Supersymmetric strongly-coupled Higgs sector and Electroweak baryogenesis

Toshifumi Yamada

KEK -> National Central University (Taiwan)

In collaboration with
S.Kanemura (Toyama), E.Senaha(Nagoya) and T.Shindou (Kogakuin).

Based on papers
Phys.Rev.D86 (2012) 055023 [arXiv:1206.1006 [hep-ph]] and
arXiv:1211.5883 [hep-ph].

Contents

1. Introduction

 ―Extended Higgs models and Electroweak baryogenesis

2. UV complete extended Higgs model that can realize strongly first order electroweak phase transition

3. Electroweak phase transition in the model

4. Collider signatures of the model

5. Conclusions

Introduction

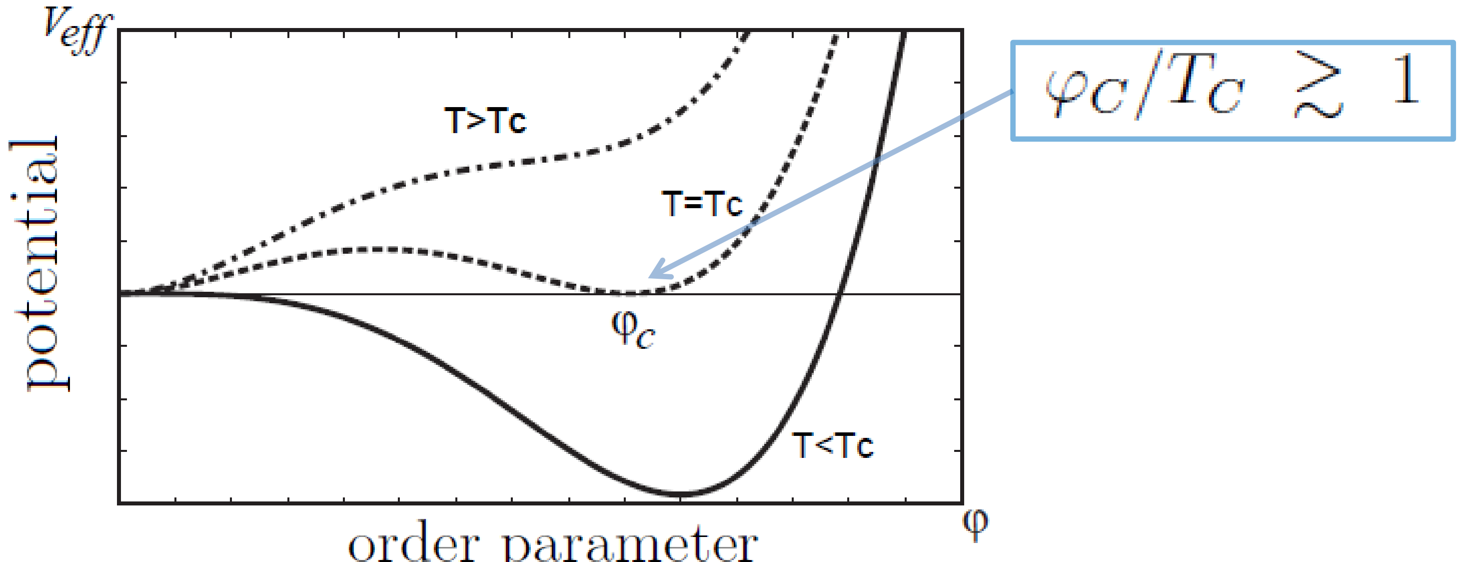
Electroweak baryogenesis is a **falsifiable** scenario for explaining baryon asymmetric Universe.

It requires

1. Large CP-violating phase beyond SM

   ⇦ testable thru, *e.g.*, Electric Dipole Moment measurements.

2. Strongly first order EW phase transition (not realized in SM).



⇦ connected with the true structure of the Higgs potential.

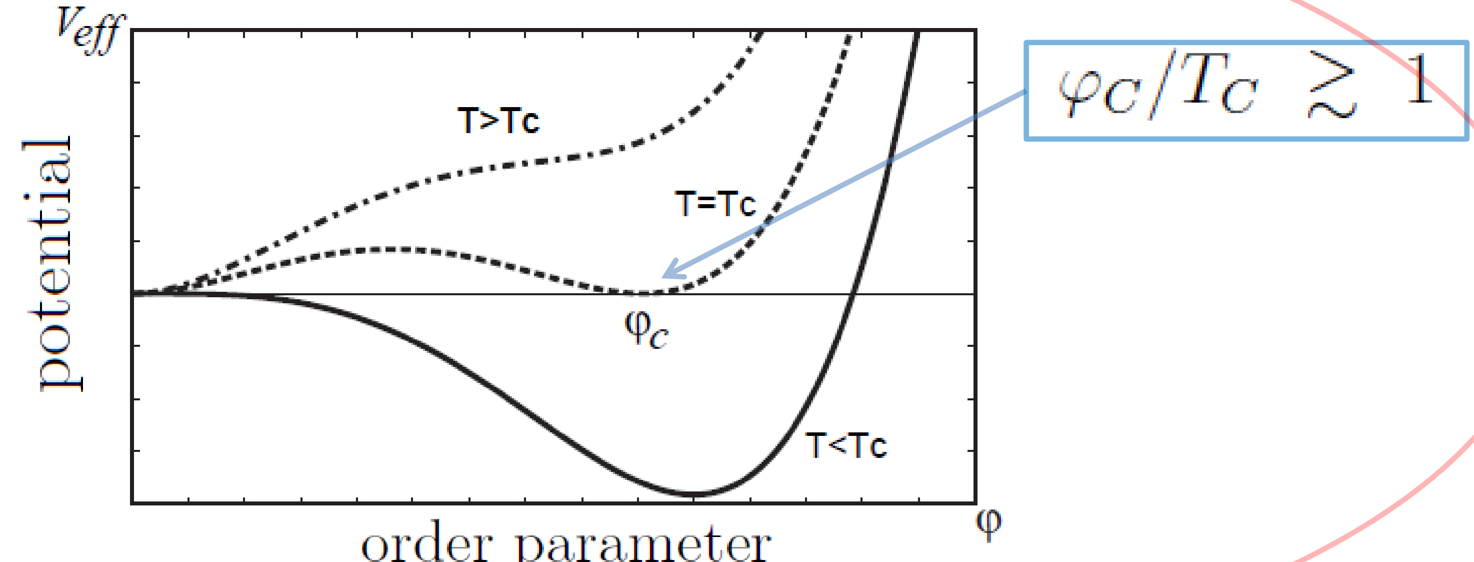
Electroweak baryogenesis is a **falsifiable** scenario for explaining baryon asymmetric Universe.

