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SUSY Strong-but-Light Higgs scenario for Electroweak Baryogeneisis and Radiative Seesaw

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What is duscussed

We here consider a new UV complete model based on the SUSY gauge theory with the confinement in order to solve baryon asymmetry of universe, neutrino mass, and dark matter problems at the TeV scale.

M. Aoki, S.K., O. Seto, Phys. Rev. Lett. 102 (2009) 051805.
M. Aoki, S.K., O. Seto, Phys. Rev. D80 (2009) 033007.
M. Aoki, S.K., K. Yagyu, Phys. Rev. D83 (2011) 075016.
S.K., E. Senaha, T. Shindou, Phys. Lett. B 706, (2011) 40.
S.K., T. Shindou, T. Yamada, Phys. Rev. D86 (2012) 055023.
S.K., E. Senaha, T. Shindou, T. Yamada, JHEP1305 (2013) 066.
S.K., N. Machida, T. Shindou, T. Yamada, arXiv:1309.3207

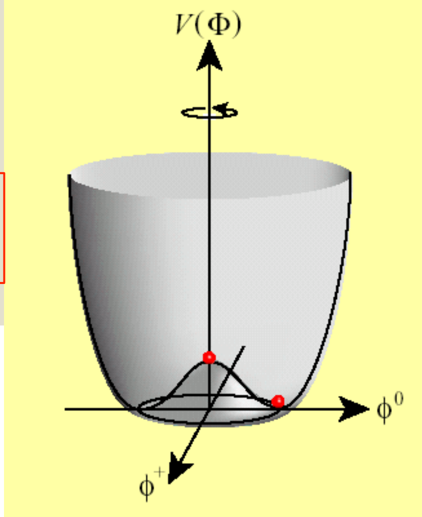
Higgs in the SM

A Higgs boson was found last year and found to be SM like

Nothing has been solved!

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

$$m_H^2 = 2\,\lambda\, v^2$$



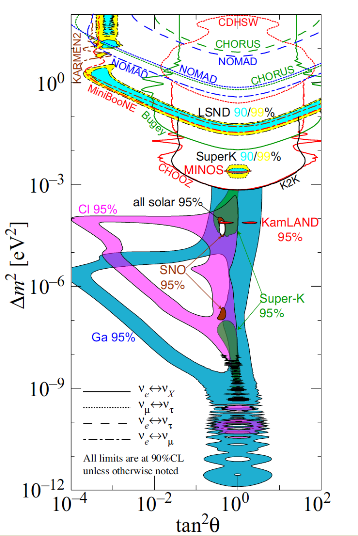
- Why 126 GeV?
- Why $-\mu^2 < 0$? (Origin of EWSB)
- Shape:
  - Minimal Higgs/Some extensions?
- Essence:
  - Elementary field/Composite?
- Dynamics: What is the origin of the Higgs force λ ?
  - Weak interaction/Strong interaction?

Phenomena beyond the SM

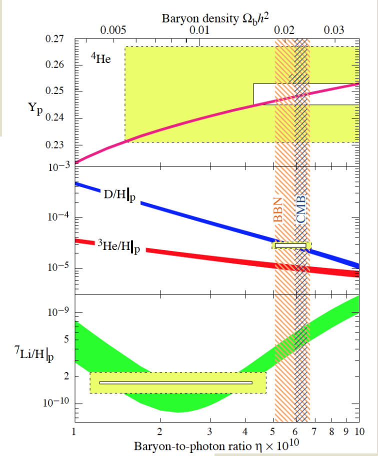
We already know BSM phenomena:

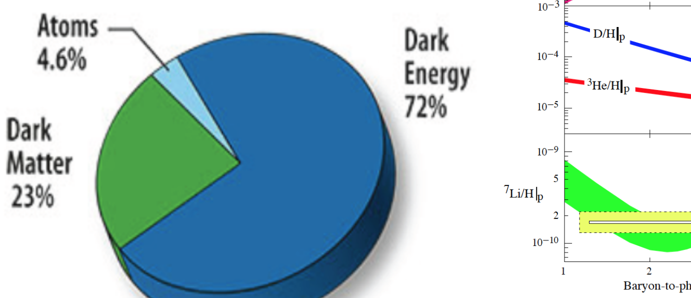
- **Neutrino oscillation**
  - $\Delta m^2 \sim 8\times10^{-5}\ \mathrm{eV}^2,\ \Delta m^2 \sim 2\times10^{-3}\ \mathrm{eV}^2$
- **Dark Matter**
  - $\Omega_{DM}h^2 \sim 0.11$
- **Baryon Asymmetry of the Universe**
  - $n_B/n_\gamma \sim 6\times10^{-10}$

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



PDG2012





NASA/WMAP Science Team

To understand these phenomena, we need to go beyond-SM

At which scale?

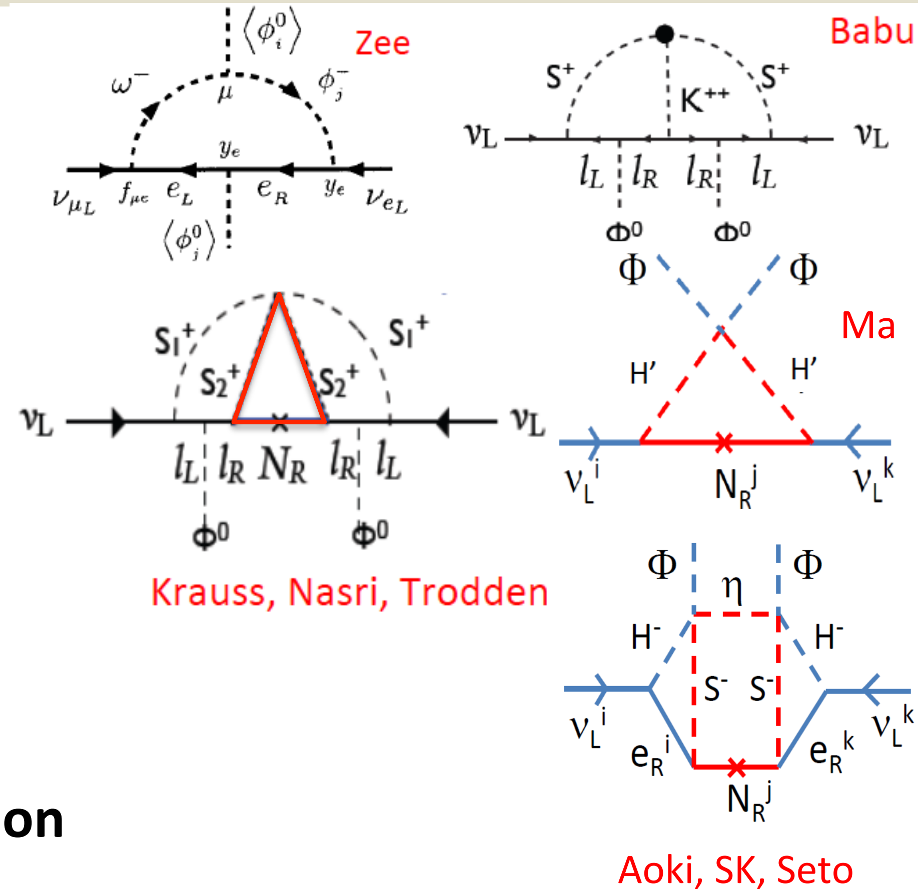
Explanations at the TeV scale physics

Radiative Seesaw Scenario

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

Electroweak Baryogenesis

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



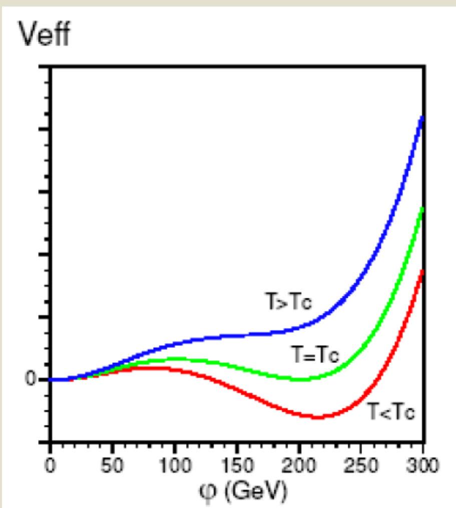
These scenarios are strongly related to the Higgs physics!

