different from the GUT over the grand desert

Not yet considered

- New benchmark point which satisfies a DD of DM.
- Baryogenesis: We here considered only EWPT
  - CP phases $\longleftrightarrow$ EDM constraints
- Mediation mechanism of SUSY breaking
- GUT?
  - Can this model be embedded into some kind of GUT?
- Another concrete models?
  - e.g. How about $SU(3)_H$ instead of $SU(2)_H$ or a non-SUSY model
- Origin of the Yukawa couplings?

Back up

1-loop effective potential

$$V_{\text{eff}} + V_0(\varphi) + \Delta_g V(\varphi) + \Delta_t(\varphi) + \Delta V(\varphi, T) + V_{\text{c.t.}}$$

Tree:

$$V_0(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4$$

1-loop at T=0:

$$\Delta_g V_(\varphi) = 2 \cdot 3F(m_W^2(\varphi)) + 3F(m_Z^2(\varphi))$$

$$\Delta_t V_(\varphi) = -4 \cdot 3F(m_t(\varphi)) \qquad F(m^2(\varphi)) = \frac{m^4(\varphi)}{64\pi^2}\left(\ln\frac{m^2(\varphi)}{M_{\text{ren}}^2} - \frac{3}{2}\right)$$

1-loop at T≠0:

$$\Delta V(\varphi, T) = \frac{T^4}{2\pi^2}\left[\sum_{i=W,Z} n_i I_B(a_i^2) + n_t I_F(a_t^2)\right]$$

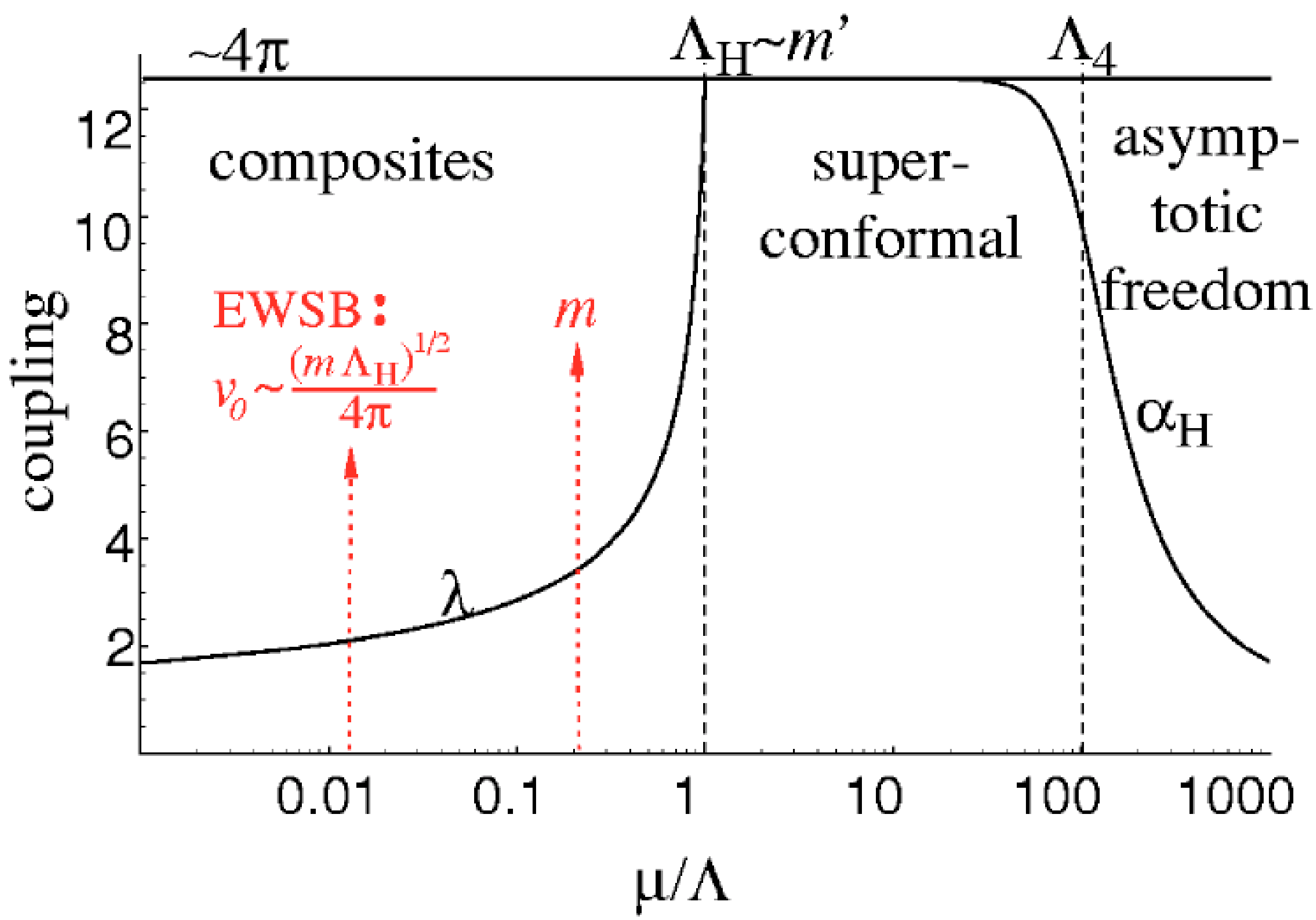
$$I_{B,F}(a^2) = \int_0^\infty dx x^2 \ln\left(1 \mp e^{-\sqrt{x^2+a^2}}\right) \qquad a^2 = \frac{m^2(\varphi)}{T^2}$$

