Extended Higgs Sector for Neutrino Mass, Baryogenesis and Dark Matter

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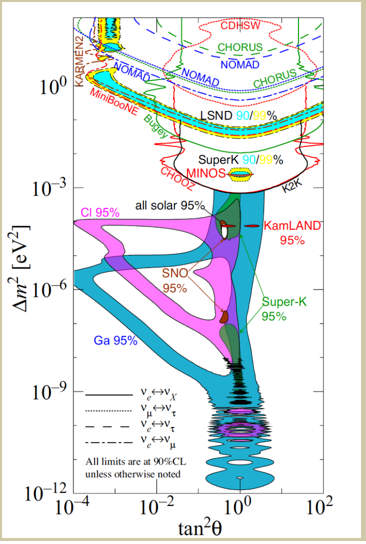
S.K., N. Machida, T. Shindou, arXiv:1405.5834

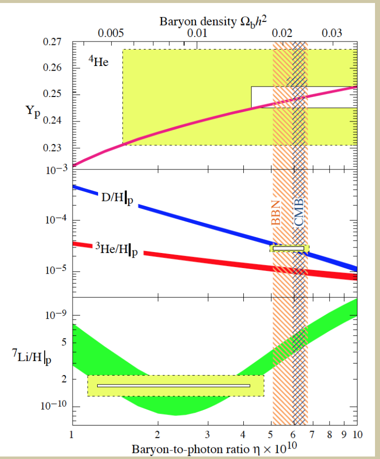
Multi-Higgs Models, Lisbon, 2-5. Sep. 2014

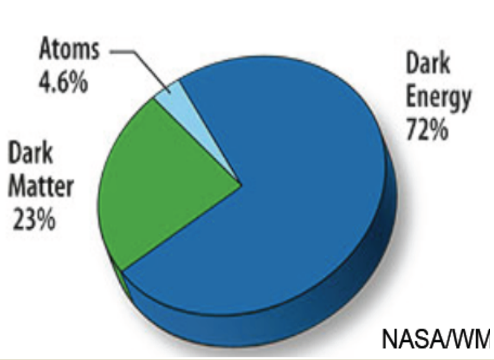
Phenomena beyond the SM

We already know BSM phenomena:

- **Neutrino oscillation**
  - $\Delta m^2 \sim 8\times10^{-5}\ \mathrm{eV}^2,\ \Delta m^2 \sim 2\times10^{-3}\ \mathrm{eV}^2$
- **Dark Matter**
  - $\Omega_{DM}h^2 \sim 0.12$
- **Baryon Asymmetry of the Universe**
  - $n_B/n_\gamma \sim 6\times10^{-10}$







New physics is necessary!
Which scale?

If NP appears at the TeV scale, it should have a strong connection with the physics behind the Higgs sector

$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

Dynamics behind the 125 GeV Higgs

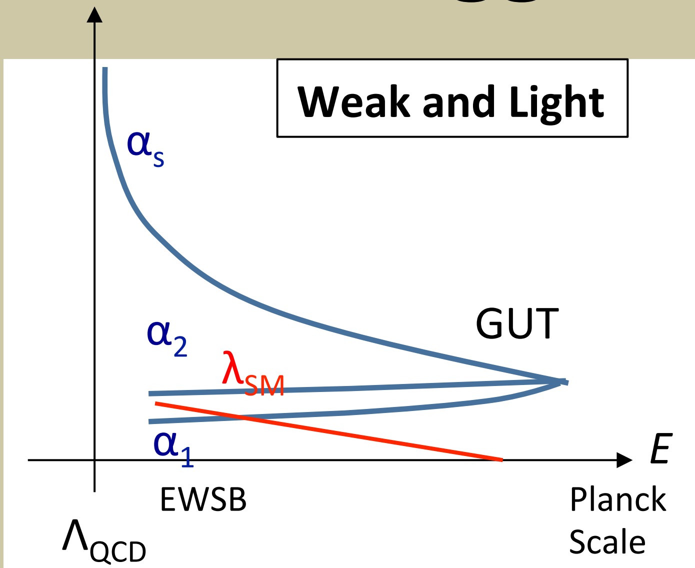
- **Weak and Light Scenario**
  - Perturbative
  - Grand Desert
  - Traditional Grand Unification

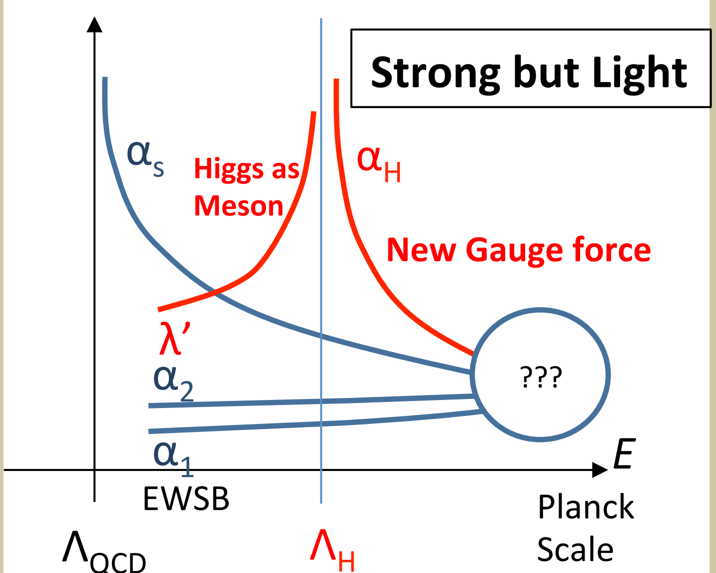
$$m_h^2 \propto \lambda v^2$$

- **Strong but Light Scenario**

$$m_h^2 \propto \frac{\lambda'^2}{(4\pi)^2} v^2$$

  - IR theory:
    Higgs as a composite field
    Landau pole at Λ_H
  - UV theory:
    A new gauge symmetry with confinement at Λ_H





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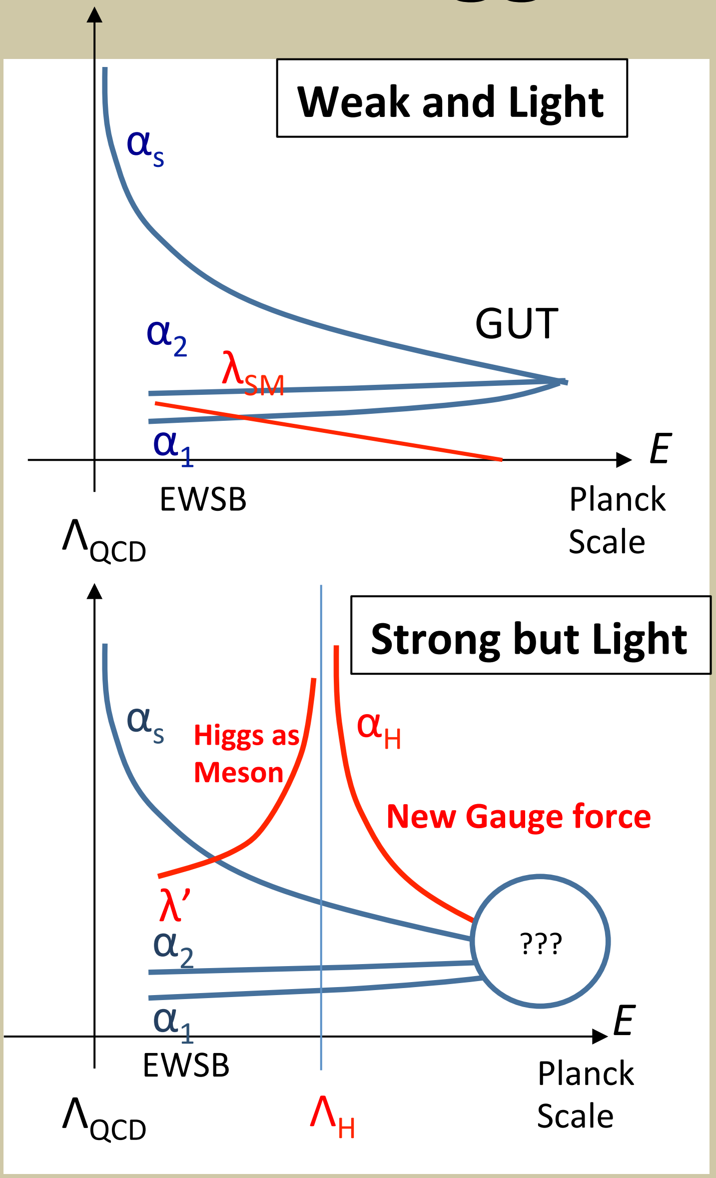
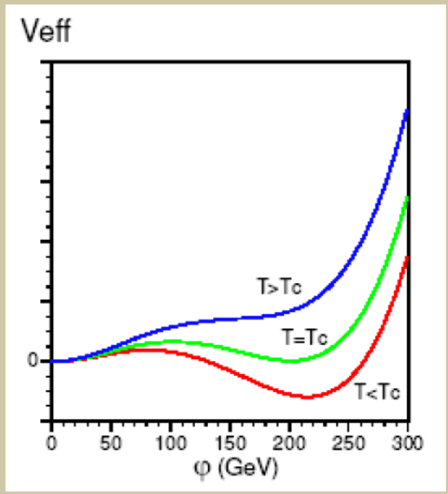


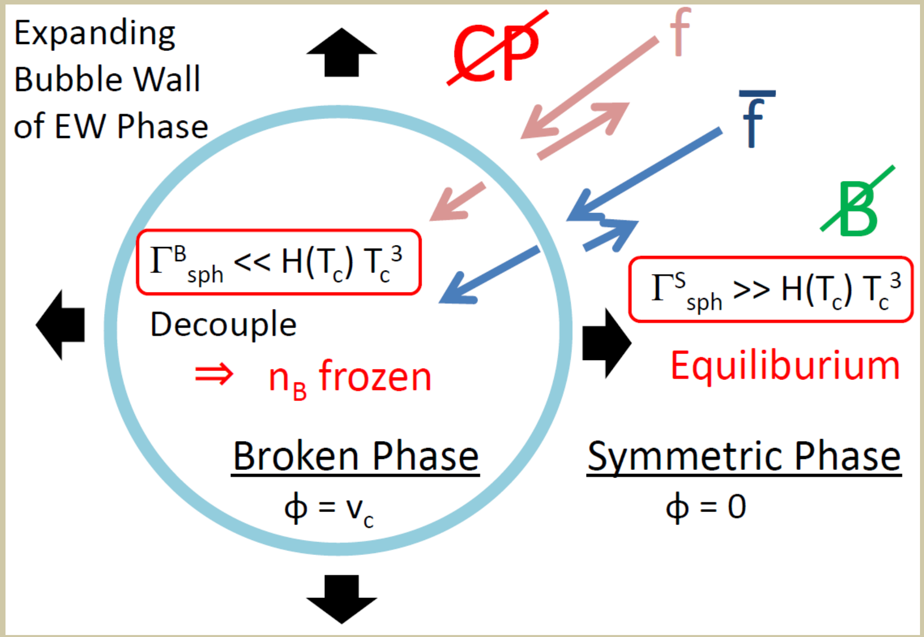
Electroweak Baryogenesis

$$\Gamma \sim e^{-E_{\rm sph}/T} \ (T < T_c)$$
$$\Gamma \sim \kappa(\alpha_W T)^4 \ (T_c < T)$$

Sakharov's conditions:

- B Violation → Sphaleron transition at high *T*
- C and CP Violation → CP Phases in extended scalar sector
- Departure from Equilibrium → 1st Order EW Phase Transition





Quick sphaleron decoupling is required to retain sufficient baryon number in Broken Phase

(Sphaleron Rate) < (Expansion Rate) ⇒

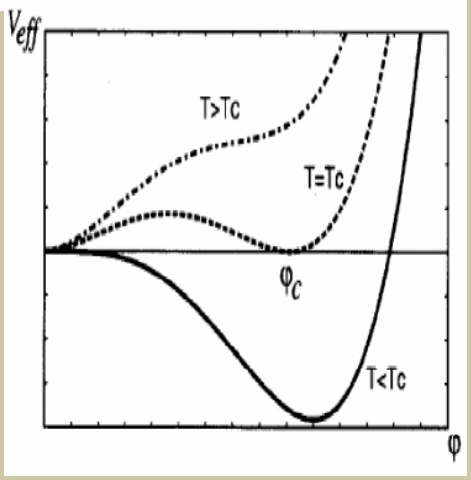
$$\frac{\varphi_c}{T_c} \gtrsim 1$$

Condition of Strong 1st OPT ($\varphi_c/T_c > 1$)

Finite Temperature Potential

$$V_T(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + \ldots..$$

$$\phi_c/T_c > 1 \Rightarrow 2E/\lambda_{T_c} > 1$$



EWBG not viable in the SM with 125GeV Higgs

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) \quad \Rightarrow \quad m_h < 80 \text{ GeV!}$$