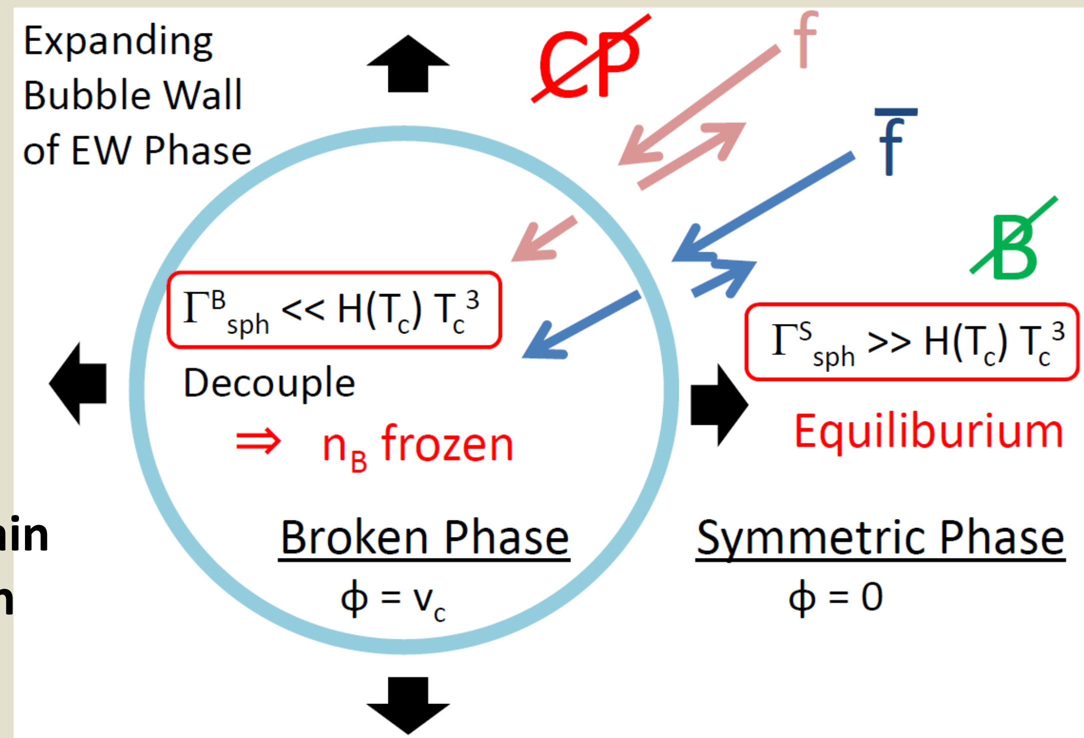
Electroweak Baryogenesis

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

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 to retain sufficient baryon number in Broken Phase

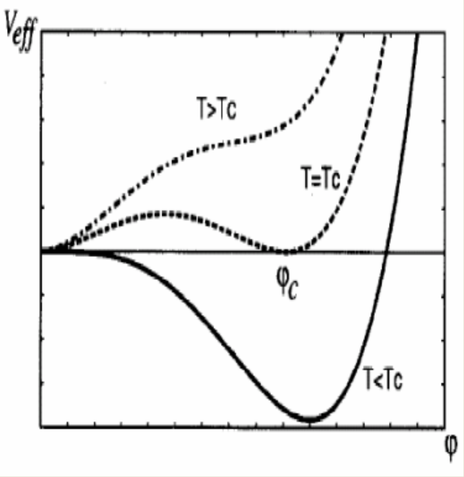
$$\frac{\varphi_c}{T_c} \gtrsim 1$$

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

Finite Temperature Potential

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

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



Excluded in the SM

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) \quad \Rightarrow \quad m_h << 126\ \text{GeV!}$$

Muti-Higgs models can satisfy the condition

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

$$E \propto \frac{m_\Phi^3}{\lambda_T} = \frac{(\lambda')^{3/2}}{\lambda_T} \quad \Rightarrow \quad \lambda' > \lambda_{SM} = 0.3 \ \ (\text{for } m_h = 126\ \text{GeV})$$

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

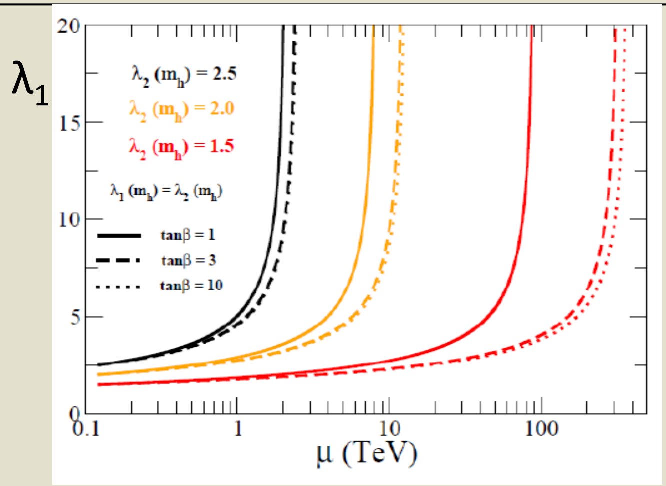
EW Phase Transition and Landau Pole

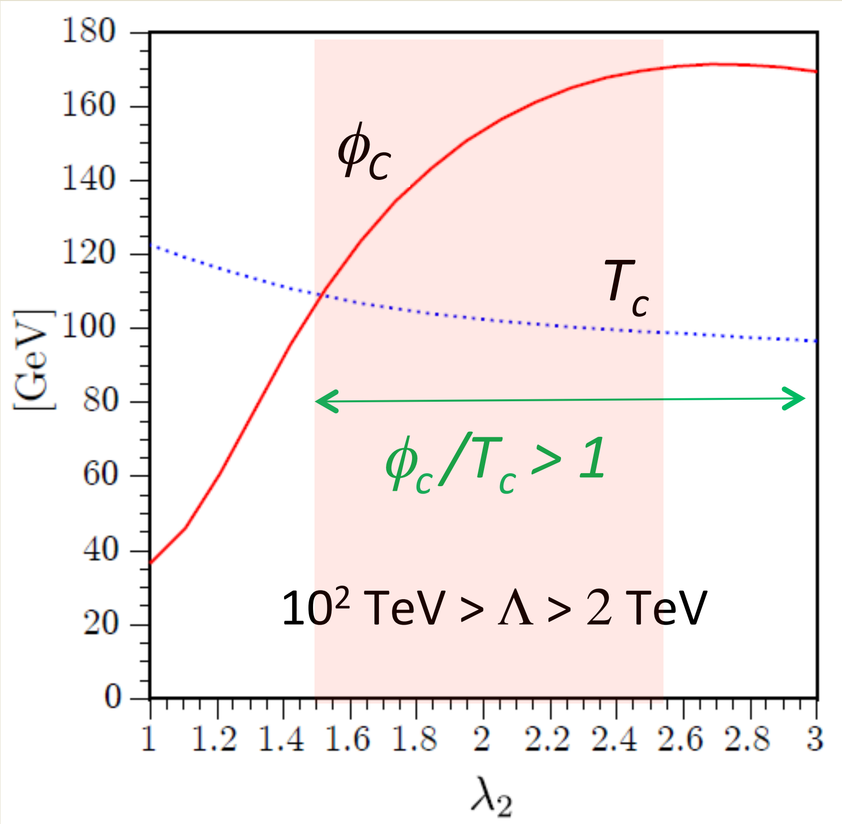
Strong 1st OPT → large λ' at EW
→ Landau pole

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

Ex) 4HDM+Ω

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





$$\varphi_c/T_c > 1 \Rightarrow \Lambda_{cutoff} = 2 - 100 \text{ TeV}$$

What is the UV theory?