Top Yukawa coupling

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

Introducing two extra doublets $W = m' T^7 T^8$

The theory is in the superconformal window.



Top Yukawa coupling

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

Introducing several new fields

$$W_f = M_f(\varphi_u\bar{\varphi}_u + \bar{\varphi}_d\varphi_d) + \bar{\varphi}_d T T_4 + \bar{\varphi}_u T T_3 \qquad T = \begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$$
$$+ h_u^{ij} Q_i u_j \varphi_u + h_d^{ij} Q_i d_j \varphi_d + h_e^{ij} L_i e_j \varphi_d$$

conformal enhancement

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

$\varphi_{u,d}, \bar{\varphi}_{u,d}$: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

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

$$W = h_u^{ij} Q_i u_j H_u + h_d^{ij} Q_i d_j H_d + h_e^{ij} L_i e_j H_d \qquad \text{for } M_f \sim \Lambda_H$$

Sensitivity for finger printing

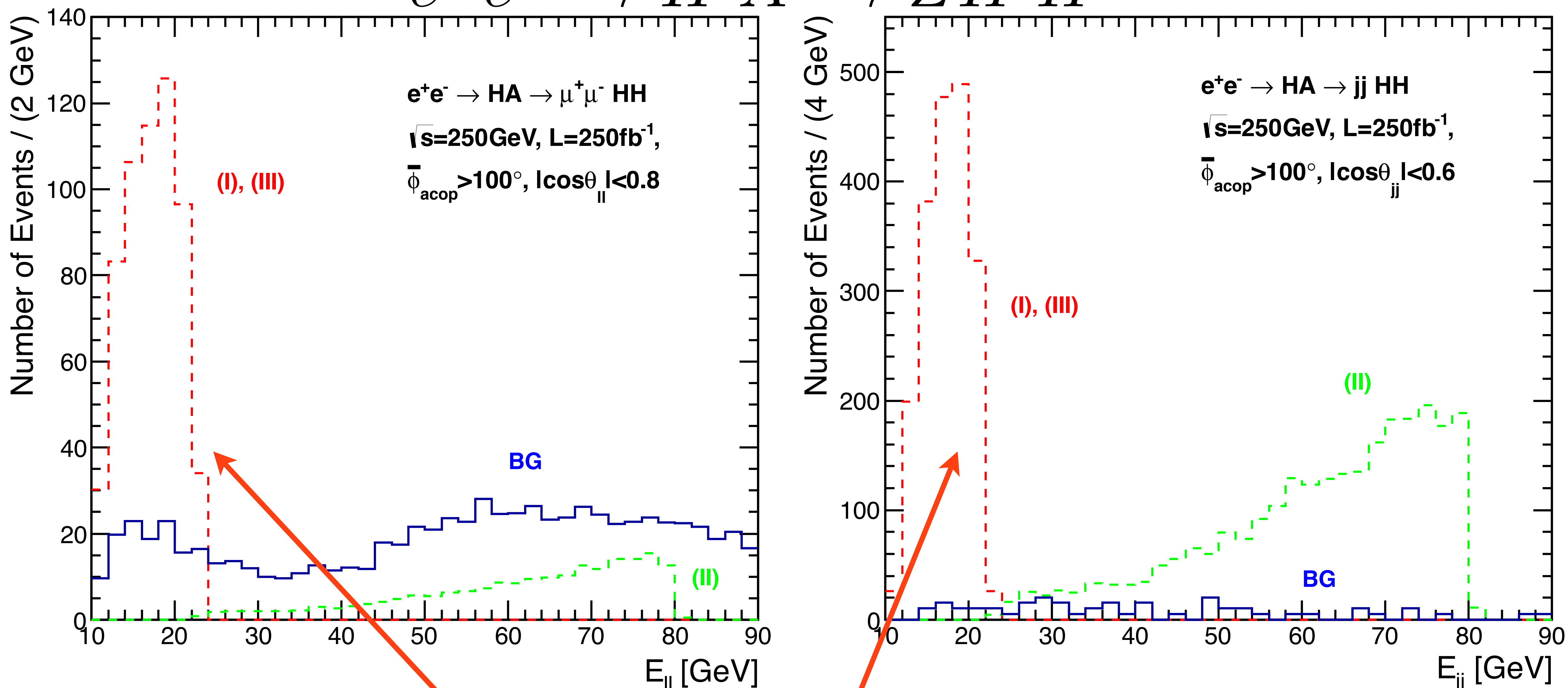
Higgs WG report on snowmass 2013, arXiv:1310.8361