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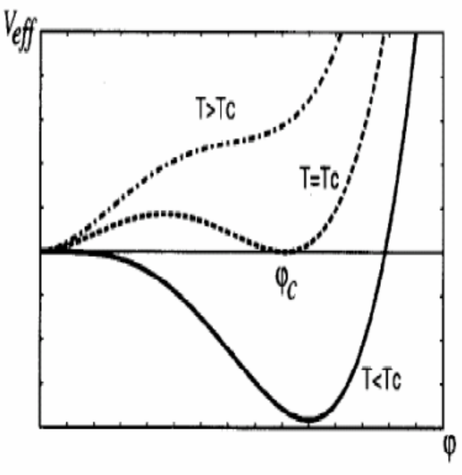

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Muti-Higgs models can satisfy the condition

$$V(\phi_{SM}, \Phi) = .. + \lambda_{SM}\, \phi_{SM}^4 + \lambda'\, \phi_{SM}^2\, \Phi^2 + \ldots$$

$$E \propto \frac{m_\Phi^3}{\lambda_T} = \frac{(\lambda')^{3/2}}{\lambda_T} \quad \Rightarrow \quad \lambda' >> \lambda_{SM} = 0.13 \;\; (\text{for } m_h = 126 \text{ GeV})$$

$\phi_c/T_c > 1$ when $\lambda' > O(1)$

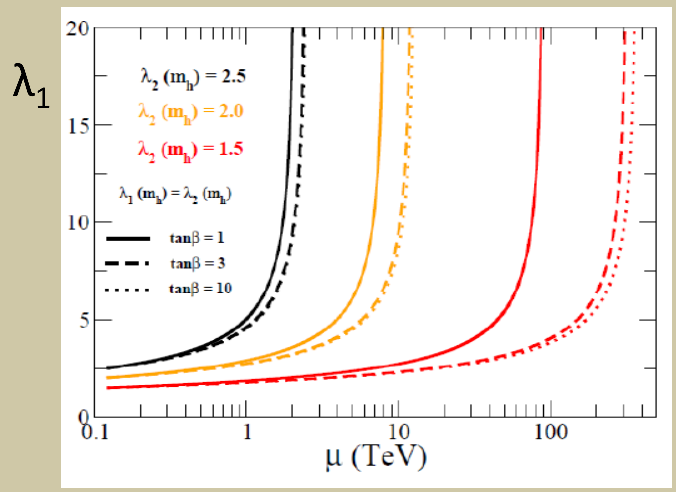
Strong-but-Light !

EW Phase Transition and Landau Pole

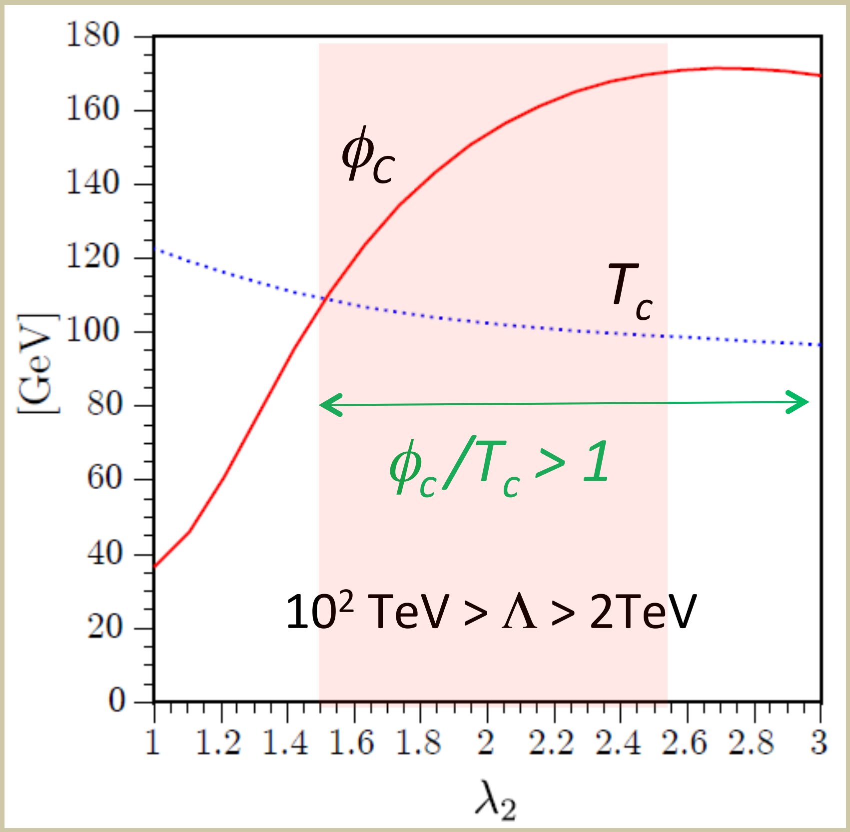
Strong 1st OPT → large λ' at EW
→ Landau pole

Ex) SUSY 4HDM+Ω

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



S.K., E. Senaha, T. Shindou 2011



$\varphi_c/T_c > 1 \Rightarrow \Lambda_{cutoff} < 100$ TeV

What is the fundamental theory above the Landau Pole?

Neutrino Mass

Neutirno Mass Term (= Effective dim-5 operator)

$$L^{eff} = (c_{ij}/M)\, \nu^i{}_L \nu^j{}_L\, \phi\, \phi$$

$\langle\phi\rangle = v = 246\text{GeV}$

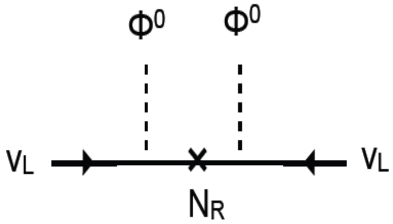
Mechanism for tiny masses:

$$m^\nu{}_{ij} = (c_{ij}/M)\, v^2 \quad < 0.1\ \text{eV}$$

Seesaw (tree level)

$$m^\nu{}_{ij} = y_i y_j\, v^2/M$$

Minkowski
Yanagida
Gell-Mann et al



(M>> 1TeV)

Quantum Effects (Radiative seesaw)

N-th order of perturbation

$$m^\nu{}_{ij} = [g^2/(16\pi^2)]^N\, C_{ij}\, v^2/M$$

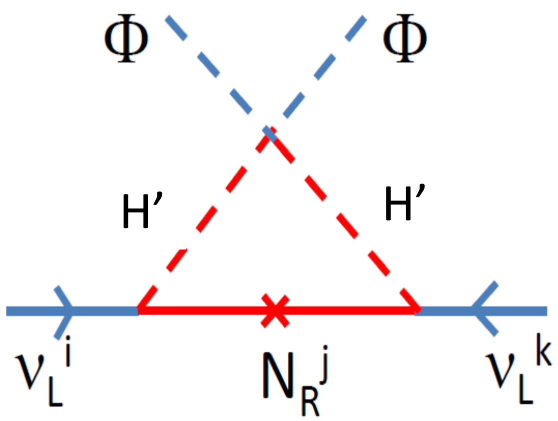
(M can be 1 TeV)

Radiative seesaw with Z_2

Z_2-parity plays roles:
1. **No tree-level Yukawa** (Radiative neutrino mass)
2. **Stability** of the lightest Z_2-odd particle (WIMP)

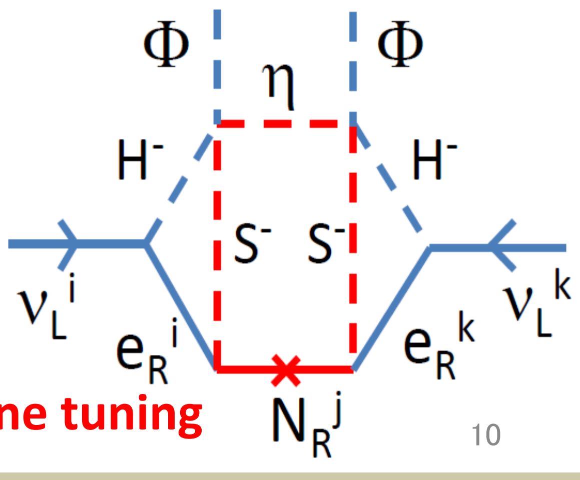
Ex1) 1-loop *Ma (2006)*

- Simplest model
- SM + Inert scalar doublet (H') + N_R
- DM candidate [H' or N_R]



Ex2) 3-loop *Aoki-SK-Seto (2008)*

- Neutrino mass from O(1) coupling
- 2 Higgs doublets + η^0 + S^+ + N_R
- DM candidate [η^0 (or N_R)]
- Electroweak Baryogenesis



All 3 problems may be solved by TeV physics w/o fine tuning

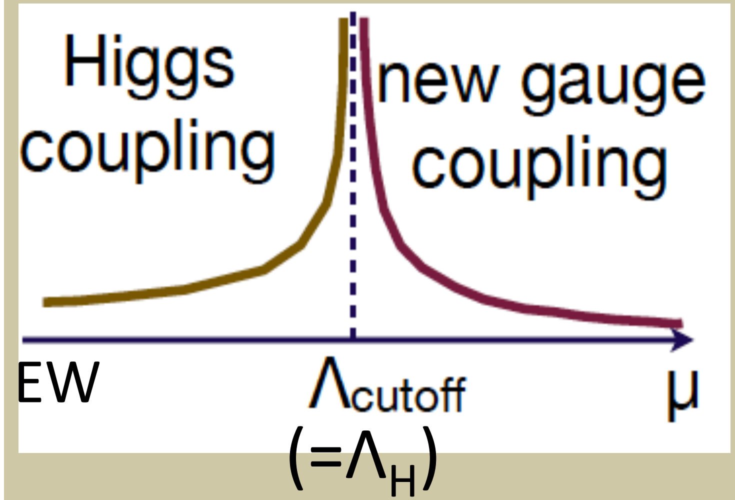
Problems in these TeV models

- Radiative Seesaw models
  - We may be able to explain all BSM phenomena
    Neutrino mass, Dark Matter, Baryon Asymmetry
  - TeV scale ⇒ Testable at colliders (Big bonus)
- However, there are problems in such scenario
  - EW Baryogenesis ⇒ Landau pole !
  - Many scalars introduced ⇒ Ad hoc !
  - Non-SUSY ⇒ Hierarchy Problem
- Can we have a consistent UV theory?

This is the subject of my talk

Outline of the Model

- Origin of the Higgs force (λ) is the SU(N_c) SUSY gauge symmetry (N_c=2, N_f=3) [Similar to Minimal SUSY Fat Higgs model]
  Harnik, et al
- Confinement ($N_f = N_c$+1) occurs at Λ_H (∼ Landau Pole) *Intriligator and Seiberg*
- At low energy 4 doublets + many singlets appear with a coupling λ (Higgs as Meson)
- λ(EW) is set by EWBG $\phi c/Tc > 1$ (strong) but within perturbative ⇒ Λ_H = O(10) TeV



SK, Shindou, Yamada 2012

By adding the Z_2 parity to the model, and by introducing a RH Neutrino, a radiative seesaw scenario is realized at TeV scale

SK, Shindou, Machida, Yamada 2013

SUSY $SU(2)_H$ gauge theory

Minimal model for confinement (*N_c=2, N_f=3*)
→ 3 pairs of $SU(2)_H$ fundamental rep. *T_i* (*i*=1-6)

Six $SU(2)_H$ doublets *T_i* charged under the SM gauge groups and Z_2-parity

Field	$SU(2)_L$	$U(1)_Y$	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	$-1/2$	$-$

SK, T. Shindou, T. Yamada, 2012

Put current mass terms to give masses of *T_i*

$$W_m = m_1 T_1 T_2 + m_3 T_3 T_4 + m_5 T_5 T_6$$

Effective Theory

- It is strongly coupled at $\Lambda_{H,}$ and T_i (i=1-6) are confined

  K. Intriligator and N. Seiberg (1996)

- Below Λ_H the theory is described by 15 Meson Superfields

$$M_{ij} = T_i T_j$$

- Effective Superpotential

$$W_{eff} = \frac{1}{\Lambda^3} \epsilon_{ijklmn} M_{ij} M_{kl} M_{mn} + m_1 M_{12} + m_3 M_{34} + m_5 M_{56}$$

- Using Naïve Dimensional Analysis (NDA), it is rewritten by canonically normalized fields

$$W_{eff} \simeq \lambda\, \epsilon_{ijklmn} \hat{M}_{ij} \hat{M}_{kl} \hat{M}_{mn} + \frac{m_1 \Lambda_H}{4\pi} \hat{M}_{12} + \frac{m_3 \Lambda_H}{4\pi} \hat{M}_{34} + \frac{m_5 \Lambda_H}{4\pi} \hat{M}_{56}$$

- The coupling λ becomes non-perturbative at Λ_H

$$\lambda(\mu = \Lambda_H) \simeq 4\pi$$ Naïve Dimesional Analysis

Higgs fields as Mesons

Fifteen mesons $M_{ij} = T_i T_j$ can be identified as the MSSM Higgs superfields and extra superfields

Additional Super-fields

	Field	$SU(2)_L$	$U(1)_Y$	Z_2
MSSM Higgs doublets	H_u	2	$+1/2$	$+$
	H_d	2	$-1/2$	$+$
Extra Higgs doublets	Φ_u	2	$+1/2$	$-$
	Φ_d	2	$-1/2$	$-$
Charged Higgs singlets	Ω^+	1	$+1$	$-$
	Ω^-	1	-1	$-$
Z_2-even Higgs singlets	$N,\ N_\Phi,\ N_\Omega$	1	0	$+$
Z_2-odd Higgs singlets	$\zeta,\ \eta$	1	0	$-$