Ex) **Minimal SUSY Fat Higgs Model**

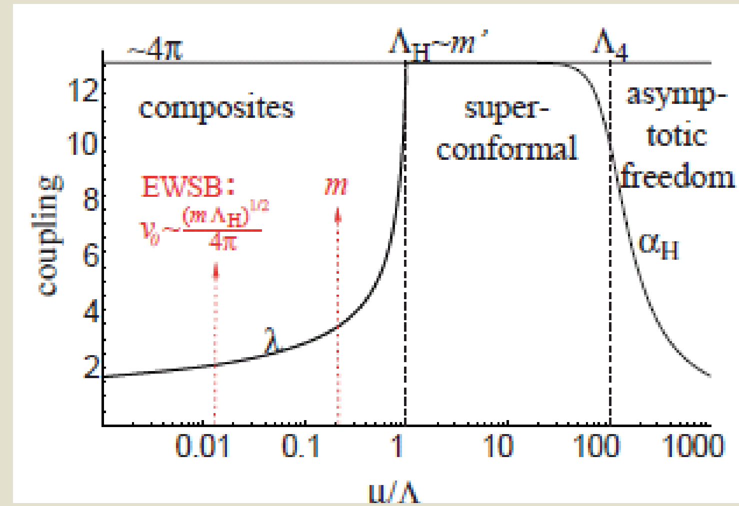
Harnik, Kribs, Larson, Murayama, 2004

- **$SU(2)_H$ gauge theory with N_f=4→3**
- **Confinement at the cutoff Λ_H**
- **Below Λ_H, Higgs fields appear as composite states**

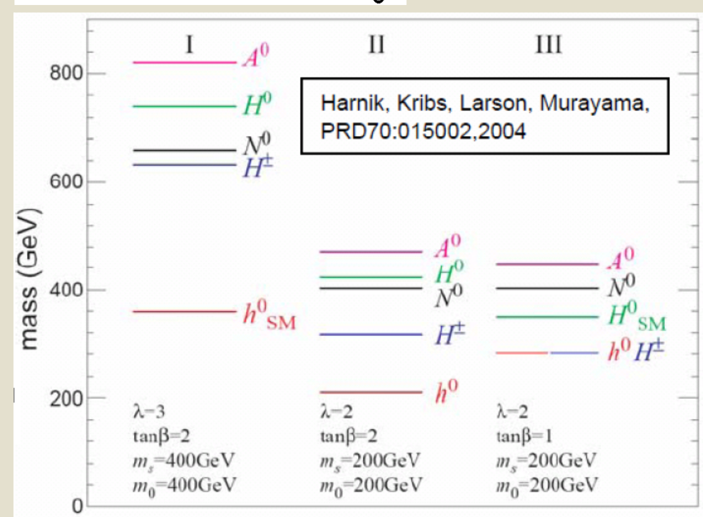
  H_1, H_2, N

- **Low energy effective theory is minimized to be the *nMSSM***
- **SM-like Higgs boson is heavy (fat)**

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



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



Revisit the minimal SUSY Fat Higgs

- Particles are minimal at low energy (nMSSM) — H_1, H_2, N
  - In $SU(2)_H$ with N_f=3 model, 15 composite states appear
  - Unnecessary 10 composite superfields are made heavy in an artificial way by introducing newly additional heavy fields

- A 125 GeV can be easily possible with λ＝O(1) :

  Fat Higgs (tanβ~1) ⇔ Light Higgs (tanβ > 10)

$$m^2_{h\text{tree}} < M_Z^2 \left(\cos^2 2\beta + \frac{2\lambda^2}{g^2+g'^2}\sin^2 2\beta\right)$$

- Neutrino Masses, Baryon Asymmetry and DM are not really discussed

We reconsider the $SU(2)_H$ gauge theory with N_f=3 in order to explain these BSM problems.

Neutrino Masses in the Strong-But-Light Scenario

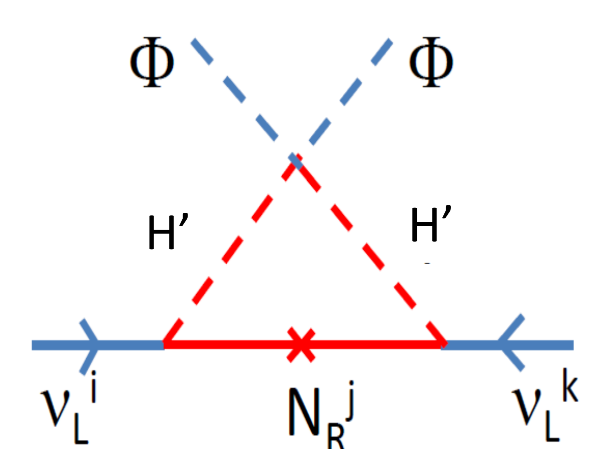
- EW Baryogenesis requires a relatively large coupling in a extended Higgs sector, which causes Landau Pole at O(10) TeV
- In such a case, we may consider the scenario where dim-5 operators ($\nu\nu\Phi\Phi$) appears below the Landau pole
- Neutrino masses are generated at O(1) TeV in the radiative seesaw scenario

Radiative seesaw **with Z_2**

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

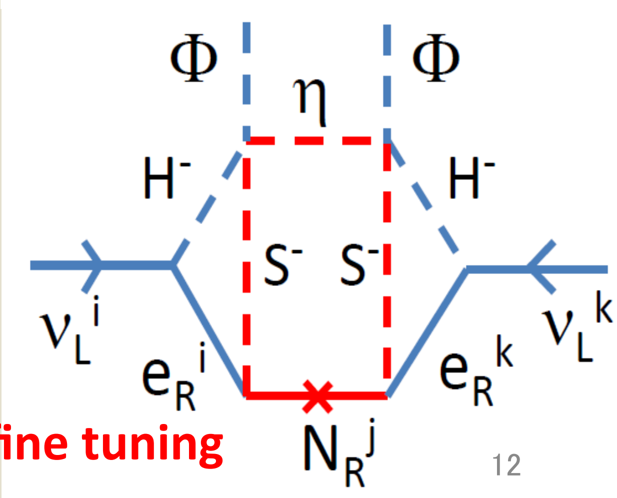
Ex1) 1-loop   Ma (2006)

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



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

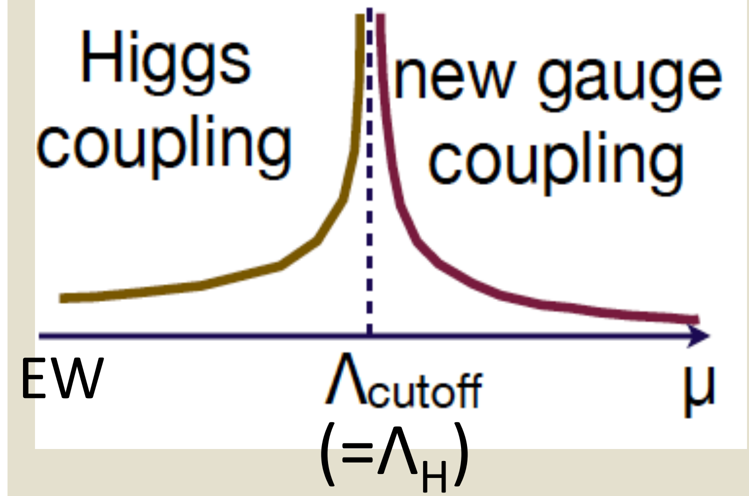
– Neutrino mass from O(1) coupling
– 2HDM + η^0 + S^+ + N_R
– DM candidate [η^0 (or NR)]
– Electroweak Baryogenesis



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

Outline of the Model

- **Origin of the Higgs force (λ) is the SU(N_c) gauge symmetry (N_c=2, N_f=3) [Same as Minimal SUSY Fat Higgs model]**
  Harnik, et al
- **Confinement ($N_f = N_c+1$) at Λ_H (∼ Landau Pole)** **Intriligator and Seiberg**
- **At low energy 4HDM+Singlets appears with a coupling λ (Higgses as Mesons)**
- **λ(EW) is set by ϕc/Tc > 1 (strong) but within perturbative ⇒ Λ_H = O(10) TeV**



By the extended Higgs sector with additional Z_2 and RH Neutrinos, radiative seesaw scenario is realized at TeV scale

SUSY $SU(2)_H$ gauge theory

Minimal model for confinement (N_f=3)
→ 3 pairs of $SU(2)_H$ fundamental rep.