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%

Light inert doublet @ ILC

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

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



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

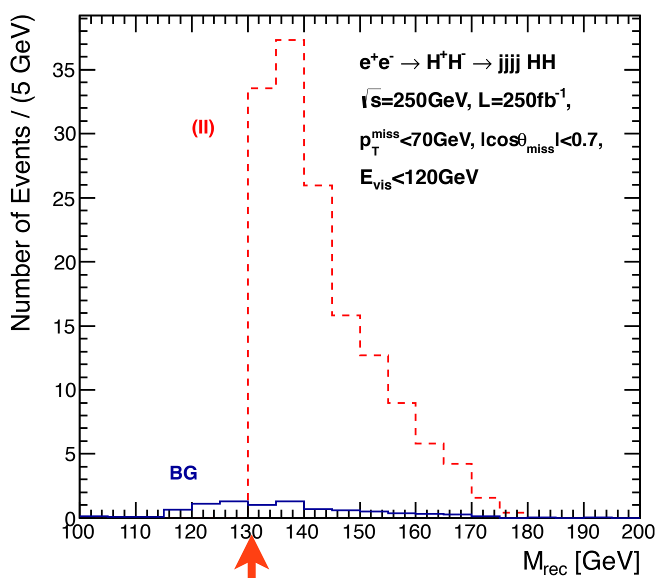
$$m_{A'} = 73\text{GeV}$$

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

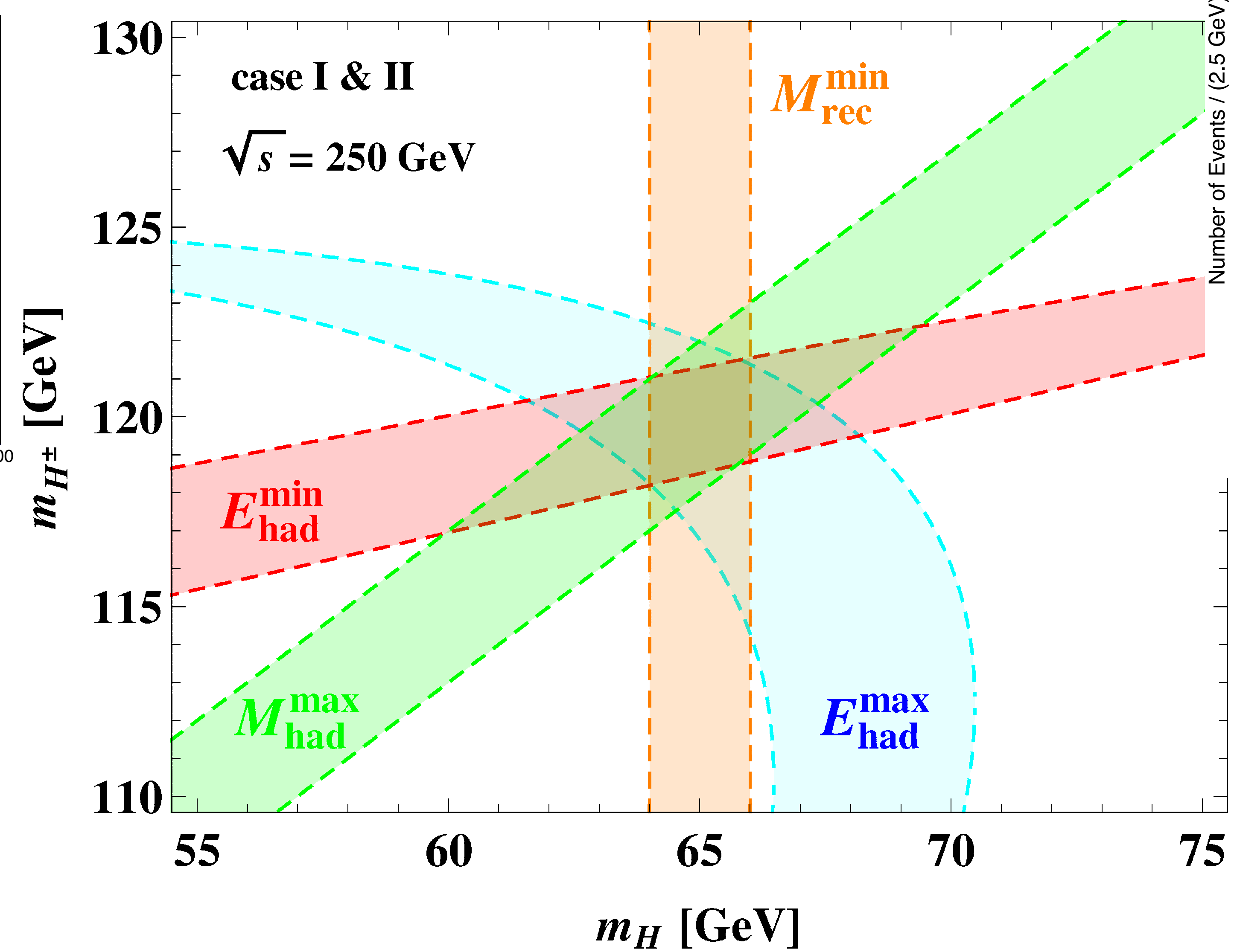
Light inert doublet @ ILC

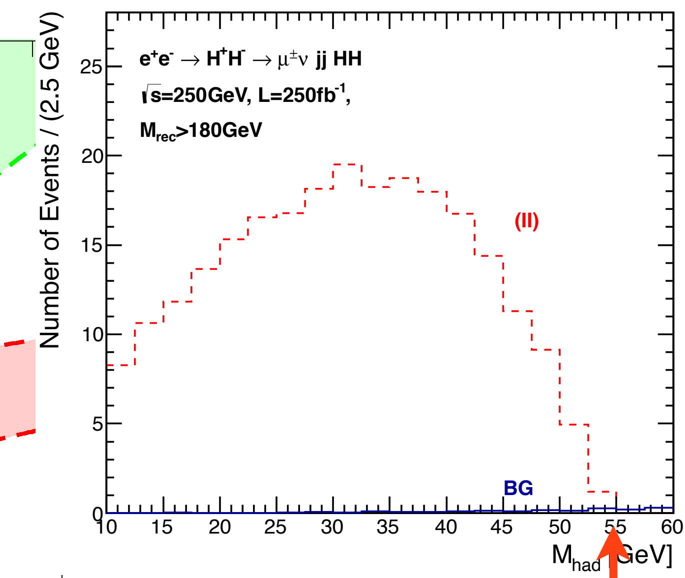
M. Aoki, S. Kanemura and H. Yokoya, PLB725,302.