It requires

1. Large CP-violating phase beyond SM

   ⇐ testable thru, *e.g.*, Electric Dipole Moment measurements.

2. Strongly first order EW phase transition (not realized in SM).



⇐ connected with the true structure of the Higgs potential.

Realizing Strongly first order EW Phase Transition

In the Higgs potential at finite temperature T , $V(\varphi, T)$,
loop corrections involving **extra scalars** enhance the cubic term,

$$V(\varphi,T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \ldots$$

which realizes strongly 1st order EW phase transition.

M.Joyce, T.Prokopec and N.Turok (1996)

For example, (non-SUSY) two Higgs doublet model with **large coupling constants** and small decoupling parameter is known to make it.

$$\begin{aligned} V_{\rm tree} \; = \; & m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + {\rm h.c.}) \\ & + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + {\rm h.c.}\right] \end{aligned}$$

$\Phi_1, \ \Phi_2$: Higgs doublets

Realizing Strongly first order EW Phase Transition

In the Higgs potential at finite temperature T , $V(\varphi, T)$,

loop corrections involving **extra scalars** enhance the cubic term,

$$V(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \ldots$$

which realizes strongly 1st order EW phase transition.

M.Joyce, T.Prokopec and N.Turok (1996)

For example, (non-SUSY) two Higgs doublet model with **large coupling constants** and small decoupling parameter is known to make it.

↓

Thru RG running, coupling constants blow up at 10~ TeV scale.

Connection to UV physics, (*e.g.* unification), is unclear.

In this talk, I propose

a **UV complete extended Higgs model** that contains extra light scalars and large coupling constants and realizes strongly first order EW phase transition based on **supersymmetric (SUSY) gauge theory.**

Model

Our framework

energy scale

UV picture = **SUSY gauge theory**

low-energy description

IR picture = Extended Higgs sector

Strongly first order phase transition

UV Picture

Consider a new **SUSY SU(2)$_H$ gauge theory** with six doublets, $T_1,\ T_2, \ldots,\ T_6$, charged under SM gauge groups.

Field	$SU(2)_L$	$U(1)_Y$
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	2	0
T_3	1	$+1/2$
T_4	1	$-1/2$
T_5	1	$+1/2$
T_6	1	$-1/2$

Mass term ("current mass"): $W_m = m_1 T_1 T_2 + m_3 T_3 T_4 + m_5 T_5 T_6$

Confinement

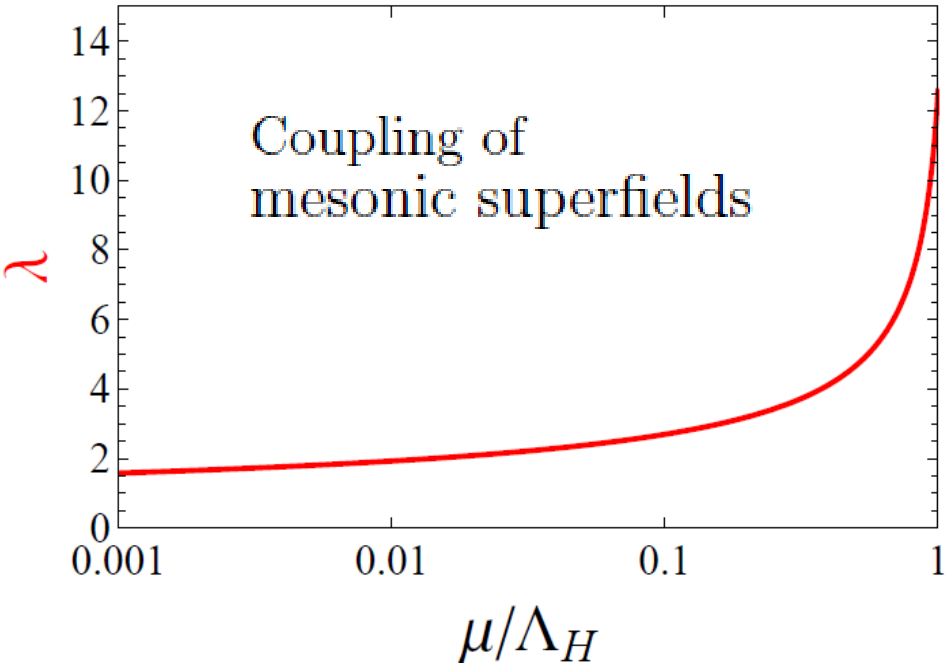
K.Intriligator and N.Seiberg (1996)