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

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

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

Effective Theory

- The theory becomes strongly coupled at Λ_H, and T_i (i=1-6) are confined

K. Intriligator and N. Seiberg (1996)

- Below Λ_H the theory is described by Meson superfields

$$M_{ij} = T_i T_j$$

- Effective Superpotential

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

- By using Naïve Dimensional Analysis, 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

Higgses as Mesons

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

Field	$SU(2)_L$	$U(1)_Y$	Z_2
H_u	2	$+1/2$	$+$
H_d	2	$-1/2$	$+$
Φ_u	2	$+1/2$	$-$
Φ_d	2	$-1/2$	$-$
Ω^+	1	$+1$	$-$
Ω^-	1	-1	$-$
N, N_Φ, N_Ω	1	0	$+$
ζ, η	1	0	$-$

MSSM Higgs doublets (H_u, H_d)

Exotic Superfields:
- Extra Higgs doublets (Φ_u, Φ_d)
- Charged Higgs singlets (Ω^+, Ω^-)
- Z_2-even Higgs singlets (N, N_Φ, N_Ω)
- Z_2-odd Higgs singlets (ζ, η)

Superpotential is rewritten as

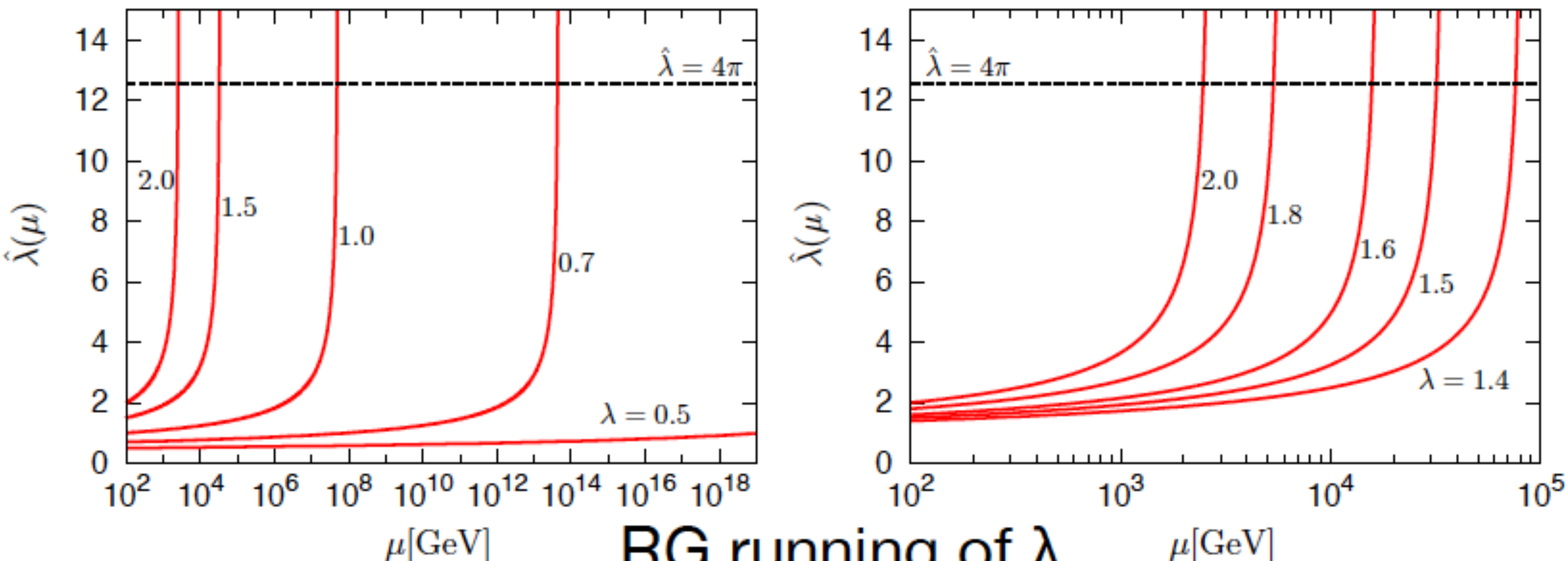
$$W_{eff} = \lambda \{ N(H_u H_d + v_0^2) + N_\Phi(\Phi_u \Phi_d + v_\Phi^2) + N_\Omega(\Omega^+ \Omega^- + v_\Omega^2) - N N_\Phi N_\Omega - N_\Omega \zeta \eta + \zeta H_d \Phi_u + \eta H_u \Phi_d - \Omega^+ H_d \Phi_d - \Omega^- H_u \Phi_u \}$$

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.

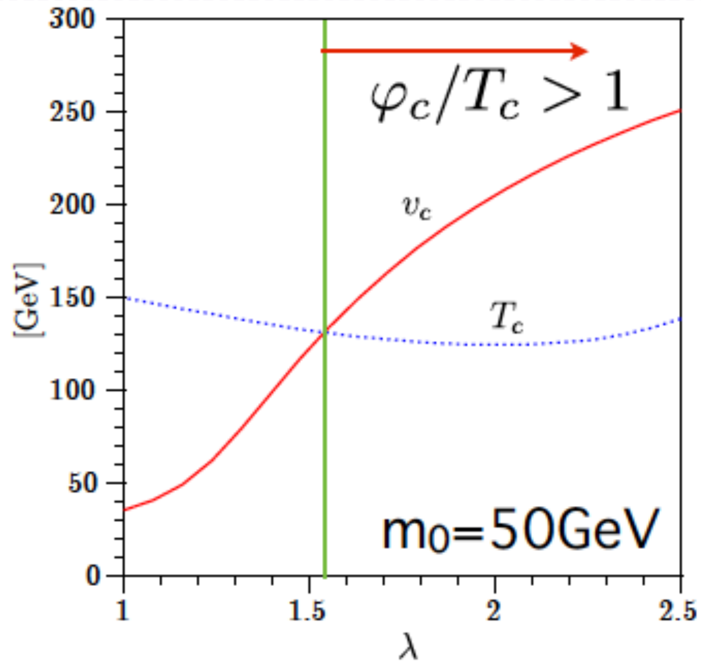
Benchmark:

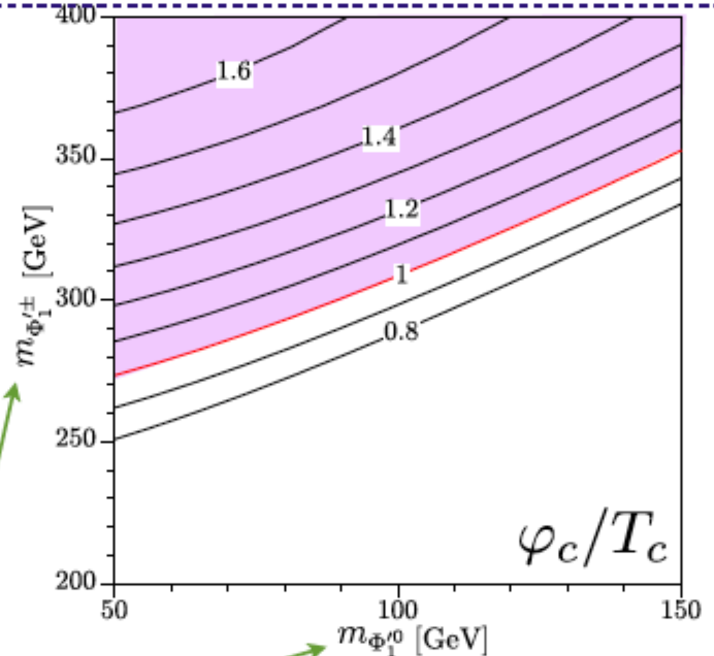
m_h=126GeV

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

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

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



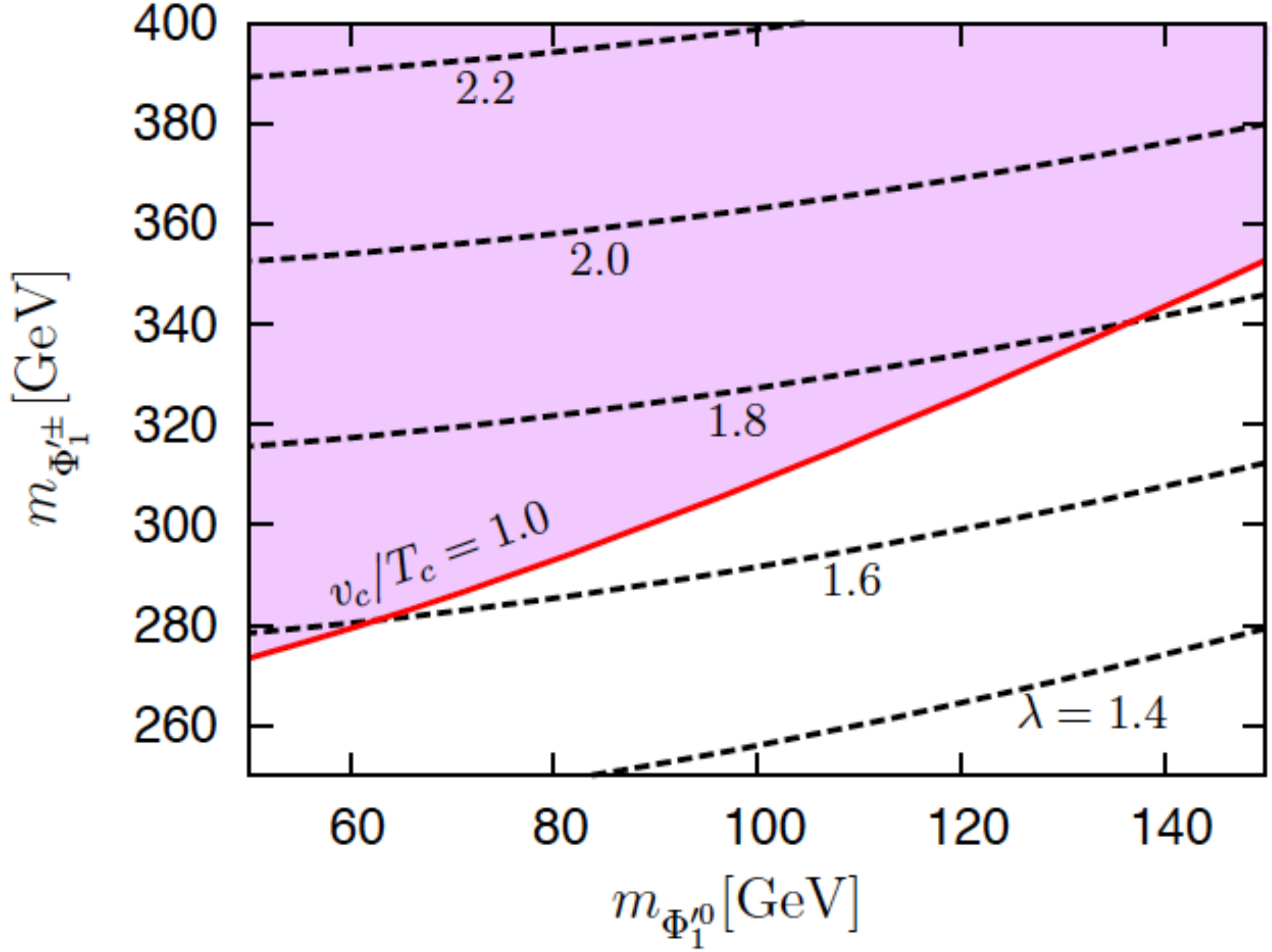


$\varphi_c/T_c > 1$ can be satisfied!!

Lightest Z_2 odd masses

1st order EWPT

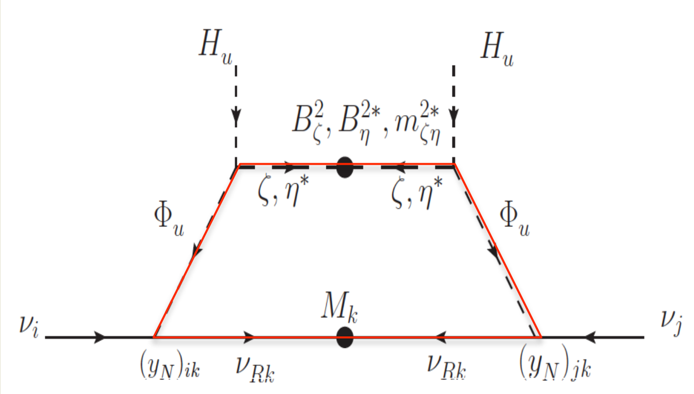
S.K., E. Senaha, T. Shindou, T. Yamada, JHEP1305 (2013) 066.

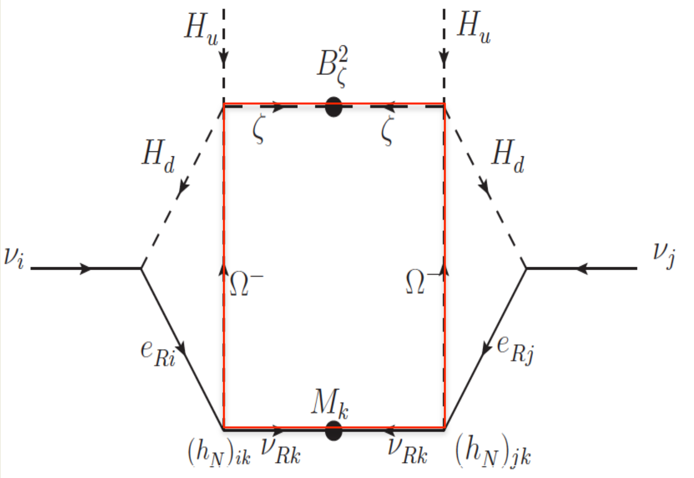


$$\varphi_c/T_c > 1 \Longrightarrow \lambda \gtrsim 1.5 \quad (\Lambda_H \lesssim 20\text{TeV})$$

Radiative Seesaw

- **Addition of right handed neutrinos N_R^i which are Z_2 odd**
- **Neutrino masses can be generated at 1- and 3-loop diagrams (all necessary particles are already prepared in the $SU(2)_H \times Z_2$ model!)**
- **SUSY Extension of**
  - **1-loop: Model by Ma**
  - **3-loop: Model by Aoki, SK and Seto**
- **Lightest Z_2-odd particle is the other candidate of DM than LSP**
  → Rich phenomenology of
  Multi-component DM!