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

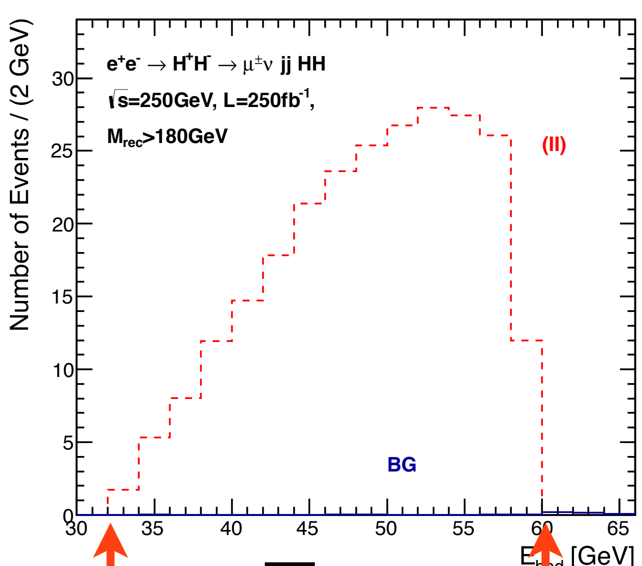


M_{rec}





M_{had}



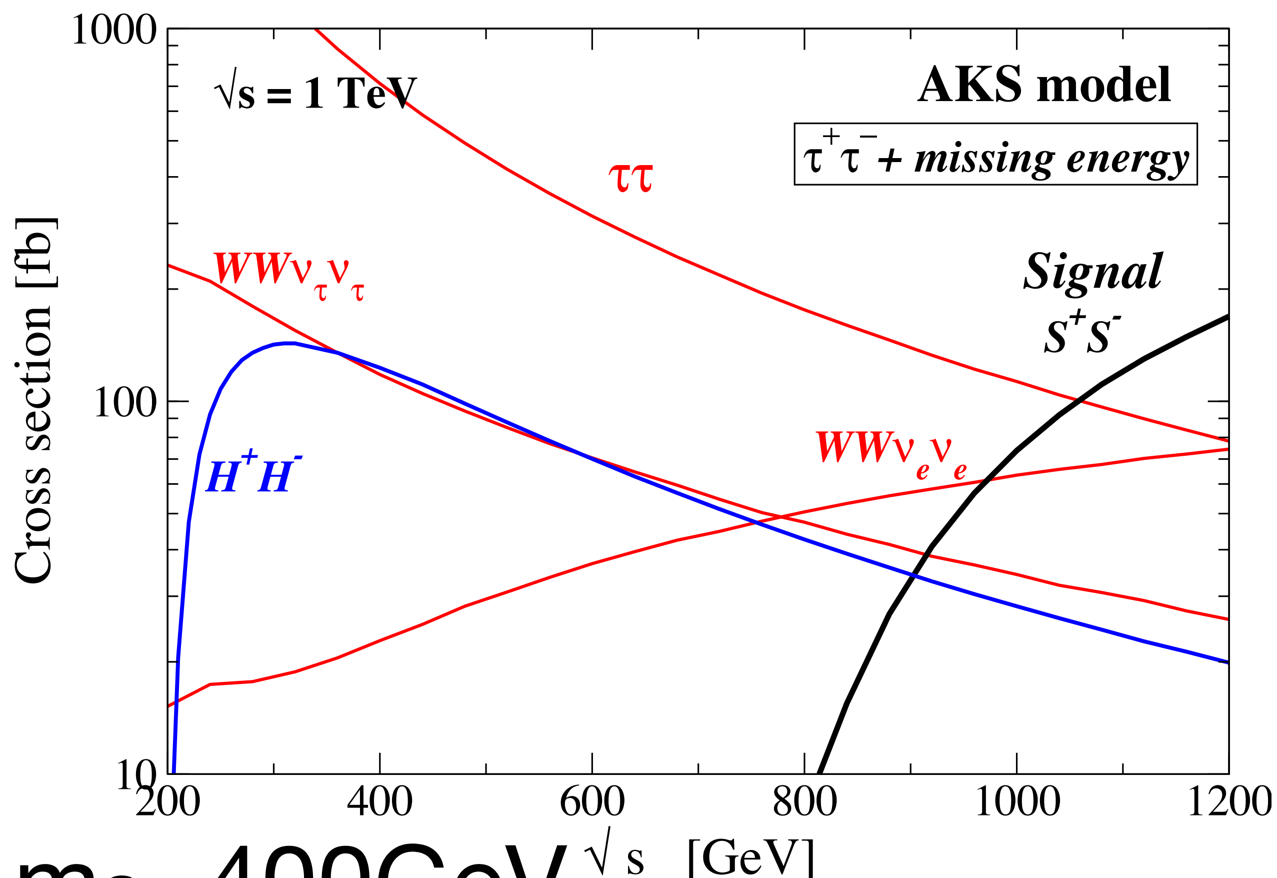