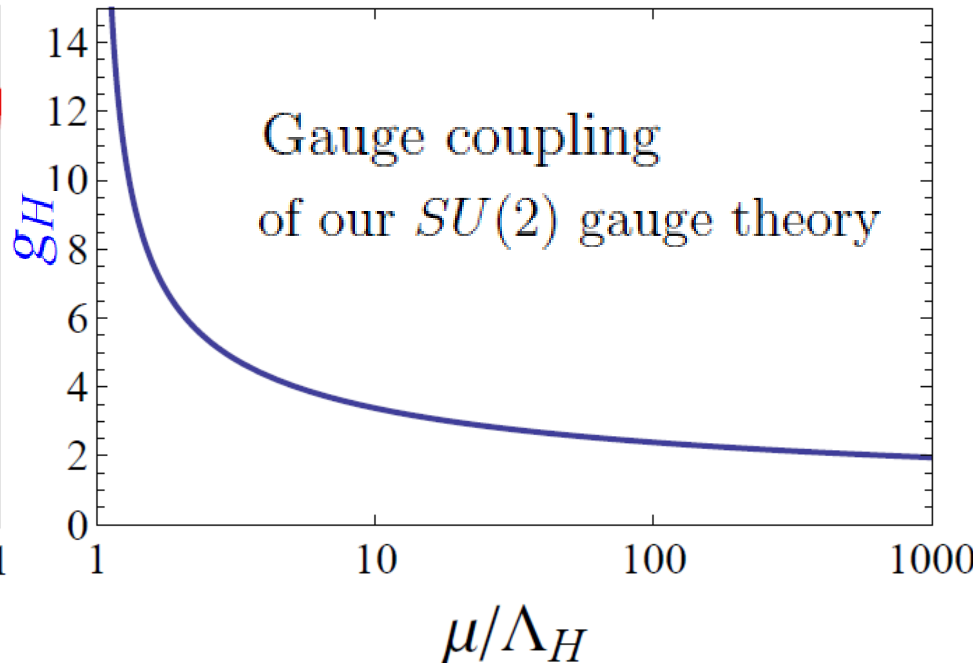
- SU(2)$_H$ gauge theory becomes strongly-coupled at some IR dynamical scale Λ_H , and the doublets are confined.
- Below Λ_H , the theory is described in terms of **mesonic superfields,** $M_{ij} \propto T_i T_j$, with the following emergent superpotential:

$$W_{eff} = \lambda \, \epsilon_{ijklmn} M_{ij} M_{kl} M_{mn} + \xi_1 M_{12} + \xi_3 M_{34} + \xi_5 M_{56}$$

Naïve Dimensional Analysis

- *Naïve Dimensional Analysis* suggests that the coupling constant λ becomes non-perturbative at Λ_H , *i.e.*, $\lambda(\mu = \Lambda_H) \simeq 4\pi$.





IR Picture

We identify fifteen mesons, $M_{ij} \propto T_i T_j \quad (i, j = 1, 2, \dots, 6)$, with MSSM Higgs and exotic fields as

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

$\Leftrightarrow \quad M_{ij}$

(*c.f.* R.Harnik *et al.* (2003))

The superpotential can be rewritten as

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

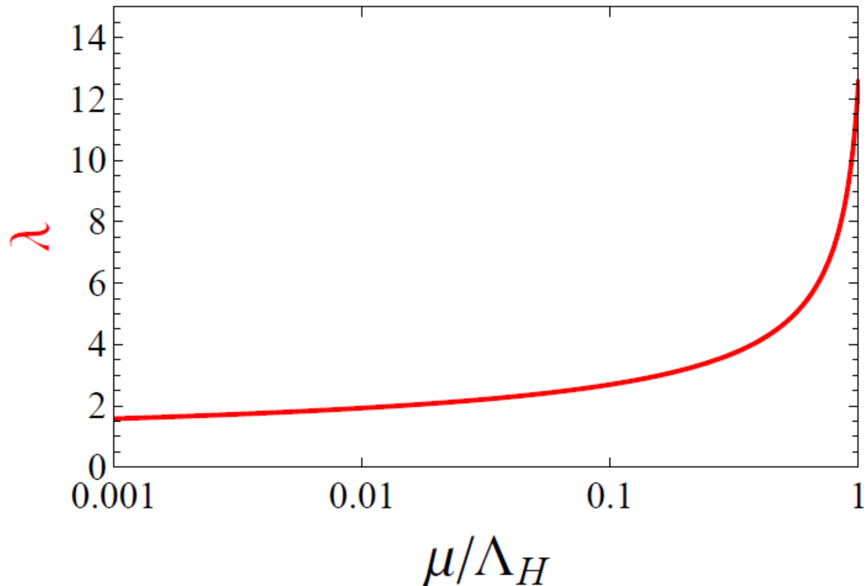
- Effective μ-terms arise from the VEVs of $N,\ N_\Phi,\ N_\Omega$ triggered by the tadpole terms.

$$\begin{aligned} W_{eff} &= -\mu H_u H_d - \mu_\Phi \Phi_u \Phi_d - \mu_\Omega(\Omega^+\Omega^- - \zeta\eta) \\ &+ \lambda\{\, n H_u H_d + H_d \Phi_u \zeta + H_u \Phi_d \eta - H_u \Phi_u \Omega^- - H_d \Phi_d \Omega^+ \,\} \\ &+ \text{(terms irrelevant to phenomenology)} \end{aligned}$$

- The coupling constant λ is **large**.