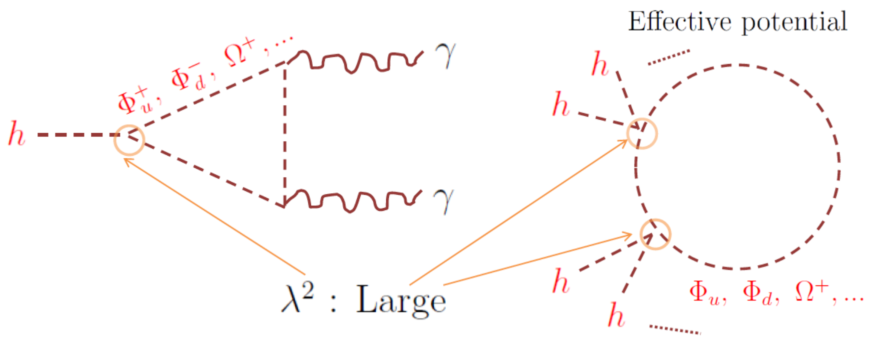
Example of dim-5 operators for neutrino masses below Λ_H

S.K., N. Machida, T. Shindou, T. Yamada, arXiv:1309.3207

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** (essence of Strong-but-Light scenario)
  - Non-decoupling effect
  - Deeply connected with $\varphi c/Tc > 1$



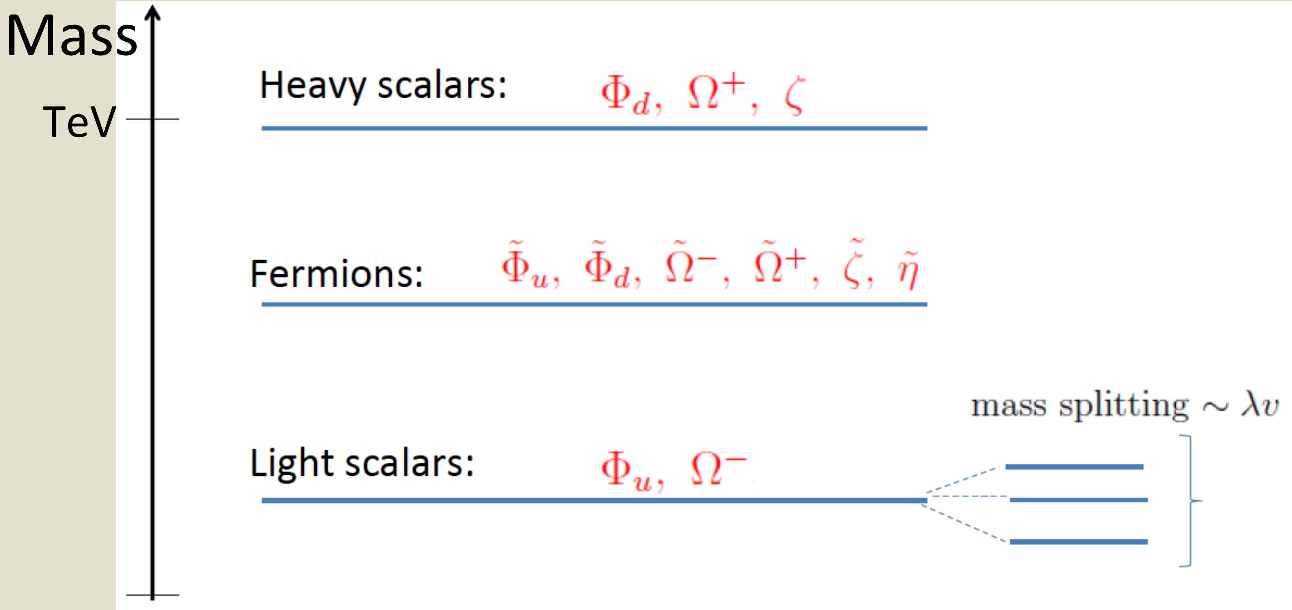
- **Coupling meausrement**
  - *hγγ coupling* O(10) % at HL-LHC and ILC500
  - *hhh coupling* O(10) % at ILC1000

Benchmark spectrum

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

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

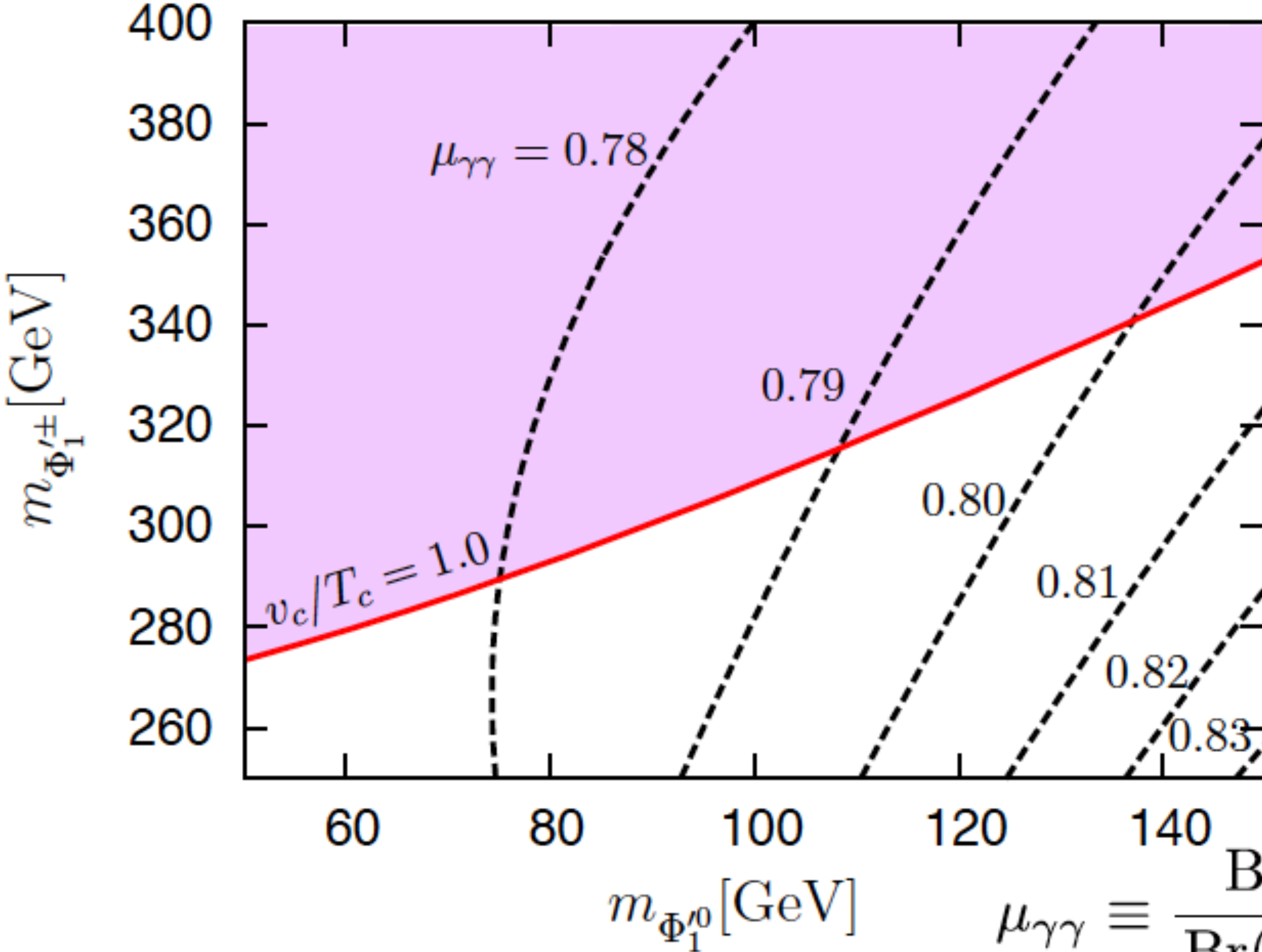
$$m_0^2 \equiv \bar{m}^2_{\Phi_u} = \bar{m}^2_{\Omega_-} \text{ (Scanned)} \qquad (m_\phi^2 = \bar{m}_\phi^2 + c_\phi \lambda^2 v^2)$$



- Light scalars are essential for strongly first order phase transition.
- Some of the scalars are assumed to be heavy in order that radiative corrections to the SM-like Higgs mass is not negative.