E_{had}

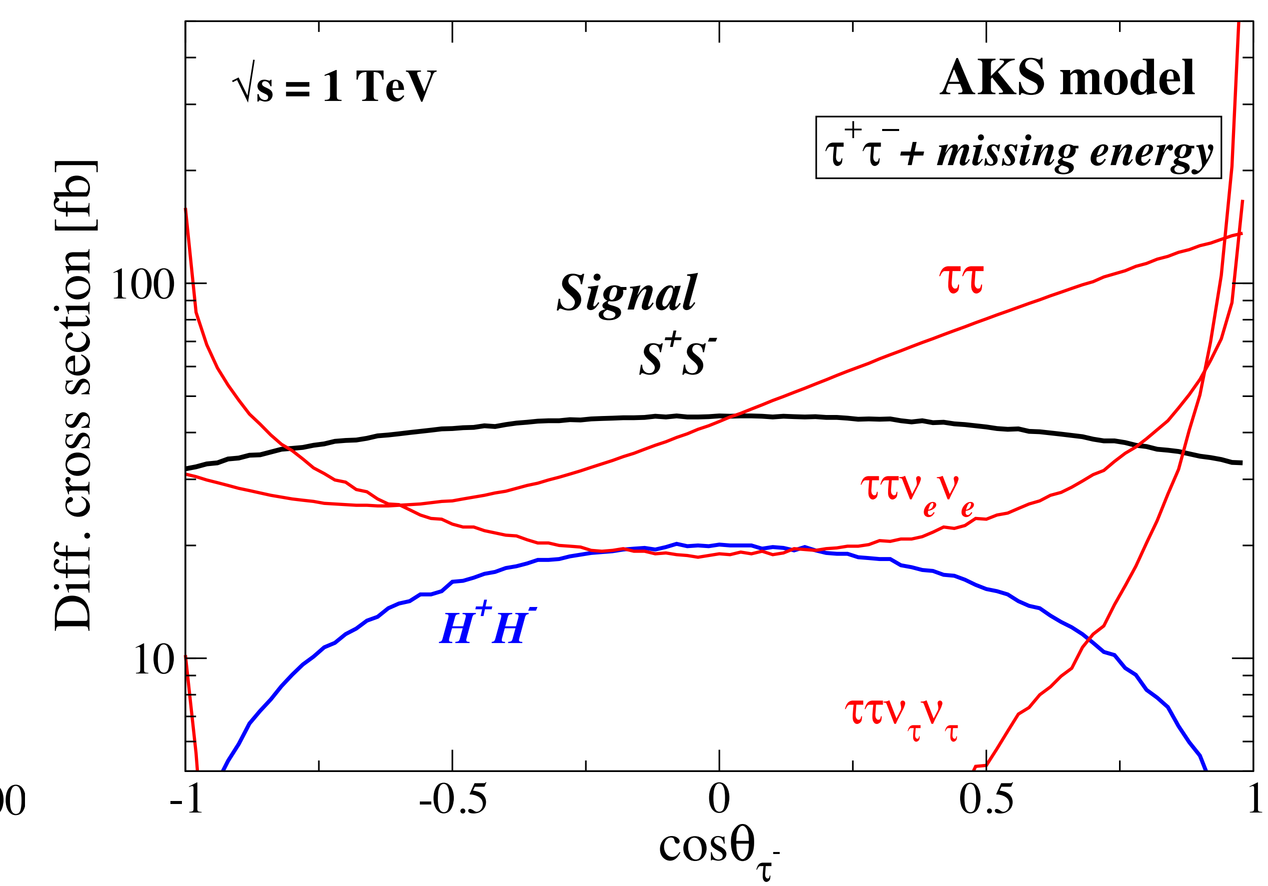
The masses can be precisely determined

Singlet like scalar @ILC

Aoki&Kanemura, PLB689,28.