Superpotential is rewritten as

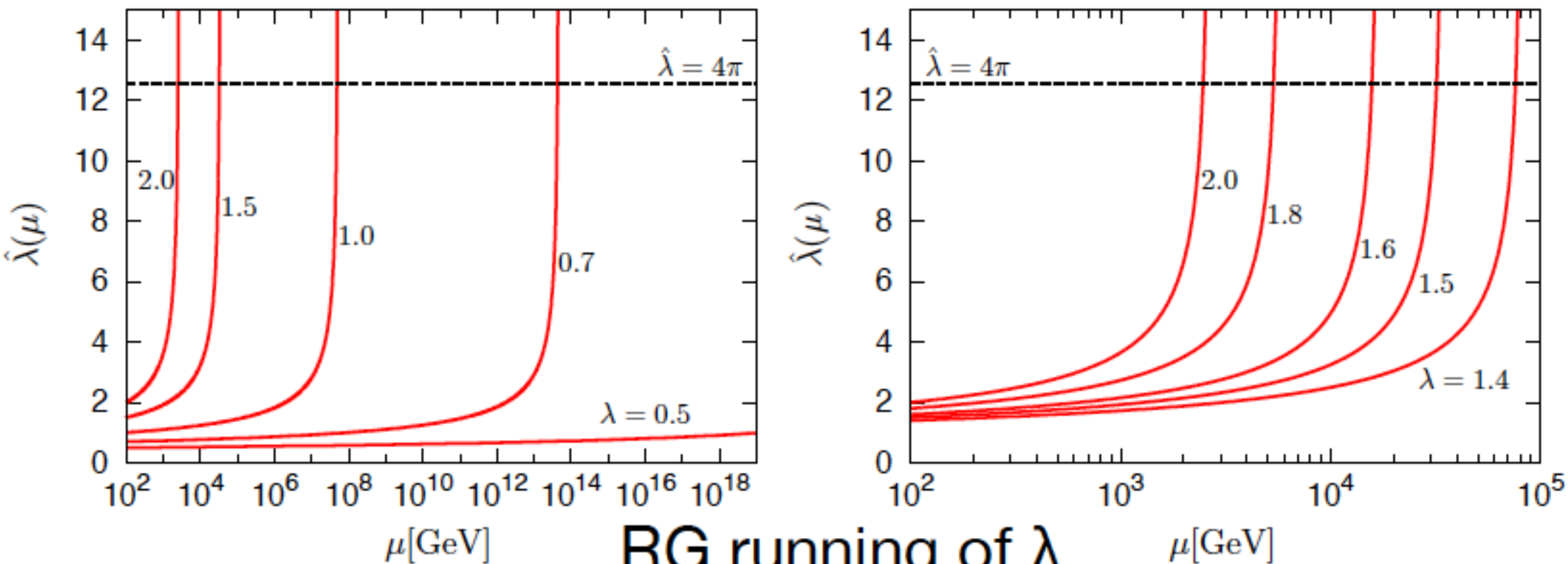
$$\begin{aligned} W_{eff} &= \lambda \{ N(H_u H_d + v_0^2) + N_\Phi(\Phi_u\Phi_d + v_\Phi^2) + N_\Omega(\Omega^+\Omega^- + v_\Omega^2) \\ &- N N_\Phi N_\Omega - N_\Omega \zeta\eta + \zeta H_d \Phi_u + \eta H_u \Phi_d - \Omega^+ H_d \Phi_d - \Omega^- H_u \Phi_u \} \end{aligned}$$

The low energy theory is 4HDM+Singlets but with a common λ !

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)

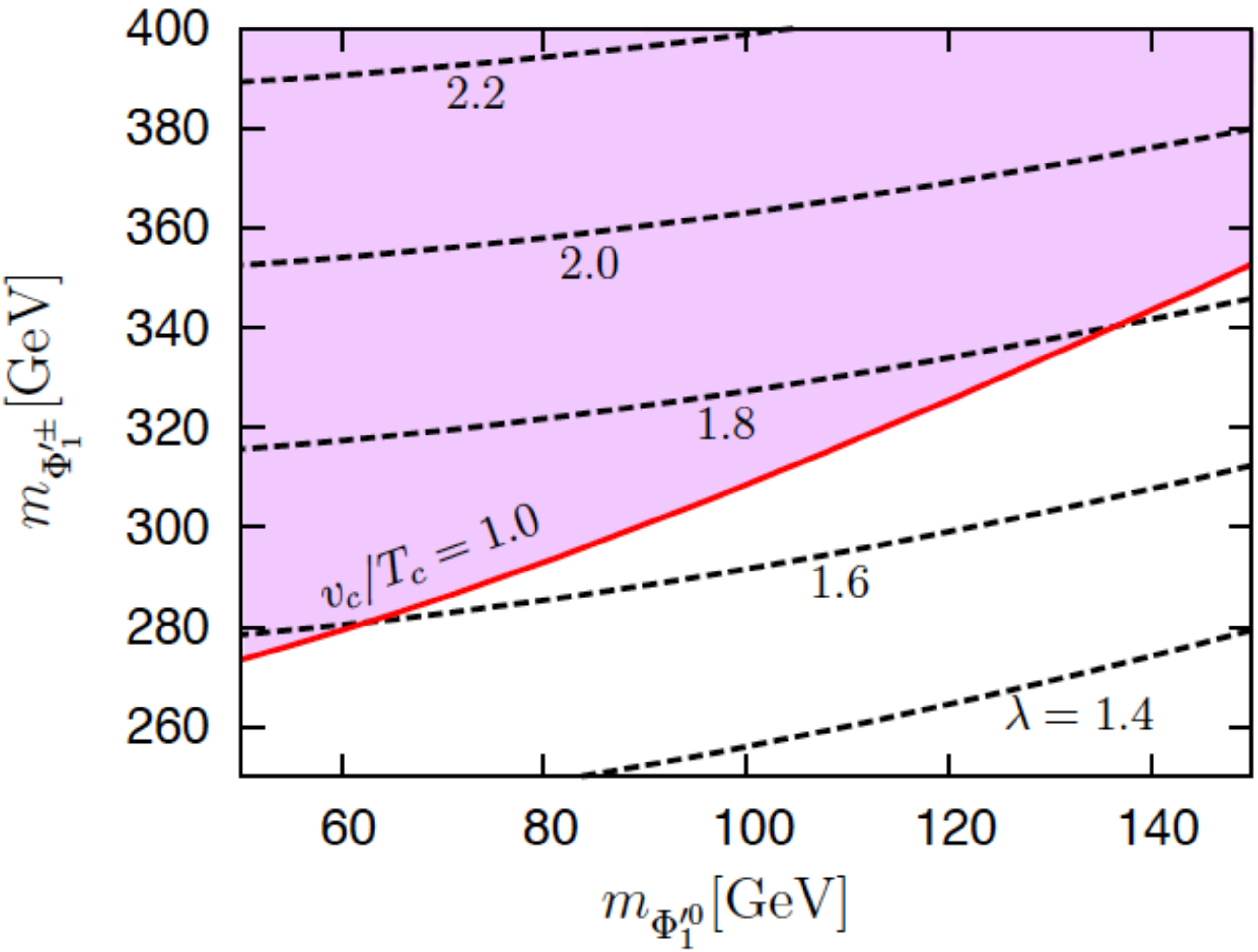


RG running of λ

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

1st order EWPT

S.K., E. Senaha, T. Shindou, T. Yamada, JHEP1305 (2013) 066.



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

Neutrino Mass

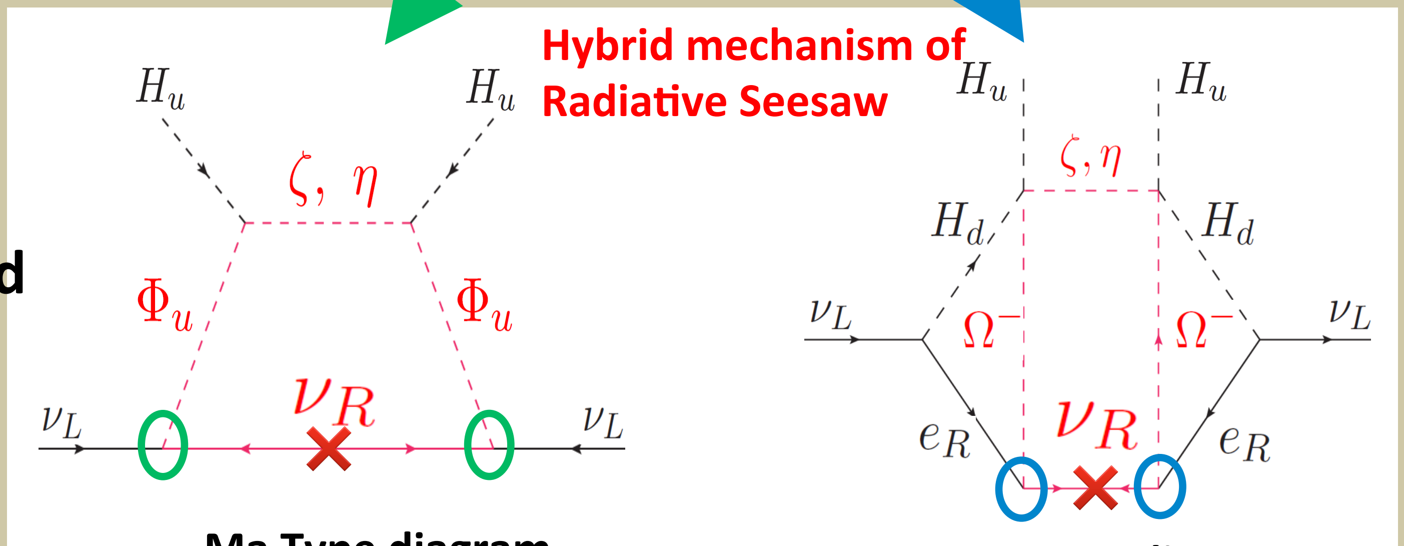
Mass generation mechanism is ***hybrid*** of Ma model and AKS model

Two tiny mass scales are naturally induced

One generation of ν_R is enough

All scalars in the Higgs sector contribute to the neutrino masses

$$W_{\text{eff}}^N = \frac{\kappa}{2} N \nu_R^c \nu_R^c + y_N^i \nu_R^c L_i \Phi_u + h_N^i \nu_R E_i^c \Omega^- + \frac{M}{2} \nu_R^c \nu_R^c$$



Ma Type diagram

AKS Type diagram

$$\Delta m_{\text{sol}}^2 \sim 7 \times 10^{-5} \text{eV}^2$$
$$\Delta m_{\text{atm}}^2 \sim 2 \times 10^{-3} \text{eV}^2$$

$$\sin^2 2\theta_{12} = 0.857 \pm 0.024$$
$$\sin^2 2\theta_{23} > 0.95$$
$$\sin^2 2\theta_{13} = 0.095 \pm 0.010$$