For $\Lambda_H = 10\ \text{TeV}$, we have $\lambda(\mu = M_Z) \sim 2$.

➡ Large radiative correction to the SM-like Higgs boson.



Deriving Yukawa Couplings

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

$$W_{Yuk} = (T_1, T_2)T_3H'_d + (T_1, T_2)T_4H'_u + mH'_uH'_d$$
$$+ y_{u\,ij}\,Q^iH'_uU^j + y_{d\,kl}\,Q^kH'_dD^l + \ldots$$

$m \sim \Lambda_H$

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.

Soft SUSY Breaking

N.Arkani-Hamed and R.Rattazzi (1998)

- Soft SUSY breaking terms for UV superfields, $T_1,\ T_2, \ldots,\ T_6$, are 'inherited' by IR superfields, M_{ij} $(i, j = 1,\ 2,\ \ldots,\ 6)$.

- For SU(2) SUSY gauge theory w/ six doublets, we have the following formula at the leading order:

$$m^2_{M_{ij}}(\mu_{IR}) + m^2_{M_{kl}}(\mu_{IR}) + m^2_{M_{mn}}(\mu_{IR}) \simeq 0$$

where i, j, k, l, m, n are all different.

Some of the mesonic superfields have negative soft mass squared $m^2_{M_{ij}} < 0$.

⇒ EW symmetry breaking w/o radiative breaking.
Many light scalars.

Electroweak Phase Transition in the Model

We have built a **UV complete extended Higgs model** w/ large coupling constant λ between MSSM Higgs fields $H_u,\ H_d$ and extra fields $N,\ \Phi_u,\ \Phi_d,\ \Omega^+,\ \Omega^-$.

Strongly first order phase transition is possible due to thermal loop corrections involving the scalar components of $N,\ \Phi_u,\ \Phi_d,\ \Omega^+,\ \Omega^-$.
(Thermal loops involving the fermionic components work negatively. Scalar components need to be lighter than fermionic components.)

We will evaluate the order of the phase transition by taking a benchmark mass spectrum.

Benchmark Mass Spectrum

$$W_{eff} = -\mu H_u H_d - \mu_\Phi \Phi_u \Phi_d - \mu_\Omega(\Omega^+\Omega^- - \zeta\eta)$$
$$+ \lambda \{ H_d \Phi_u \zeta + H_u \Phi_d \eta - H_u \Phi_u \Omega^- - H_d \Phi_d \Omega^+ \}$$

(+ soft SUSY breaking terms.)

(Fixed parameters)

MSSM Higgs parameters: $\tan\beta = 3, \quad m_{H^\pm} = 400 \text{ GeV}$.

μ-terms for exotic superfields: $\mu_\Phi = \mu_\Omega = 250 \text{ GeV}$.

Soft SUSY breaking terms: (*A, B* terms for exotic fields) = 0 .

$$m_{\Phi_d}^2 + \mu_\Phi^2 = m_{\Omega_+}^2 + \mu_\Omega^2 = m_\zeta^2 + \mu_\Omega^2 = (1000 \text{ GeV})^2 .$$

Stops and sbottoms are almost decoupled.

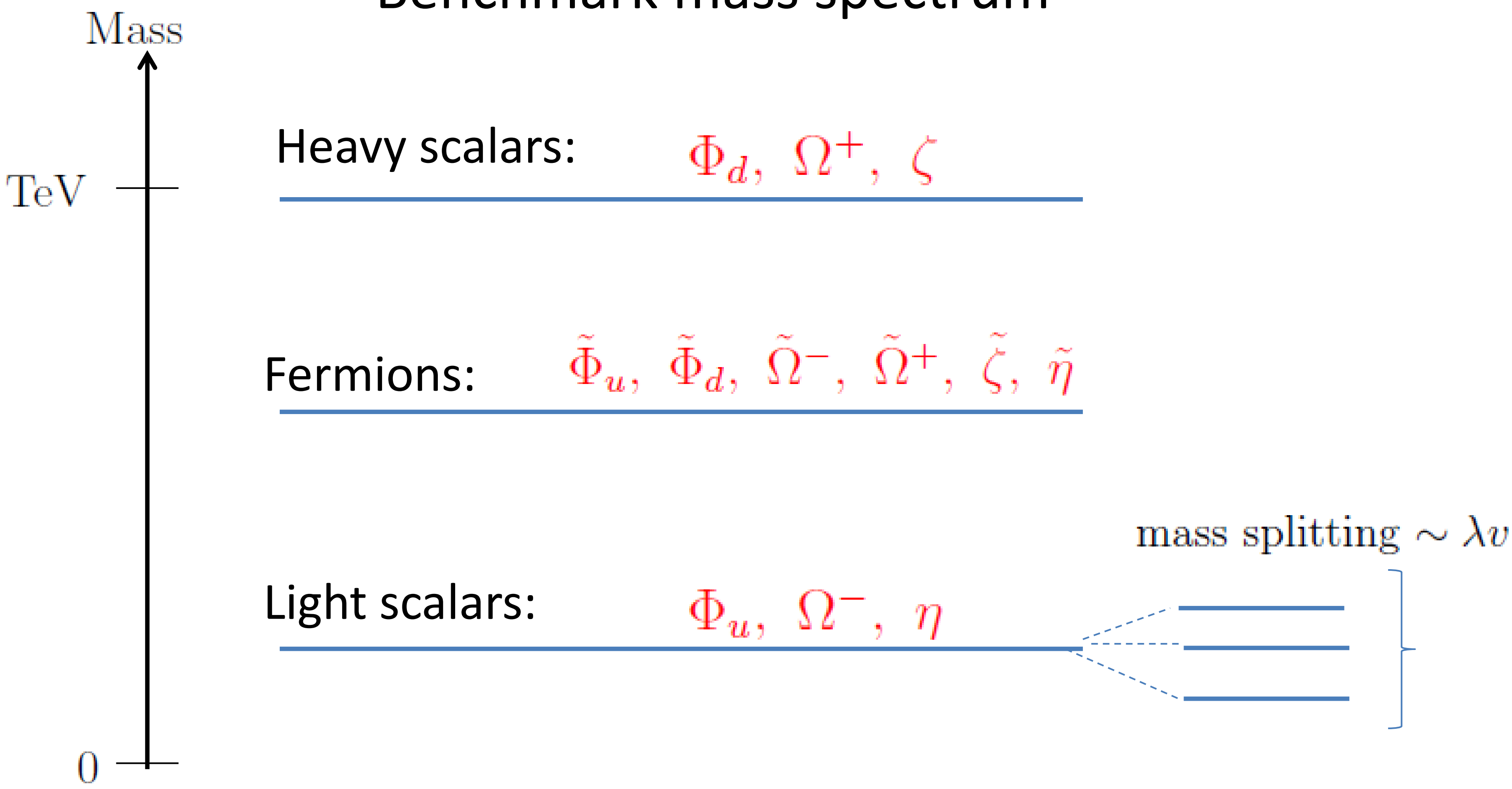
(Free parameters)