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



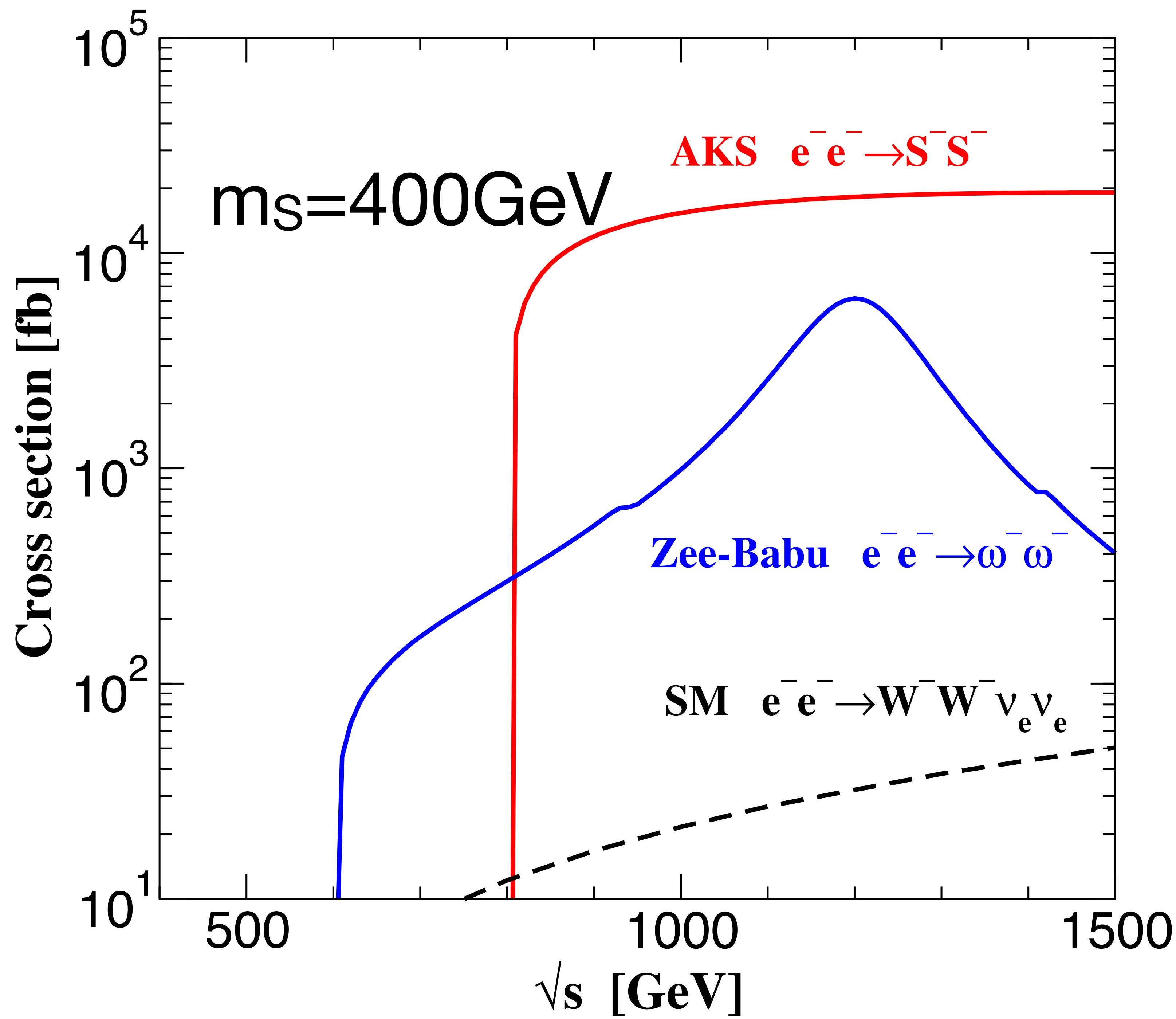


m_S=400GeV

A signal can be seen at the ILC@1TeV

Singlet like scalar @e^-e^- collider

Aoki&Kanemura, PLB689,28.



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