Benchmark parameter set

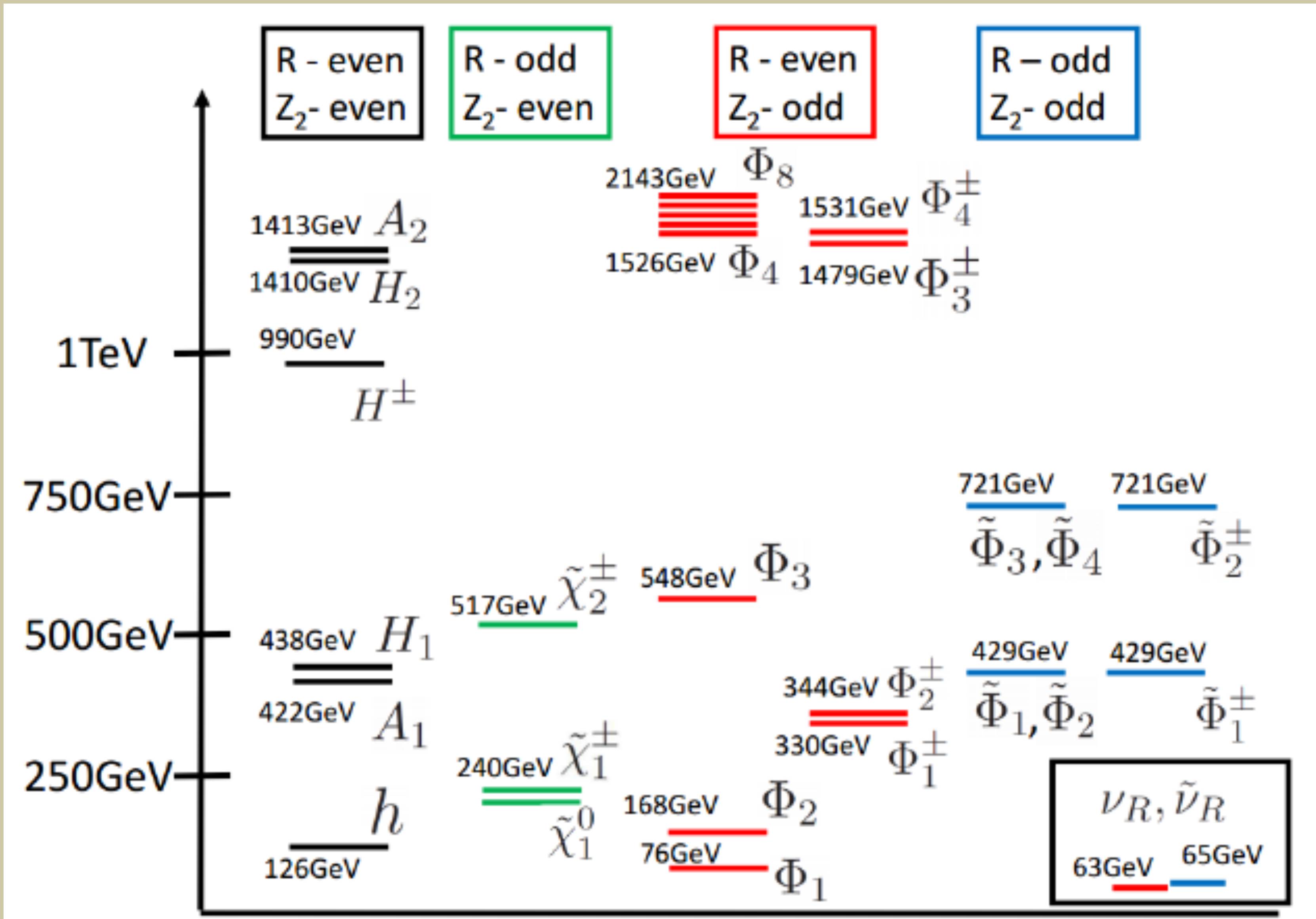
λ, $\tan\beta$, and μ-terms
$\lambda = 1.8\ (\Lambda_H = 5\ \text{TeV})\quad \tan\beta = 15\quad \mu = 250\ \text{GeV}\quad \mu_\Phi = 550\ \text{GeV}\quad \mu_\Omega = -550\ \text{GeV}$
Z_2-even Higgs sector
$m_h = 126\ \text{GeV}\quad m_{H^\pm} = 990\ \text{GeV}\quad m_N^2 = (1050\ \text{GeV})^2\quad A_N = 2900\ \text{GeV}$
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
$m_{\nu_R} = 63\ \text{GeV}\quad m_{\tilde{\nu}_R} = 65\ \text{GeV}\quad \kappa = 0.9$
$y_N = (3.28i, 6.70i, 1.72i) \times 10^{-6}\quad h_N = (0, 0.227, 0.0204)$
Other SUSY SM parameters
$m_{\tilde{W}} = 500\ \text{GeV}\quad m_{\tilde{q}} = m_{\tilde{\ell}} = 5\ \text{TeV}$

Output

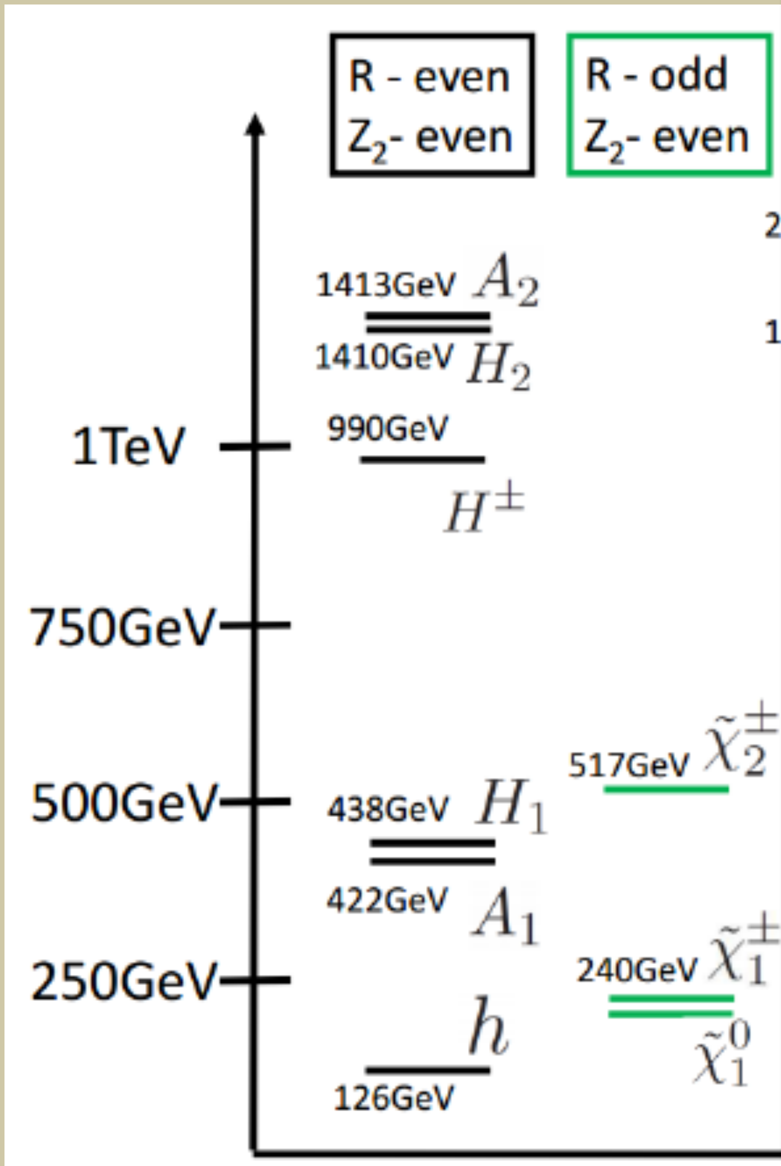
Non-decoupling effects
$\varphi_c/T_c = 1.3 \quad \lambda_{hhh}/\lambda_{hhh}\vert_{\rm SM} = 1.2 \quad {\rm B}(h \to \gamma\gamma)/{\rm B}(h \to \gamma\gamma)\vert_{\rm SM} = 0.78$
Neutrino masses and the mixing angles
$(m_1, m_2, m_3) = (0, 0.0084\ {\rm eV}, 0.0050\ {\rm eV}) \quad \sin^2\theta_{12} = 0.32 \quad \sin^2\theta_{23} = 0.50 \quad \vert\sin\theta_{13}\vert = 0.14$
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
$\Omega_{\nu_R}h^2 = 0.055 \quad \Omega_{\bar{\nu}_R}h^2 = 0.065 \quad \Omega_{\rm DM} = \Omega_{\nu_R}h^2 + \Omega_{\bar{\nu}_R}h^2 = 0.12$

All data can be satisfied

Mass Spectrum



Mass Spectrum



Z_2-even sector is like NMSSM!

Mass splitting between H^+ and H/A is caused by the mixing between H/A and N, which is necessary for DM annihilation

We can distinguish from MSSM

Effect of light Z_2-odd particles deviate coupling of the Higgs *h*

hVV, hγγ, hhh, …

We can distinguish from NMSSM

Mass Spectrum

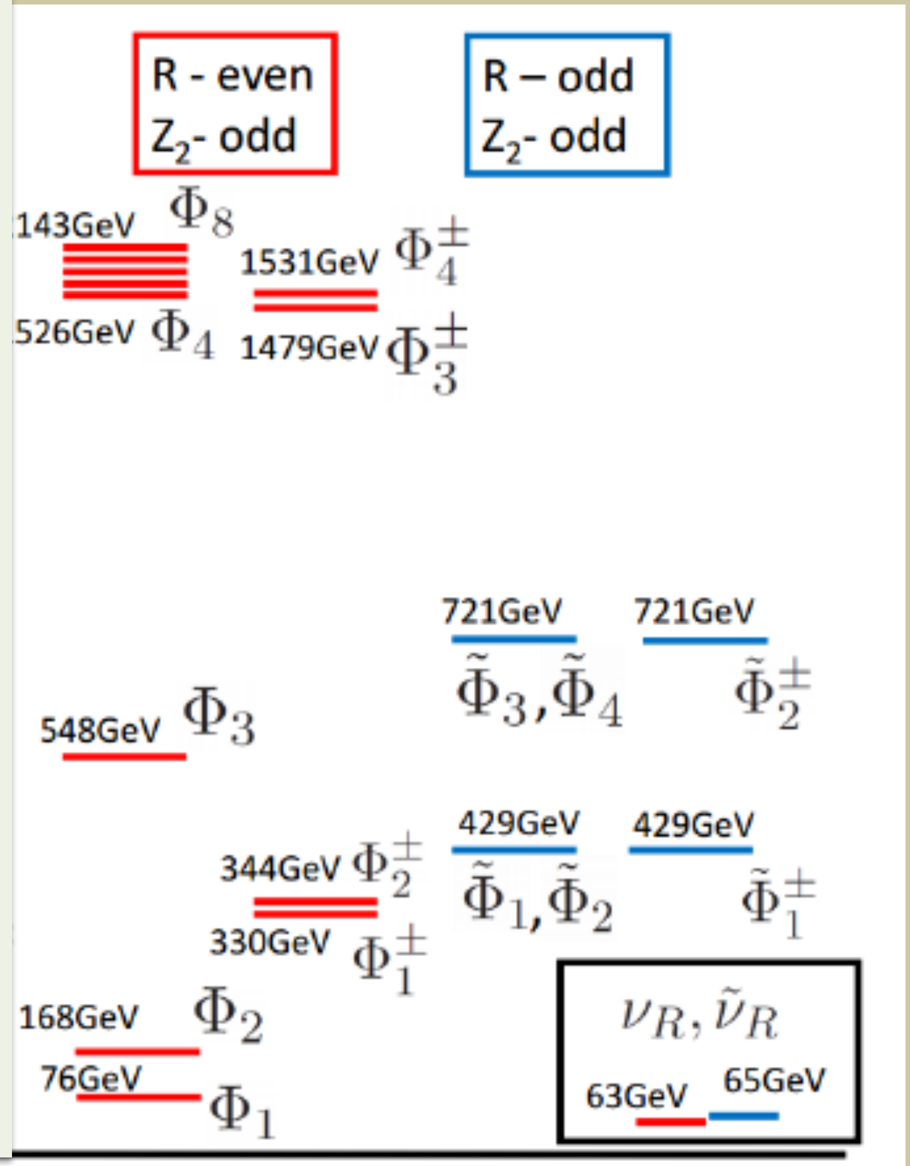
Z_2-odd sector is rich

Light neutral/charged Z_2-odd Particle is required to realize 1[st] order EW phase transition

Multi component DM from this sector

$$\nu_R, \tilde{\nu}_R$$

Z_2-odd scalars are all used to make 1 or 3 loop diagrams for neutrino masses
(Ma and AKS type)



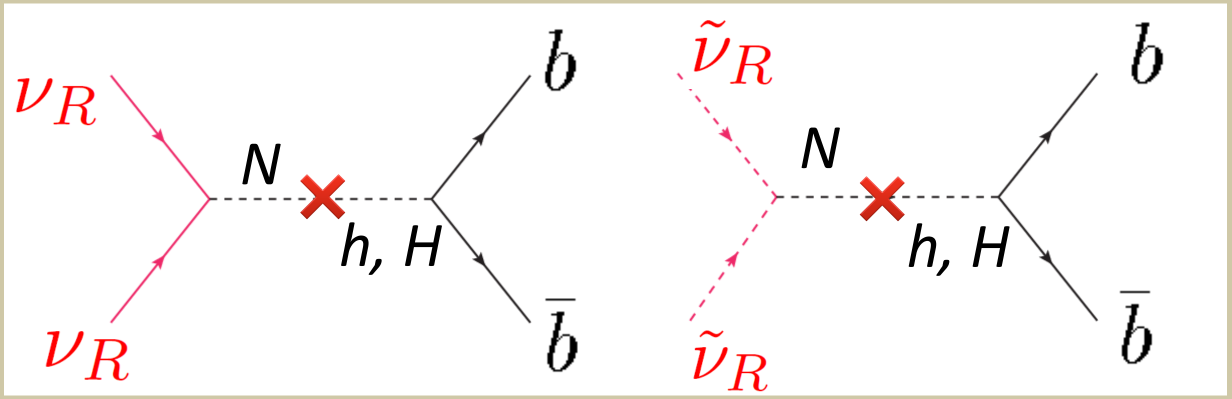
Dark Matter (RHN and RHSN)