$$\underline{m_{\Phi_u}^2 = m_{\Omega_-}^2 = m_\eta^2} , \quad \lambda .$$

We take **negative** values for these parameters.

(∵ Some of the scalars must be lighter than the fermions.)

Benchmark mass spectrum

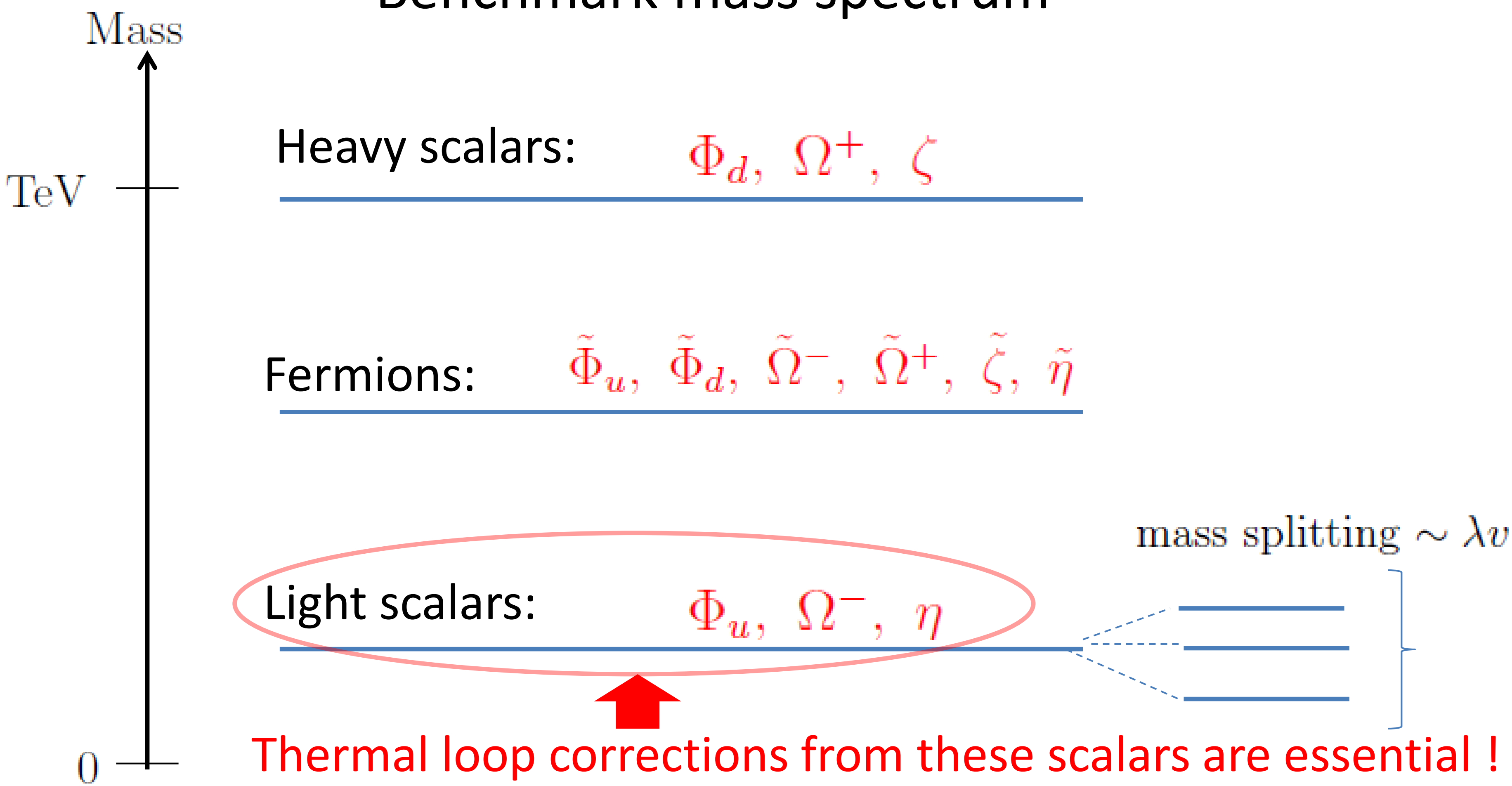


We may exchange the free parameters as

$$(m_{\Phi_u}^2 = m_{\Omega_-}^2 = m_\eta^2,\ \lambda)$$

⟺ (Mass of the charged scalars Φ_u^+ and Ω_-, Mass of the neutral scalar Φ_u^0)