Contribution to hγγ

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

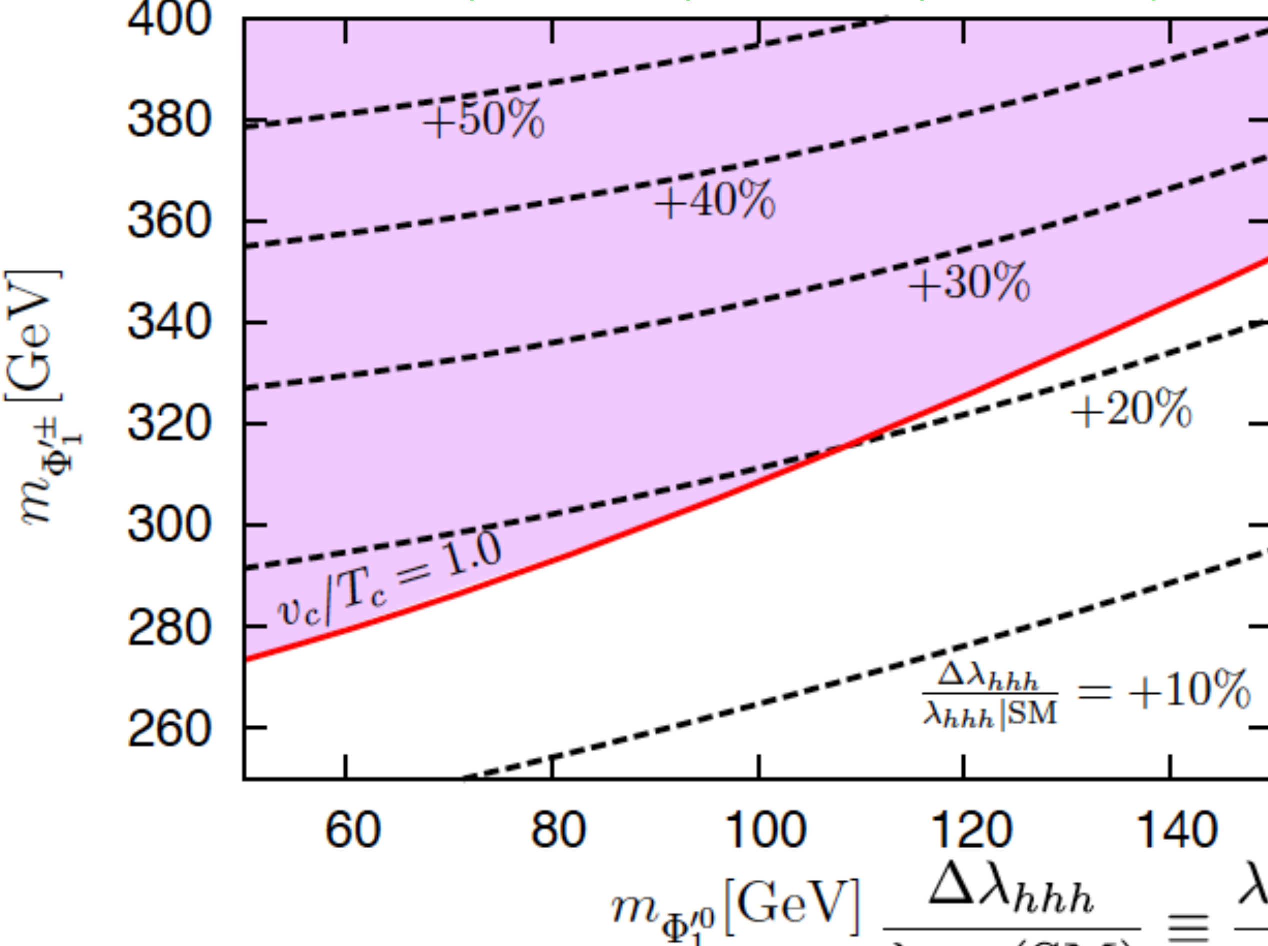


$$\mu_{\gamma\gamma} \equiv \frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to \gamma\gamma)|_{\mathrm{SM}}}$$

~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.



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

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

Conclusion

- **We have discussed the $SU(2)_H$ gauge theory with 3 flavour (same as the minimal fat Higgs model) but with additional Z_2 parity**

- **Confinement occurs at Λ_H, below which the effective theory contains the Higgs sector of 4D+Singlets with only one λ coupling in the superpotential (Higgses as Mesons)**

- **By imposing the condition of EW 1st OPT, λ is O(1), which corresponds that Λ_H is around O(10) TeV**

- **By introducing RH neutrinos, 1- and 3-loop radiative seesaw scenarios can be realized at the TeV scale without any further theory assumption**

- **In addition to 1st OPT for successful EW baryogenesis, Neutrino masses are explained and DM candidates exist. (We found benchmark scenarios)**

- **Our model can be tested at future collider experiments via many discriminative properties**

Back Up Slides

In this talk

- We discuss the Strong-but-Light scenario, requiring the condition of the 1st oder phase transition for realization of EW baryogenesis
- A UV complete model based on SUSY Yang-Mills theory to produce such phenomenological models at low energy
- Extension for explaining DM and Neutrino mass at the TeV scale (below the Landau pole), imposing the Z_2 parity
- Phenomenological consequences

EW baryogenesis and the *hhh* coupling

Finite temperature potenital

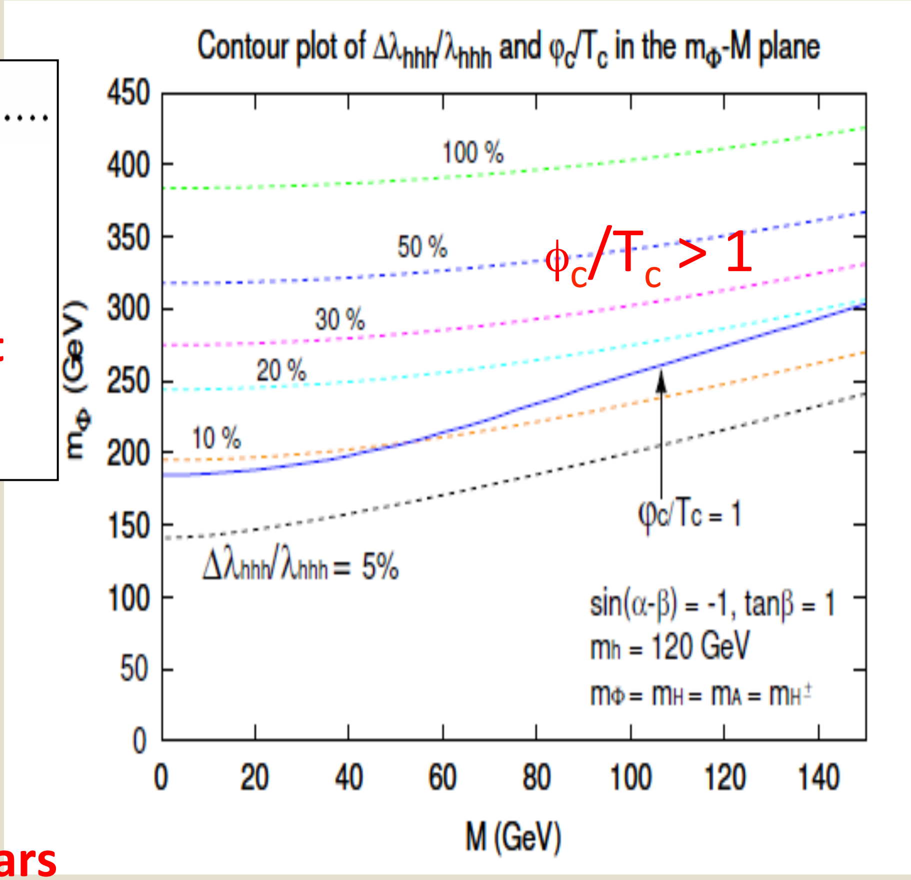
$$V_T(\phi,T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + \ldots..$$

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

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3)$$ + **New Phys. Effect**

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

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



SM: $m_h < 60$GeV **Excluded!**

2HDM: m_h = 125GeV Possible due to **Non-decoupling effect of extra scalars**

SK, Okada, Senaha (2005)

$$V(\phi,T) \Longleftrightarrow V(\phi)$$

Strong 1st OPT ⇔ Large *hhh* coupling

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.