Two discrete symmetries Z_2 and R:

$$(Z_2, R) = (-,+),\ (-,-)$$

$$\nu_R,\ \ \tilde{\nu}_R$$

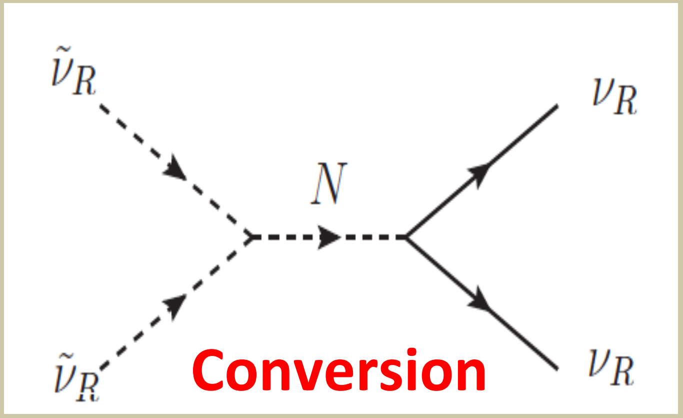
Multi-component DM



In our benchimark scenario,
the neutralino is not dark matter

$$\tilde{\chi}_1^0 \longrightarrow \nu_R \tilde{\nu}_R$$

$$(+,-) \to (-,+) \oplus (-,-)$$



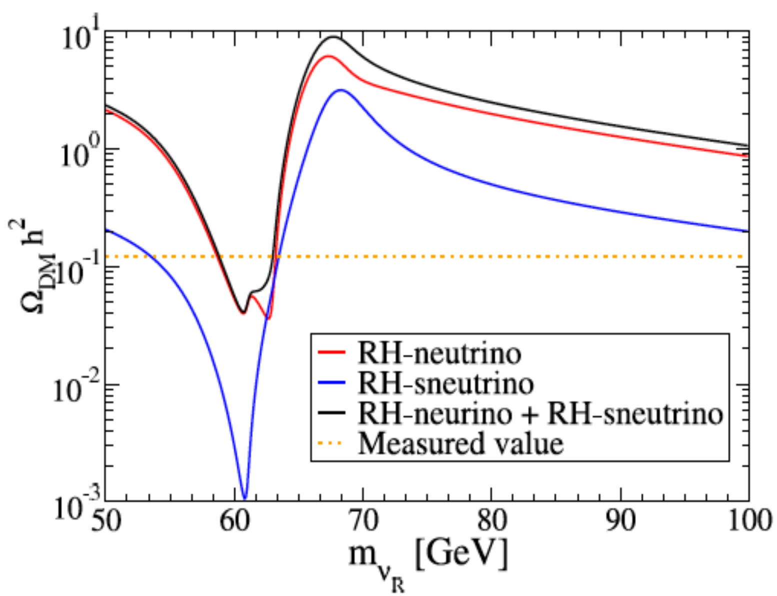
Relic Abundances of *RHN* and *RHSN*

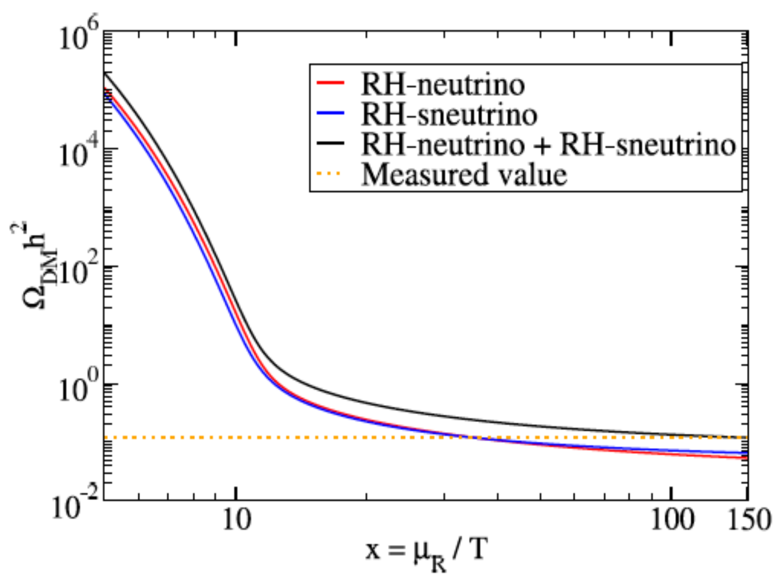
Coupled Boltzmann Equations

$$\mu_R^{-1} = m_{\nu_R}^{-1} + m_{\tilde{\nu}_R}^{-1}$$

$$\frac{dY}{dx} = 0.264 g_*^{1/2} \left(\frac{\mu_R M_P}{x^2}\right)\left\{-\langle\sigma_\nu v\rangle\left(Y^2 - Y_{\rm eq}^2\right) - \langle\sigma_{\nu\tilde{\nu}} v\rangle\left(Y^2 - \tilde{Y}^2\frac{Y_{\rm eq}^2}{\tilde{Y}_{\rm eq}^2}\right) + \langle\sigma_{\tilde{\nu}\nu} v\rangle\left(\tilde{Y}^2 - Y^2\frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right)\right\}$$

$$\frac{d\tilde{Y}}{dx} = 0.264 g_*^{1/2} \left(\frac{\mu_R M_P}{x^2}\right)\left\{-\langle\sigma_{\tilde{\nu}} v\rangle\left(\tilde{Y}^2 - \tilde{Y}_{\rm eq}^2\right) - \langle\sigma_{\tilde{\nu}\nu} v\rangle\left(\tilde{Y}^2 - Y^2\frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right) + \langle\sigma_{\nu\tilde{\nu}} v\rangle\left(\tilde{Y}^2 - Y^2\frac{\tilde{Y}_{\rm eq}^2}{Y_{\rm eq}^2}\right)\right\}$$





For details of DM physics, see Naoki Machida’s Talk

Summary of the Model

UV

SUSY $SU(2)_H$ Fund. Rep. with 3 flavors

Right-Handed Neutrino

Simple $T_1,\ T_2,\ T_3,\ T_4,\ T_5,\ T_6$

N_R

Summary of the Model

UV

SUSY $SU(2)_H$ Fund. Rep. with 3 flavors

Right-Handed Neutrino

Simple $T_1,\ T_2,\ T_3,\ T_4,\ T_5,\ T_6$ N_R

Z_2-odd assigned

Summary of the Model

UV

SUSY $SU(2)_H$ Fund. Rep. with 3 flavors

Right-Handed Neutrino

Simple $T_1,\ T_2,\ T_3,\ T_4,\ T_5,\ T_6$ N_R

Z_2-odd assigned

Confinement at O(10) TeV

$$H = \langle T_i T_j \rangle$$

Summary of the Model

UV

SUSY $SU(2)_H$ Fund. Rep. with 3 flavors — Right-Handed Neutrino

Simple $T_1, T_2, T_3, T_4,$ T_5, T_6 N_R

Z_2-odd assigned

Confinement at O(10) TeV $H = \langle T_i T_j \rangle$ **Higgses = Mesons**

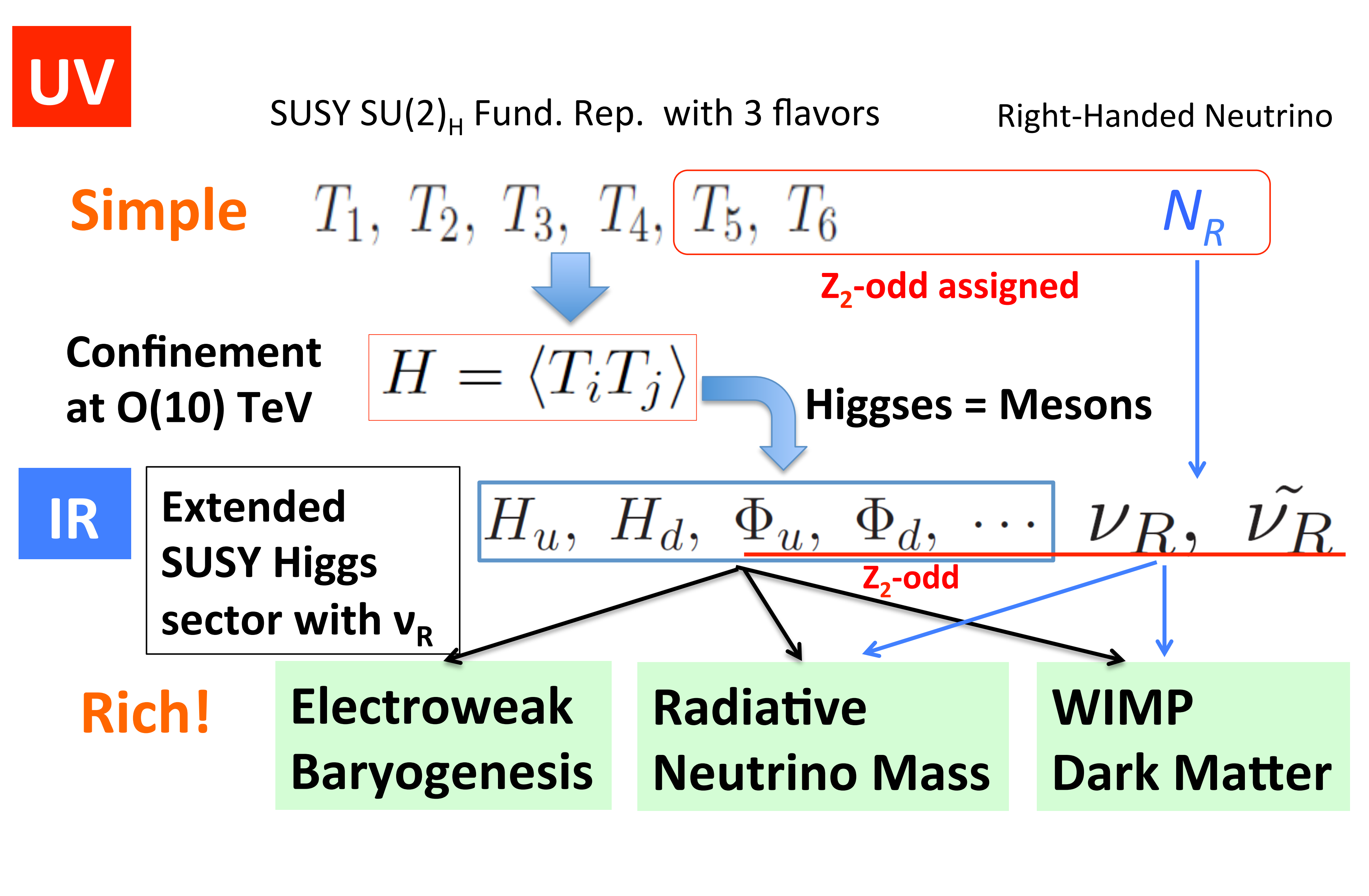
IR

Extended SUSY Higgs sector with ν_R

$H_u, H_d, \Phi_u, \Phi_d, \cdots$ $\nu_R, \tilde{\nu}_R$

Z_2-odd

Summary of the Model



Summary of the Model

UV

SUSY $SU(2)_H$ Fund. Rep. with 3 flavors — Right-Handed Neutrino

Simple: $T_1,\ T_2,\ T_3,\ T_4,\ T_5,\ T_6 \qquad N_R$

Z_2-odd assigned ($T_5,\ T_6,\ N_R$)

Confinement at O(10) TeV: $H = \langle T_i T_j \rangle$

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$H_u,\ H_d,\ \Phi_u,\ \Phi_d,\ \cdots \qquad \nu_R,\ \tilde{\nu}_R$

Z_2-odd ($\Phi_u,\ \Phi_d,\ \cdots,\ \nu_R,\ \tilde{\nu}_R$)

Rich!

- Electroweak Baryogenesis
- Radiative Neutrino Mass
- WIMP Dark Matter

All additional scalars contribute to solve the problems

How test the model at colliders

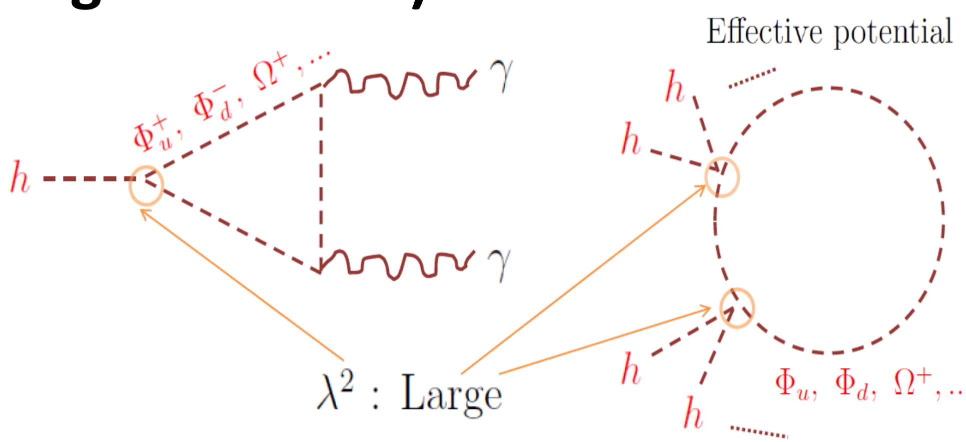
- **Direct search of exotic charged scalars and fermions at LHC (expected for 14 TeV Run) and ILC**

- **Indirect Signatures on Higgs coupling**

  (essence of Strong-but-Light scenario)

  - **Non-decoupling effect**
  - **Deeply connected with *φc/Tc > 1***

    Large deviations in the *hγγ, hhh* coupling!