Benchmark mass spectrum



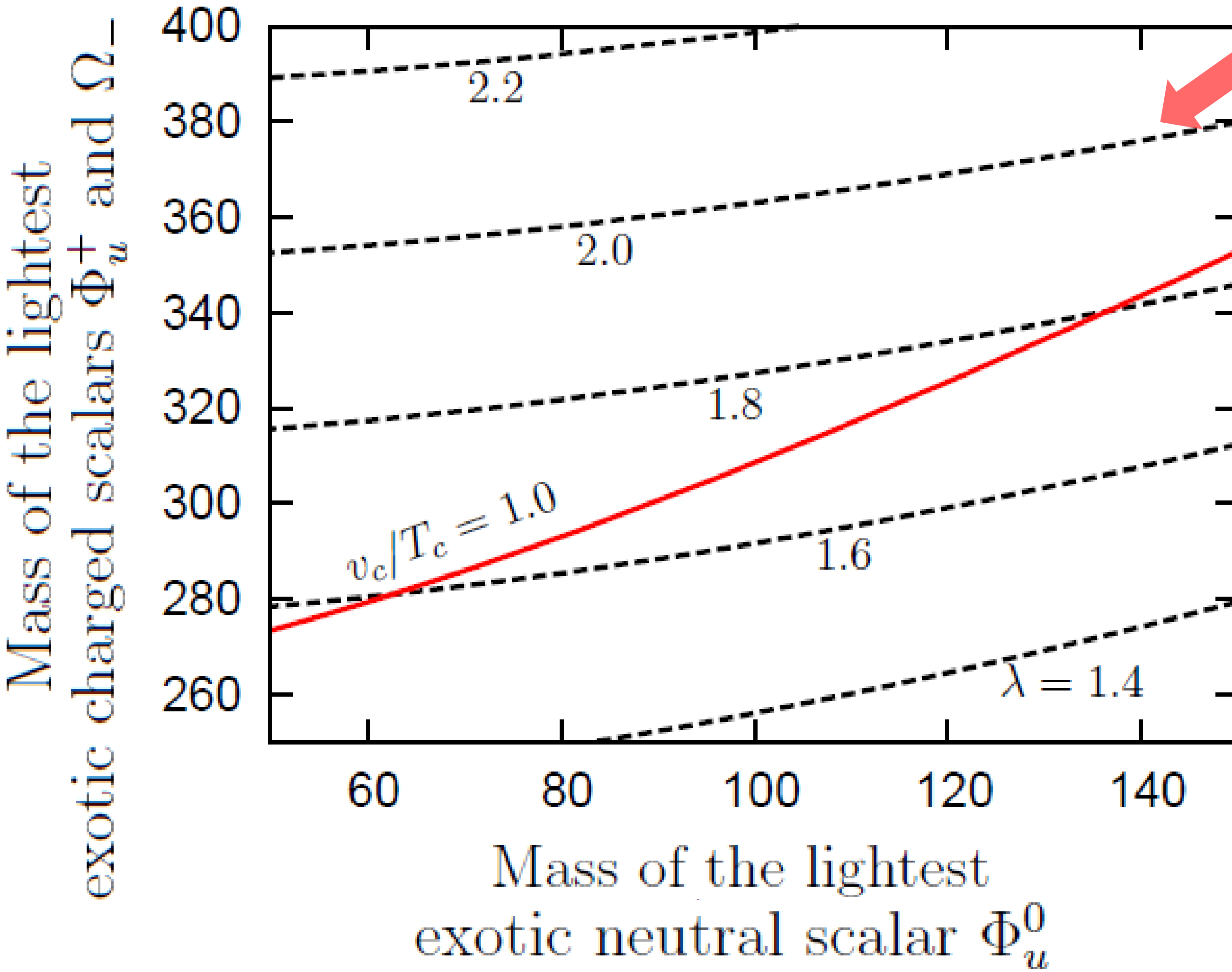
We may exchange the free parameters as

$$(m^2_{\Phi_u} = m^2_{\Omega_-} = m^2_\eta,\ \lambda)$$

$$\Leftrightarrow\ (\text{Mass of the charged scalars } \Phi_u^+ \text{ and } \Omega_-,\ \ \text{Mass of the neutral scalar } \Phi_u^0)$$

Result

$\varphi_C/T_C \gtrsim 1$ realized



λ

$\lambda \gtrsim 1.5$ is needed.