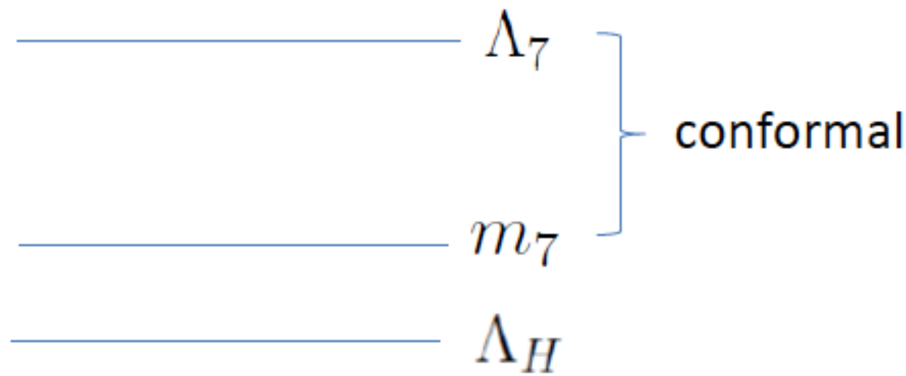
Conformal Enhancement

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 $\Lambda_7\ (> m_7)$.



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

Low Energy Theory

- **Effective μ-term is generated by the VEVs of N, N_{Φ}, N_{Ω} triggered by the tadpole terms**

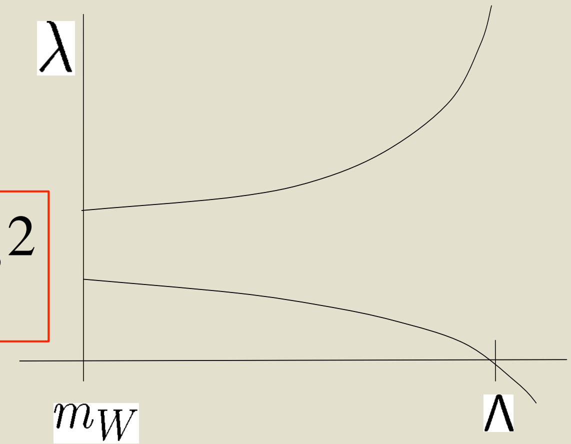
- **The coupling $\lambda(m_Z)$ depends on the scale Λ_H**
  - **→ We fix it by the condition of strong 1[st]OPT**
  - **→ Λ_H = O(10) TeV (using NDA)**

- **EW symmetry breaking is triggered by soft-SUSY breaking terms like in the MSSM**

Higgs mass is 125 GeV

- Case 1: in the SM, the 125 GeV Higgs boson implies a weakly coupled theory
  - B-function is negative
  - Vacuum stability may break down at a very high energy
  - No Landau Pole

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



$$16\pi^2 \mu \frac{d}{d\mu}\lambda = 24\lambda^2 - 6y_t^4 + \ldots.$$

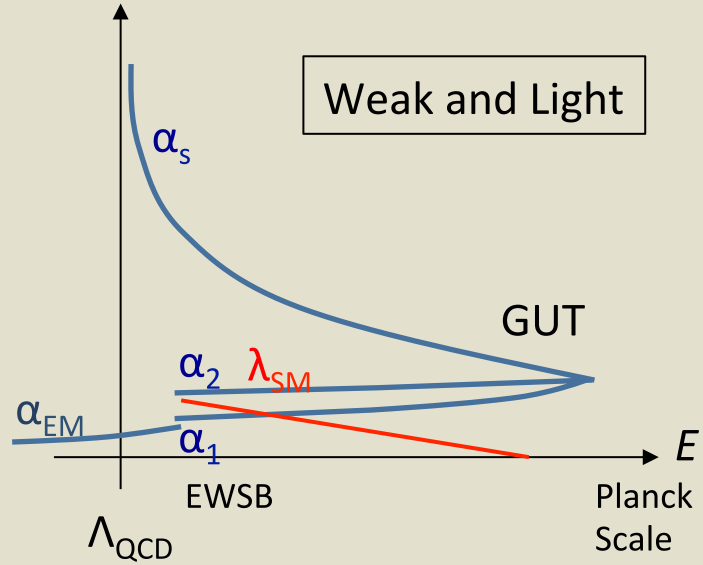
- Case 2: If the Higgs sector is non-minimal with strong couplings but predicting the 125GeV SM-like Higgs boson, a Landau pole appears below the Planck scale

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

Scenarios for Higgs boson dynamics

- Weak and Light scenario
  - Perturbative
  - Grand Desert
  - Traditional Grand Unification

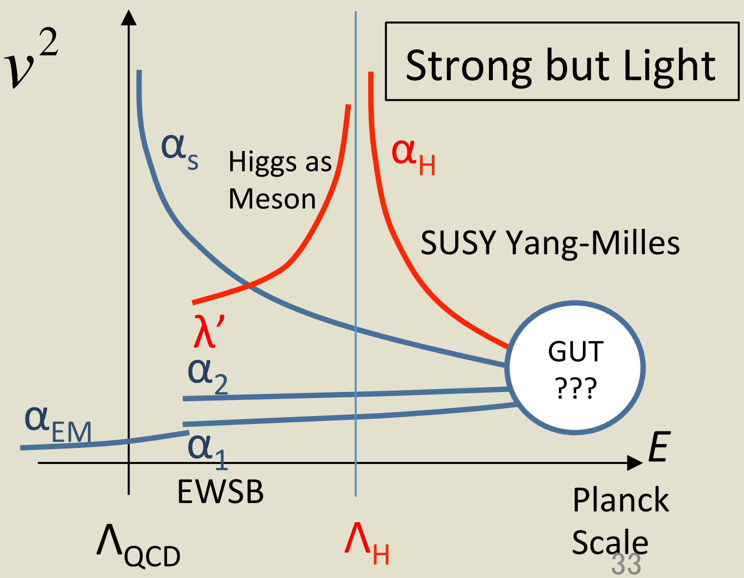
$$m_h^2 \propto \lambda v^2$$



- Strong but Light scenario

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

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



Neutrino Mass

Neutirno Mass Term (= Effective dim-5 operator)

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

$<\phi> = v = 246\text{GeV}$

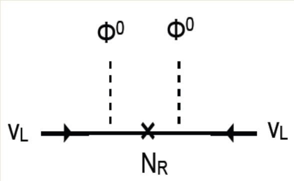
Mechanism for tiny masses:

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

Seesaw (tree level)

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

Minkowski
Yanagida
Gell-Mann et al



(M>> 1TeV)

Quantum Effects

N-th order of perturbation theory

$m^\nu{}_{ij} = [g^2/(16\pi^2)]^N\, C_{ij}\, v^2/M$ (M can be 1 TeV)