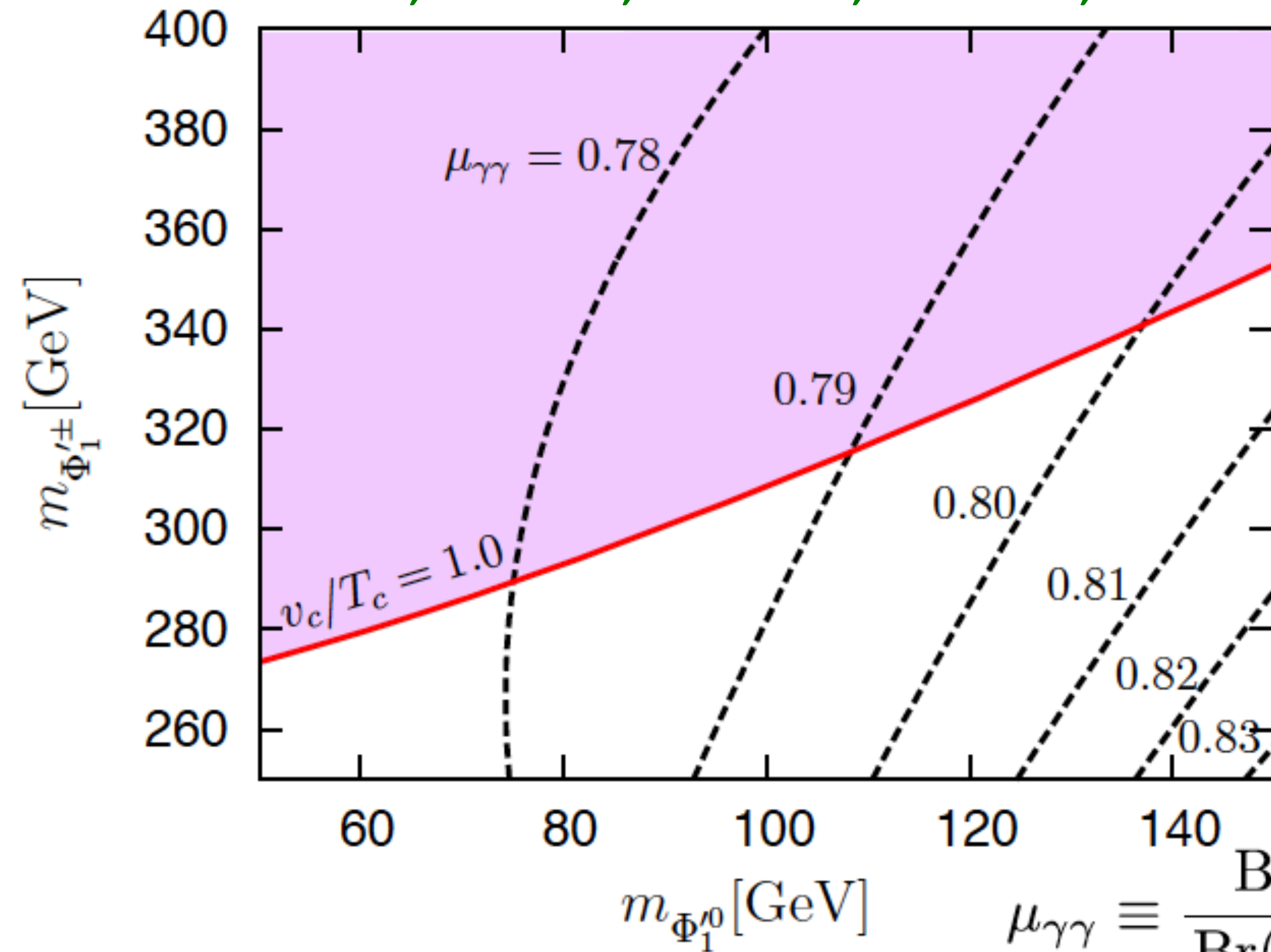


Coupling measurement

- ***hWW, hff*** **O(1)% at ILC**
- ***hγγ coupling*** **O(10) % at HL-LHC and ILC500**
- ***hhh coupling*** **O(10) % at ILC 500-1000**

Contribution to hγγ

S.K., E. Senaha, T. Shindou, T. Yamada, JHEP1305 (2013) 066.

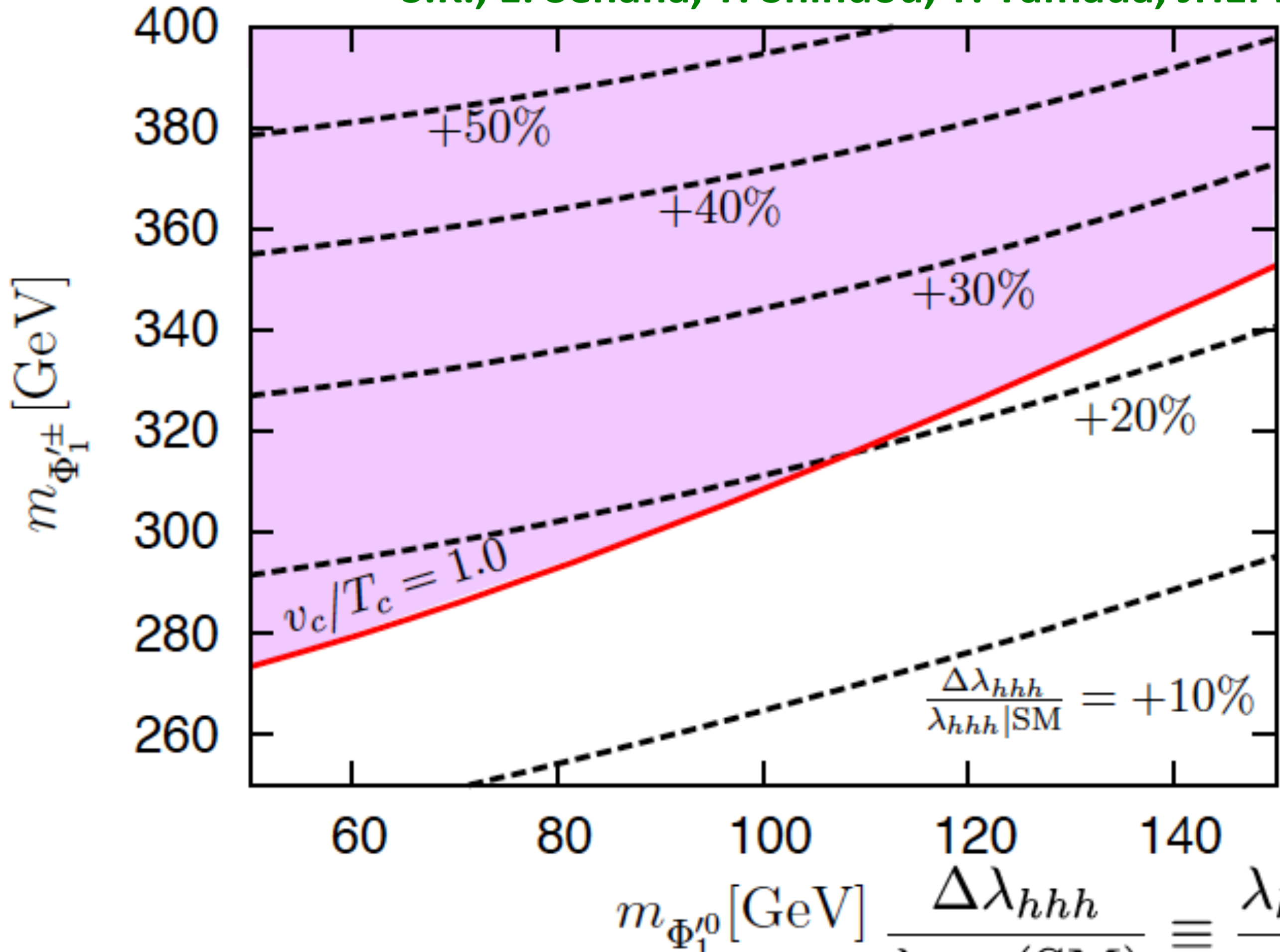


$$\mu_{\gamma\gamma} \equiv \frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to \gamma\gamma)|_{\mathrm{SM}}}$$

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

hhh coupling

S.K., E. Senaha, T. Shindou, T. Yamada, JHEP1305 (2013) 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 $v_c/T_c>1$

Conclusion

- We discussed SUSY $SU(2)_H$ gauge theory with 3 flavour with Z_2 parity
- Confinement occurs at Λ_H, below which the effective theory contains the Higgs sector with 4 Doublets + many singlets with only one λ coupling

  Higgses as Mesons [Particle content (15 mesons) for radiative seesaw]
- Imposing the condition of EW 1st OPT on λ , it turns out that Λ_H is O(10) TeV
- Introducing a Z_2-odd RH-Neutrino, 1- and 3-loop radiative seesaw scenarios can be simultaneously realized at the TeV scale, where all new scalars are used.

  (Hybrid radiative seesaw scenario)
- In our model, Strong 1st OPT, Neutrino masses and DM are explained simultaneously.

  A benchimark scenario where all relevant data are satisfied.
- Our model can be tested at colliders via many discriminative properties (large deviations in *hγγ* and *hhh* couplings, direct searches of exotic scalar fields, multi-component DM, LFV, …)

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Advertisement!

We organize
the 2nd Workshop on
"Higgs as a Probe of New Physics 2015 (HPNP2015)"
at Univ. of Toyama, Japan
11-15 February 2015

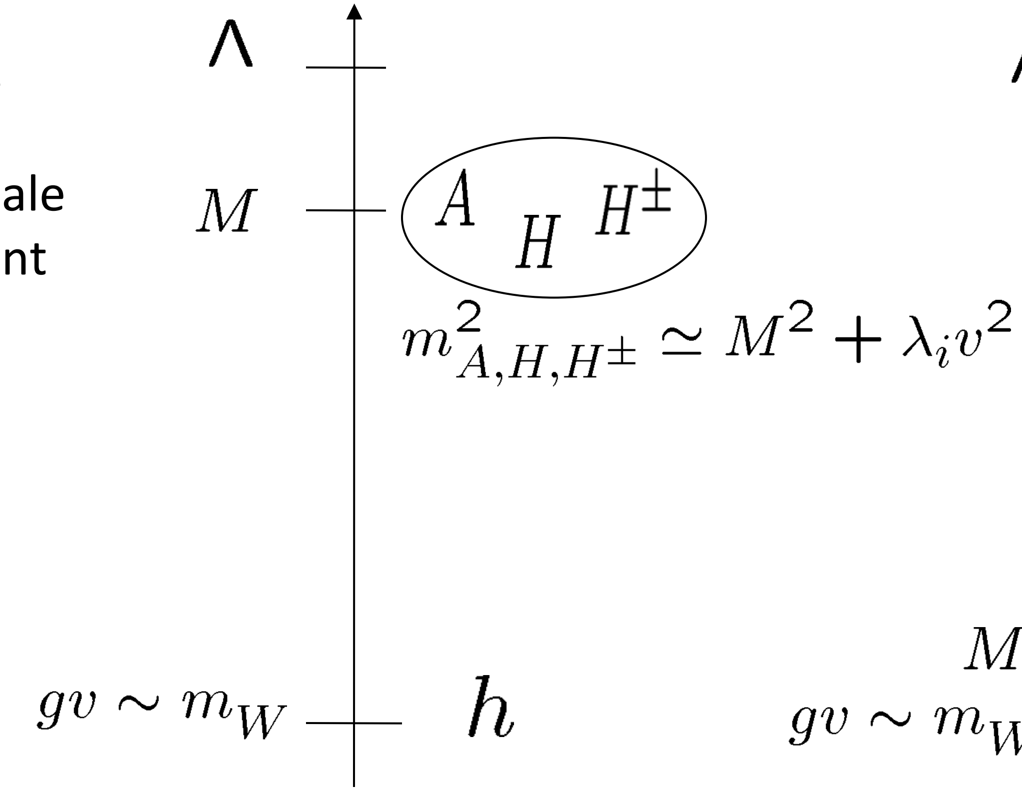
All of you are cordially invited !