⇕

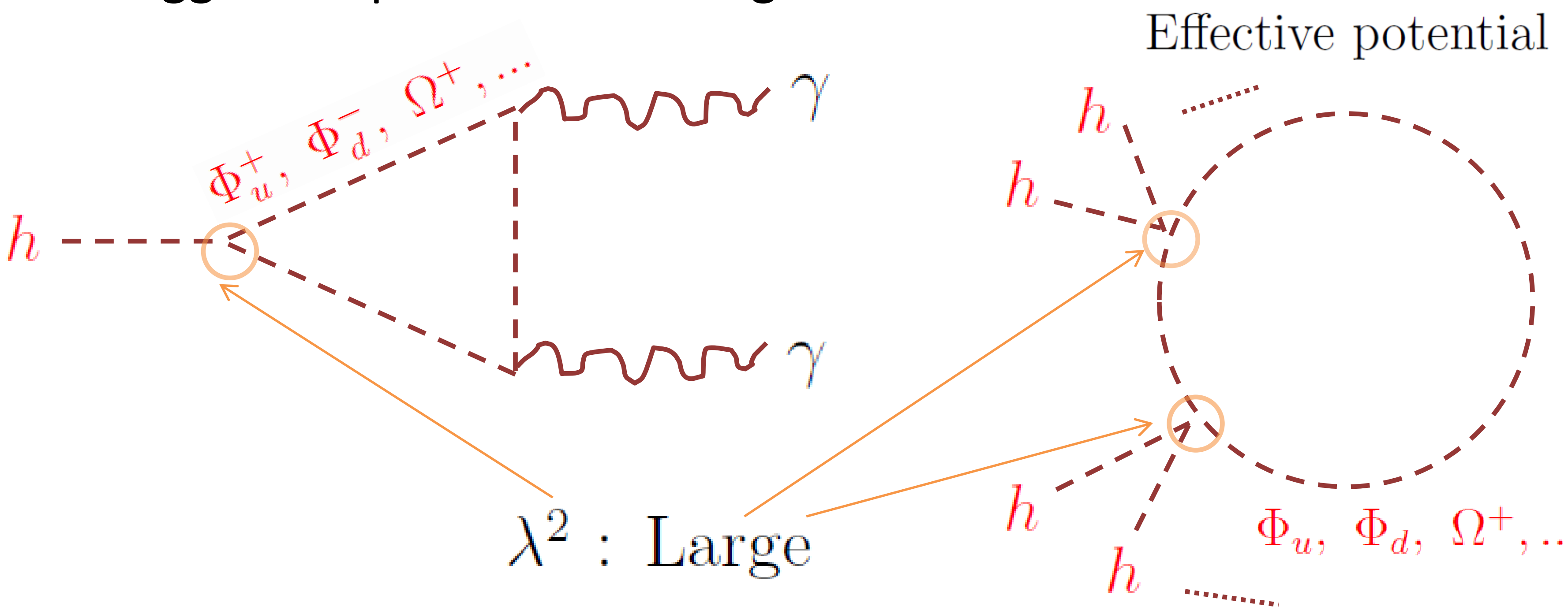
$\Lambda_H \lesssim 15$ TeV.

Collider Signatures of the Model

1. EW production of exotic charged scalars and fermions.

2. Indirect signatures:

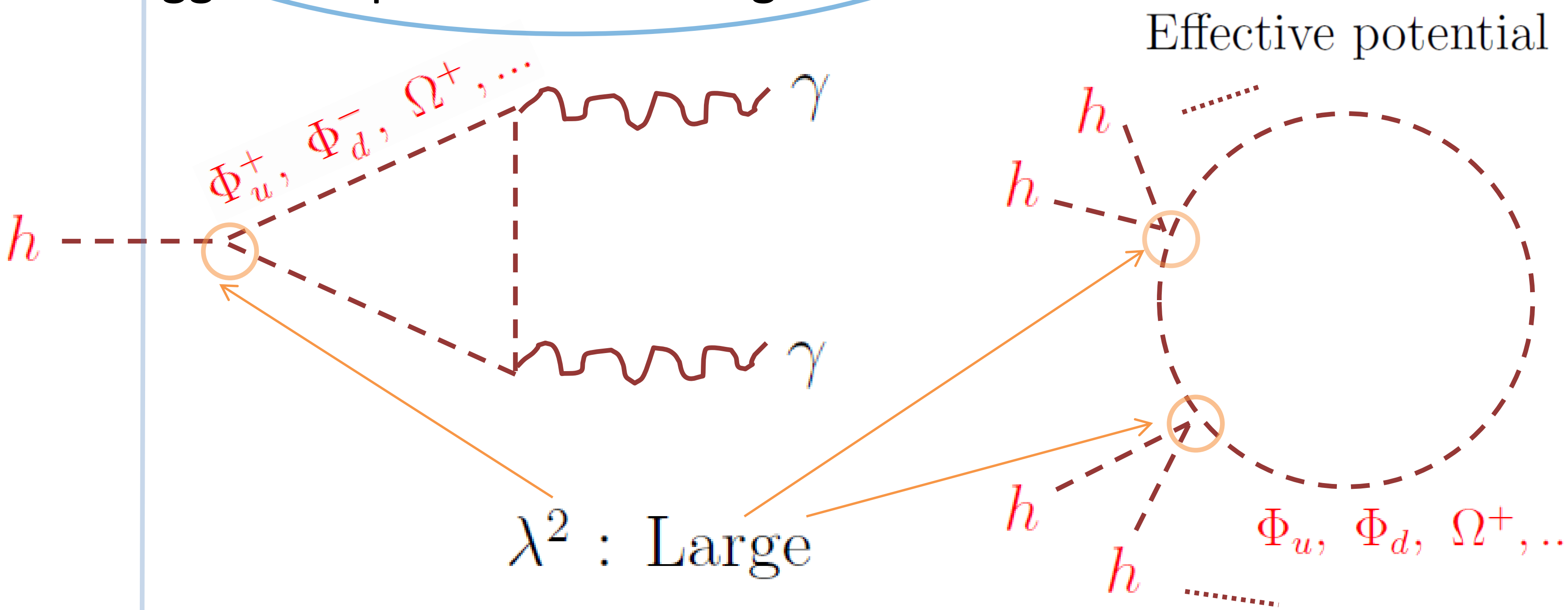
   - Triple coupling for the SM-like Higgs boson
   - Higgs to di-photon branching ratio