Back Up Slides

Two Possibilities

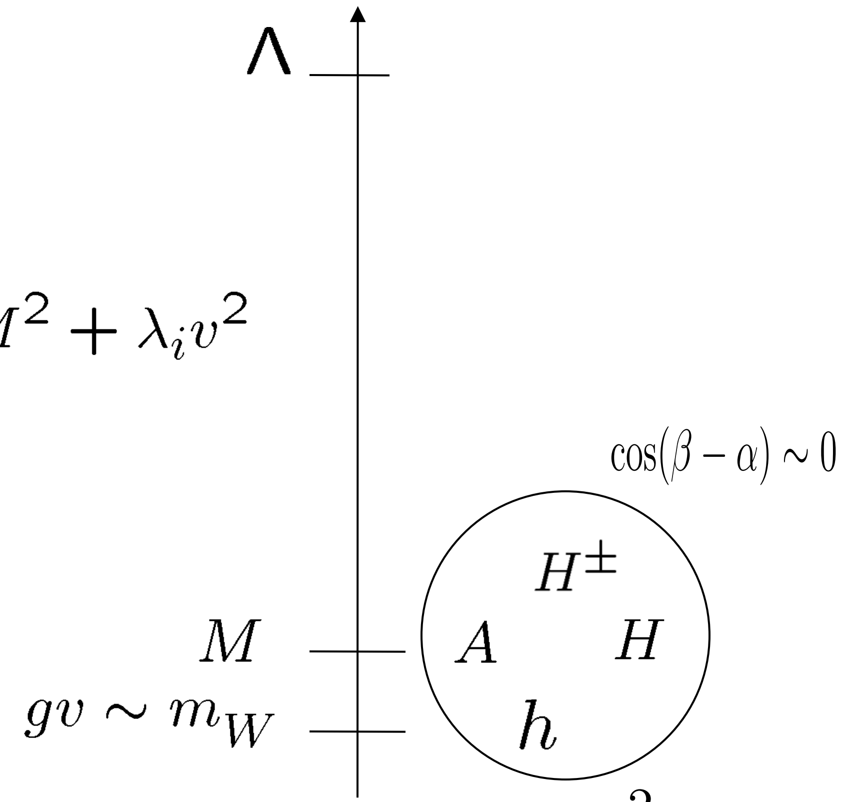
Λ: Cutoff

M: Mass scale irrelevant to VEV



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{v^2}{M^2}\mathcal{O}^{(6)}$$

Effective Theory is the SM



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{nonSM}} + \frac{v^2}{\Lambda^2}\mathcal{O}^{(6)}$$

Effective Theory is an extended Higgs sector

Non-decoupling effect

EW Baryogenesis and the *hhh* coupling

Higgs Potential at Finite Temperatures

$$V_T(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + \ldots..$$

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

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3)$$ + Non-decoupling effect of new particles

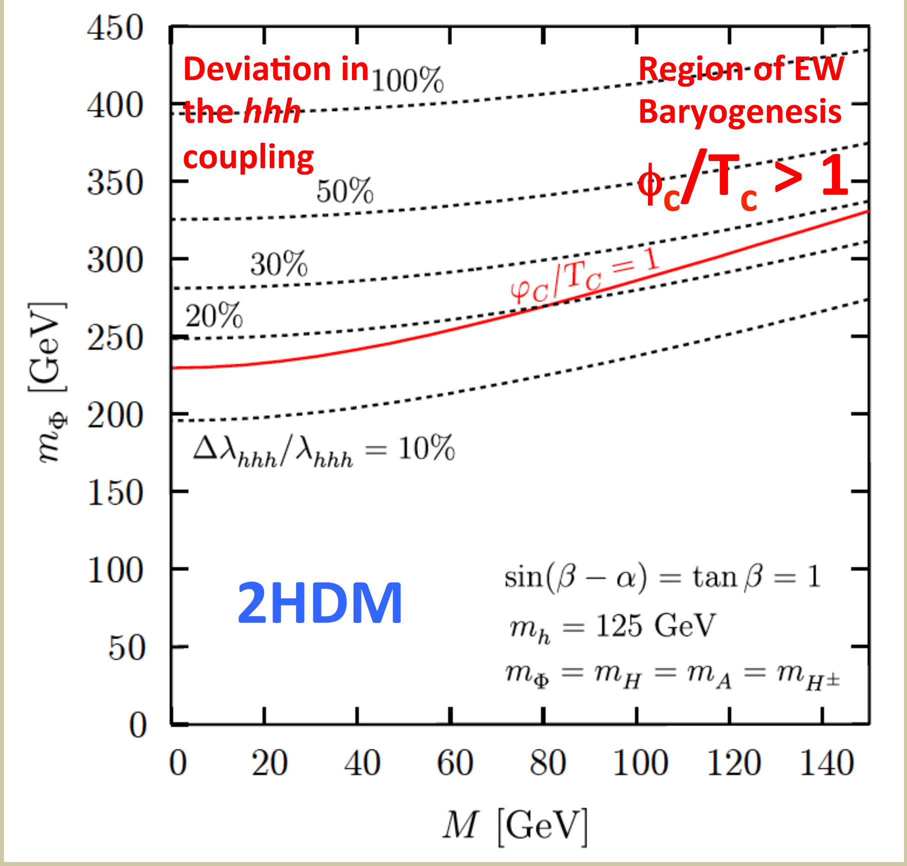
$$\lambda_T = m_h^2/2v^2 + \text{log corrections}$$

Condition of strongly 1st OPT

$$\phi_c/T_c > 1 \Rightarrow 2E/\lambda_{T_c} > 1$$

Strongly 1st OPT
⇔ Non-decoupling effect
⇔ large deviation in *hhh*

SK, Okada, Senaha (2005)



If *hhh* can be measured by 10 % at ILC, EW Baryogenesis can be tested

Connection between cosmology and collider physics

2 Higgs Doublet Model

$$V_{\text{THDM}} = +m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - m_3^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right)$$
$$+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2$$
$$+\lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + (\text{h.c.})\right]$$

$$\Phi_i = \begin{bmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + i a_i) \end{bmatrix} \quad (i = 1, 2)$$

Φ_1 and $\Phi_2 \Rightarrow h, \quad H, \quad A^0, H^\pm \oplus$ Goldstone bosons

↑ ↑ ↑charged

CPeven CPodd

Diagonalization

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} H \\ h \end{bmatrix}$$

$$\begin{bmatrix} z_1^0 \\ z_2^0 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} z^0 \\ A^0 \end{bmatrix}$$

$$\begin{bmatrix} w_1^\pm \\ w_2^\pm \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} w^\pm \\ H^\pm \end{bmatrix}$$

$$\frac{v_2}{v_1} = \tan\beta$$

$$m_h^2 = v^2 \left(\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + \frac{\lambda}{2}\sin^2 2\beta\right) + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$

$$m_H^2 = M_{\text{soft}}^2 + v^2 (\lambda_1 + \lambda_2 - 2\lambda)\sin^2\beta\cos^2\beta + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$

$$m_{H^\pm}^2 = M_{\text{soft}}^2 - \frac{\lambda_4 + \lambda_5}{2} v^2,$$

$$m_A^2 = M_{\text{soft}}^2 - \lambda_5 v^2.$$

M_{soft}: soft breaking scale

$M_{\text{soft}} \quad \left(= \frac{m_3}{\sqrt{\cos\beta\sin\beta}}\right)$:

soft-breaking scale

of the discrete symm.

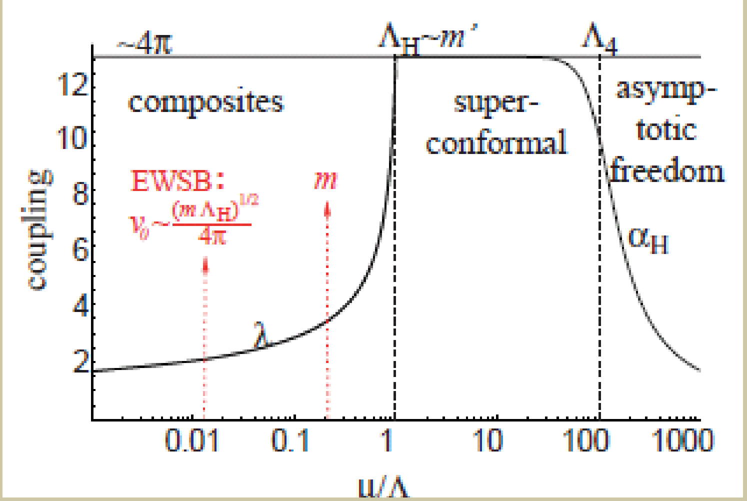
What is the UV Theory beyond Λ_{cutoff} ?

Hint) **Minimal SUSY Fat Higgs Model**

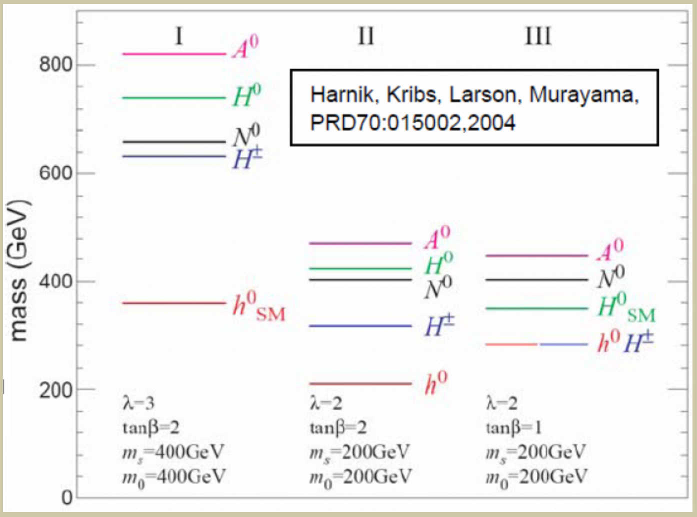
Harnik, Kribs, Larson, Murayama, 2004

- $SU(2)_H$ gauge theory with $N_f = 4 \rightarrow 3$
- Confinement at the cutoff Λ_H (N_f=3)
- Below Λ_H, Higgs fields appear as composite states
- Low energy effective theory is minimized to be the NMSSM
  (2 doublets) H_1, H_2, (1 singlet) N
  - In the $SU(2)_H$ model with N_f=3, 15 composite superfields appear
  - Unnecessary 10 composite fields are made heavy by introducing additional heavy fields
- SM-like Higgs boson is heavy (fat)

$$m_h^2 \simeq \lambda^2 v^2 + \mathcal{O}(m_Z^2)$$



$$W = \lambda(NH_1H_2 - v_0^2)$$

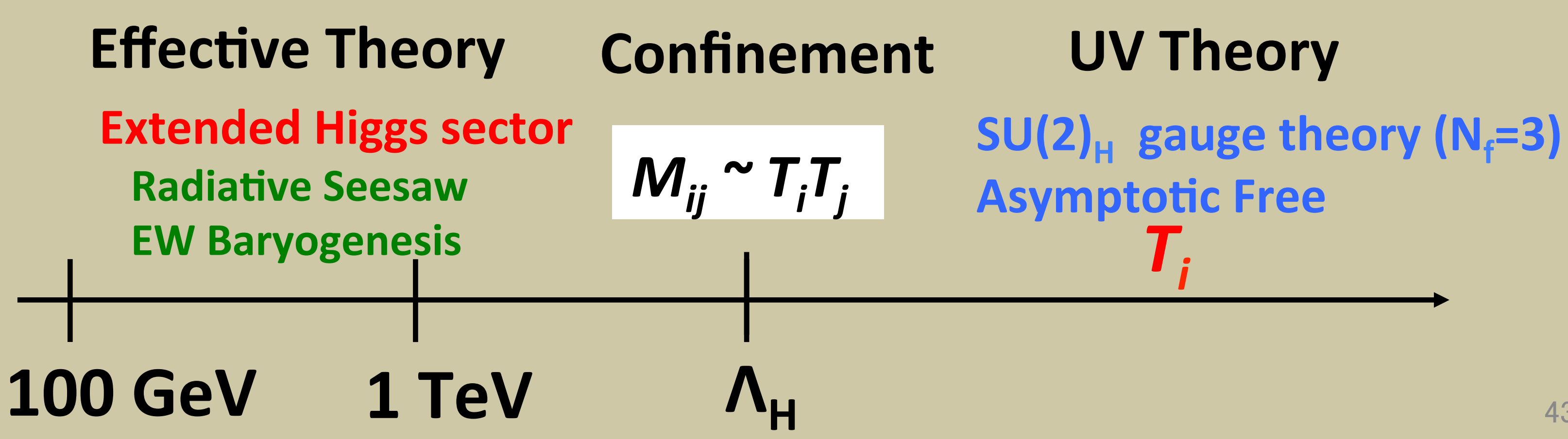


Like the minimal SUSY Fat Higgs

We here consider the model based on the SUSY $SU(2)_H$ gauge theory with N_f=3 in order to explain BSM phenomena

- **Neutirno masses**
- **Dark matter**
- **Baryon Asymmetry of the Universe**

by the TeV scale physics (below Λ_H)



Deriving Yukawa Couplings

- SM Yukawa couplings can be generated by introducing elementary $\mathrm{SU}(2)_L$ doublets, $H'_u,\ H'_d$, that couple as

$$W_{Yuk} = (T_1, T_2)T_3 H'_d + (T_1, T_2)T_4 H'_u + m H'_u H'_d + y_{u\,ij}\, Q^i H'_u U^j + y_{d\,kl}\, Q^k H'_d D^l + \ldots$$

$m \sim \Lambda_H$

and integrating them out below the scale $m\ (\sim \Lambda_H)$.

- Higgs = composite superfield

Top quark = elementary superfield

⇒ Difficulty in deriving *O(1)* top Yukawa coupling

- But we already have an elegant mechanism for this.

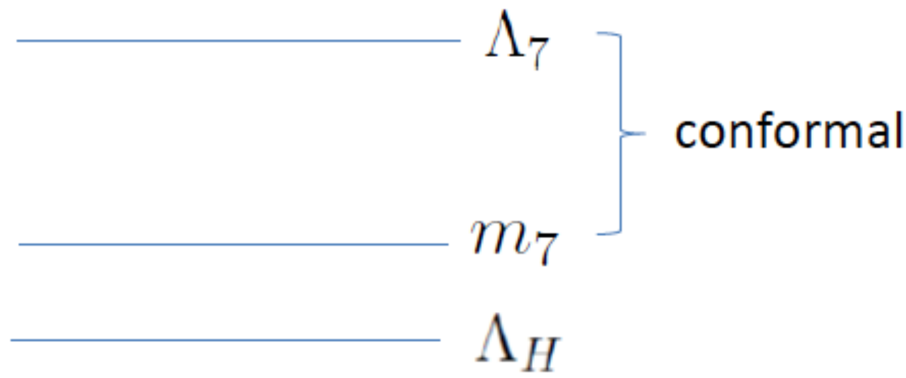
Conformal Enhancement

Murayama

Introduce two more $SU(2)_H$ doublets, T_7, T_8 , with mass term: $W_7 = m_7 T_7 T_8$ ($m_7 > \Lambda_H$).

The theory above the scale m_7 is in the conformal window.

Assume that the theory approaches to the IR fixed point at the scale Λ_7 $(> m_7)$.



➡ Yukawa couplings are enhanced by $\left(\frac{\Lambda_7}{m_7}\right)^{1/2}$ while running from Λ_7 to m_7 .

Snowmass White Paper (Aug. 2013)

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%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.44%	0.22%	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%
κ_d	$10-13\%$	$4-7\%$	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

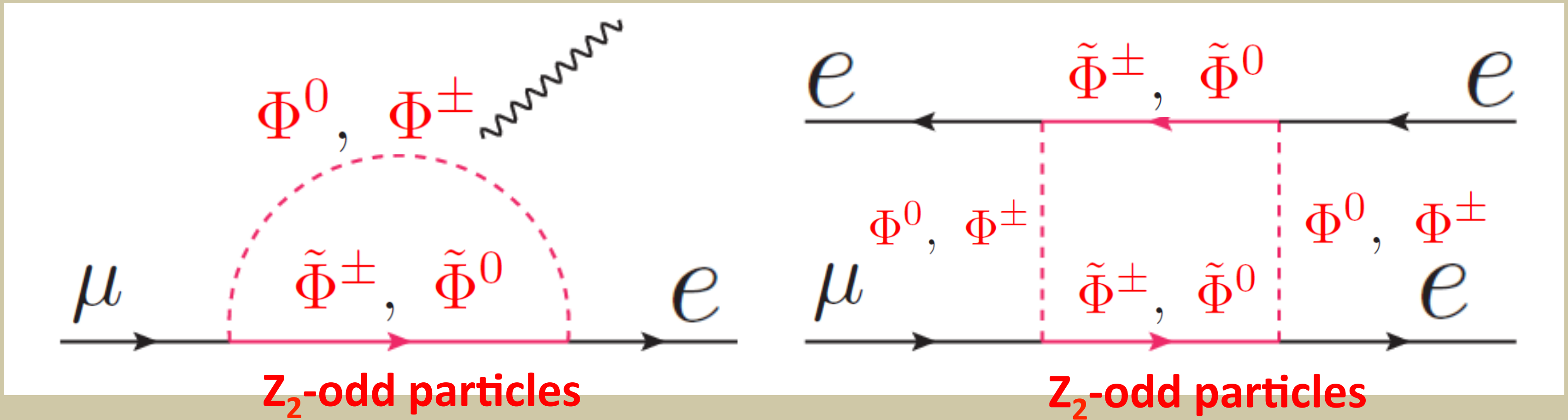
g(hxx)=κ_x g(hxx)$_{SM}$

ILC Higgs White Paper arXiv:1310.0763

Asner, Barklow, Fujii, Haber, Kanemura, Miyamoto,Weiglein, et al.

	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	17 %	8.3 %	3.8 %	2.3 %
gg	6.1 %	2.0 %	1.1 %	0.7 %
WW	4.7 %	0.4 %	0.3 %	0.2 %
ZZ	0.7 %	0.5 %	0.5 %	0.3 %
$t\bar{t}$	6.4 %	2.5 %	1.3 %	0.9 %
$b\bar{b}$	4.7 %	1.0 %	0.6 %	0.4 %
$\tau^+\tau^-$	5.2 %	1.9 %	1.3 %	0.7 %
$\Gamma_T(h)$	9.0 %	1.7 %	1.1 %	0.8 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
hhh	–	83 %	21 %	13 %
BR(invis.)	<0.7 %	<0.7 %	<0.7 %	<0.3 %
$c\bar{c}$	6.8 %	2.9 %	2.0 %	1.1 %

Lepton Flavor Violation



$Br(\mu \rightarrow e\gamma) = 2.8 \times 10^{-13}$ $(< 5.7 \times 10^{-13})$

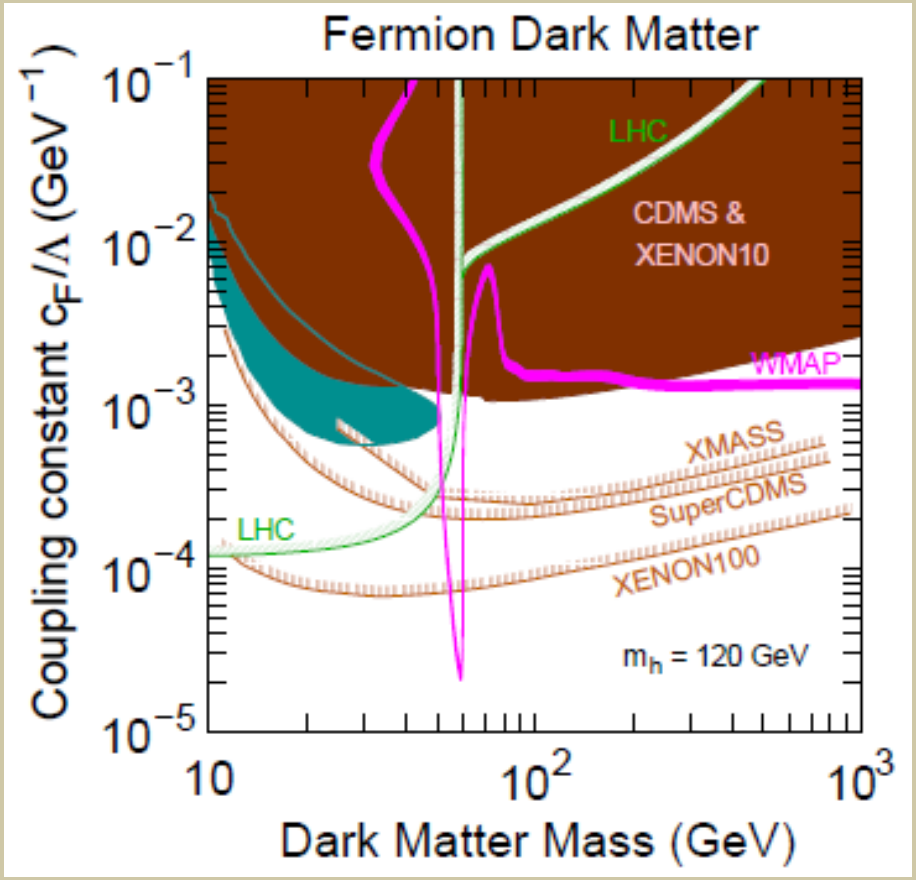
$Br(\mu \rightarrow eee) = 1.6 \times 10^{-16}$ $(< 1.0 \times 10^{-12})$

Current data

MEG:arXiv:1303.0754v2 [hep-ex]

PDG, Phys. Rev. D86, 010001 (2012)

Case of the SM-Higgs Portal DM



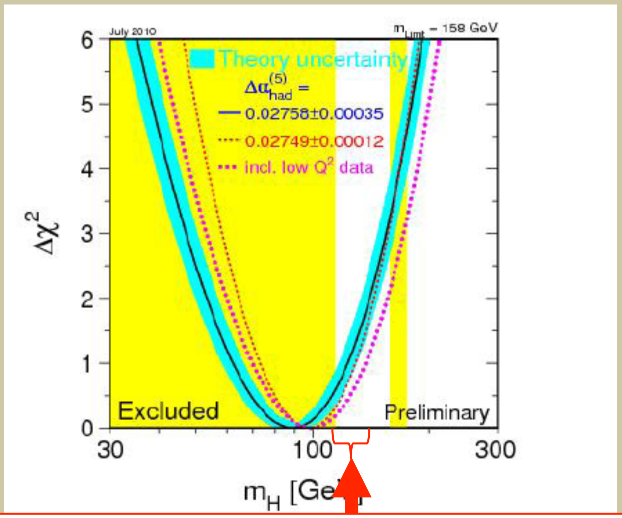
SK, S. Matsumoto, T. Nabeshima, N. Okada, 2010

In 2012 July, a boson was found

The mass is 126 GeV

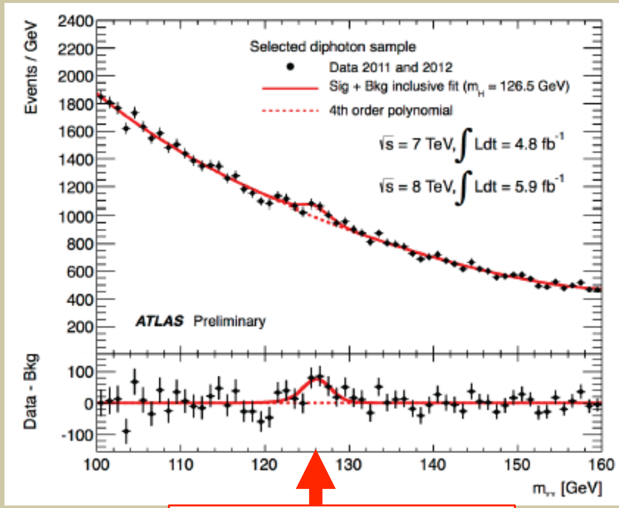
Spin/Parity 0^+

It couples to *γγ, WW, ZZ, bb, ττ, …*



Higgs Mass indicated by LEP/SLC

This is really a Higgs!



Measured Couplings look consistent with the SM Higgs

Why SM-like???

ATLAS/CMS July 2012

New Particle !

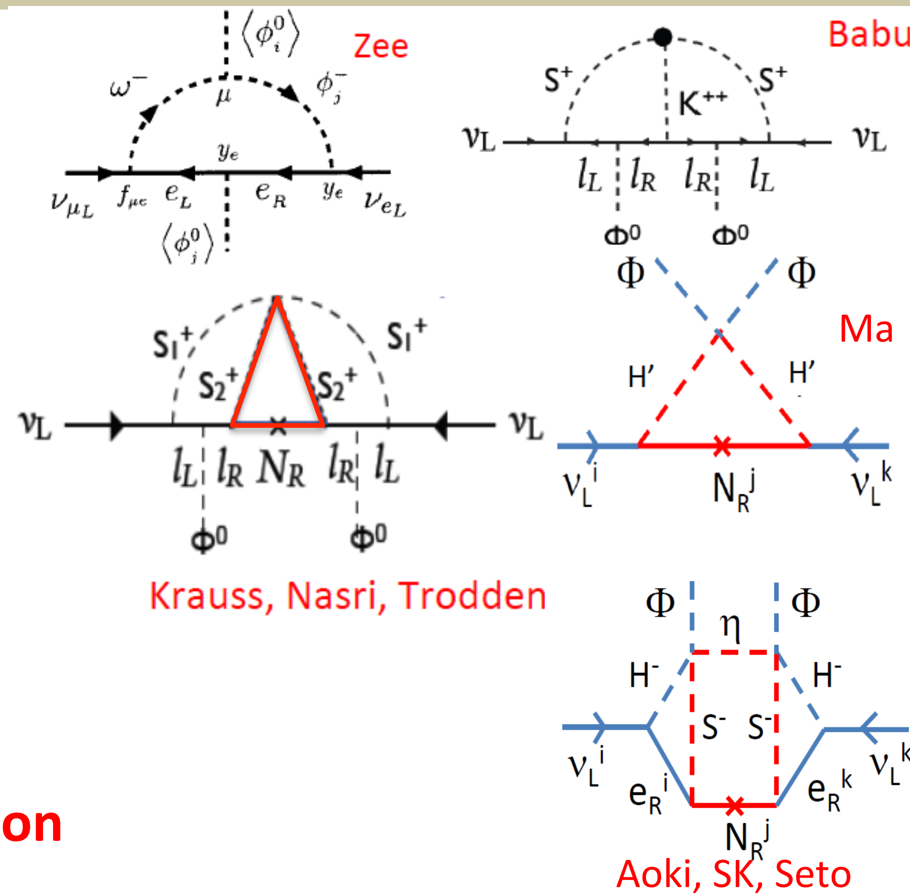
Explanations by the TeV scale physics

Radiative Seesaw Scenario

- Extended Higgs sector
- Z_2 parity
  - Neutrino mass generated at loop levels
  - WIMP Dark Matter
    - Lightest Z_2-odd particle
    - LSP (in SUSY extension)

Electroweak Baryogenesis

- Sphaleron
- Additional CP Phases
- Strong 1st Order Phase Transition



These scenarios are strongly related to the Higgs physics!