1. EW production of exotic charged scalars and fermions.

2. Indirect signatures:

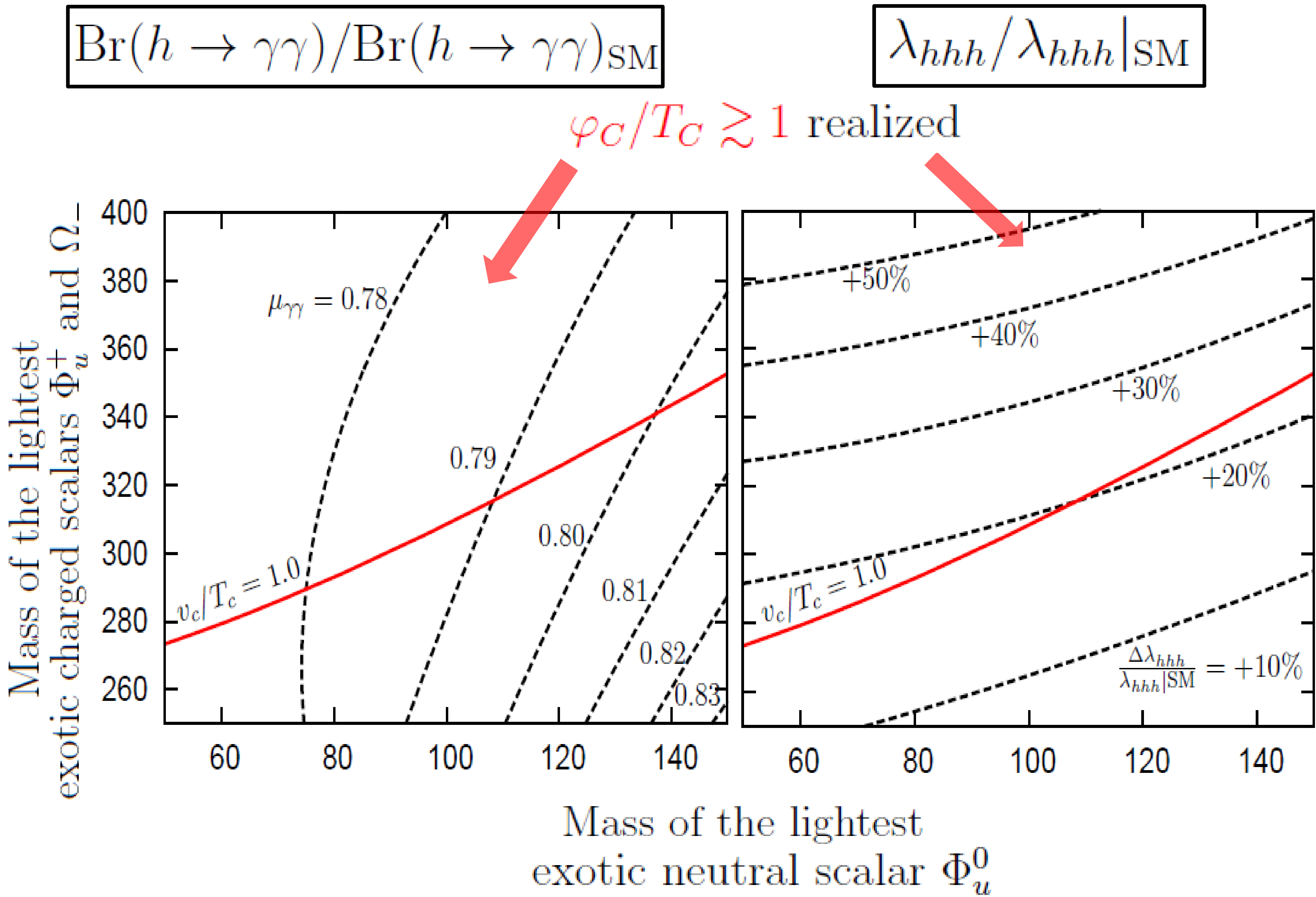
- Triple coupling for the SM-like Higgs boson
- Higgs to di-photon branching ratio



Reflect large coupling constant λ^2 .

Deeply connected with φ_C/T_C .

Same benchmark mass spectrum as before



Conclusions

- We have shown that a **simple UV complete extended Higgs model** can naturally realize **strongly 1st order EW phase transition**, one of the essential conditions for successful electroweak baryogenesis.

- Strongly-coupled extended Higgs models for electroweak baryogenesis now have a solid theoretical ground.

  Let's search for signatures of such models thru

  1. EW production of extra Higgs bosons (fermions).
  2. large deviations in the triple coupling and the di-photon branching ratio of the SM-like Higgs boson.