SUSY Extended Higgs Sector and SUSY Strong Dynamics

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arXiv:1211.5883 [hep-ph].

Contents

Introduction

Higgs boson (?) has been discovered,
but no one knows the **structure of the Higgs sector**.

Number of Higgs doublets ?

If there are several, how do they couple ?

Are there singlets ?

Many possibilities for the Higgs sector.

Need a guiding principle based on some UV theory and/or motivated by phenomenological requirements.

In this talk, we consider
"realizing **electroweak baryogenesis (EWBG)** scenario"
as the guiding principle for building a model of extended Higgs sector.

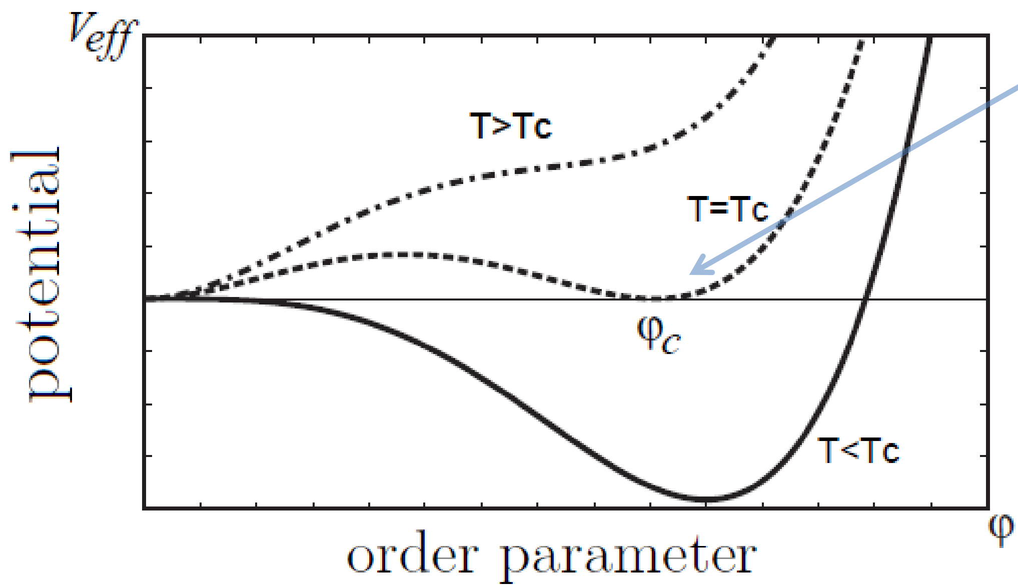
EW Baryogenesis requires …

1. Large CP-violating phase (beyond SM).

This can be added by hand, *e.g.*, CP phases of A-terms in SUSY standard models.

2. Strongly first order EW phase transition (not realized in SM with $m_h = 125\ \mathrm{GeV}$).

$\varphi_C/T_C \gtrsim 1$



This is deeply connected with the mechanism of EW symmetry breaking and the structure of the Higgs sector.

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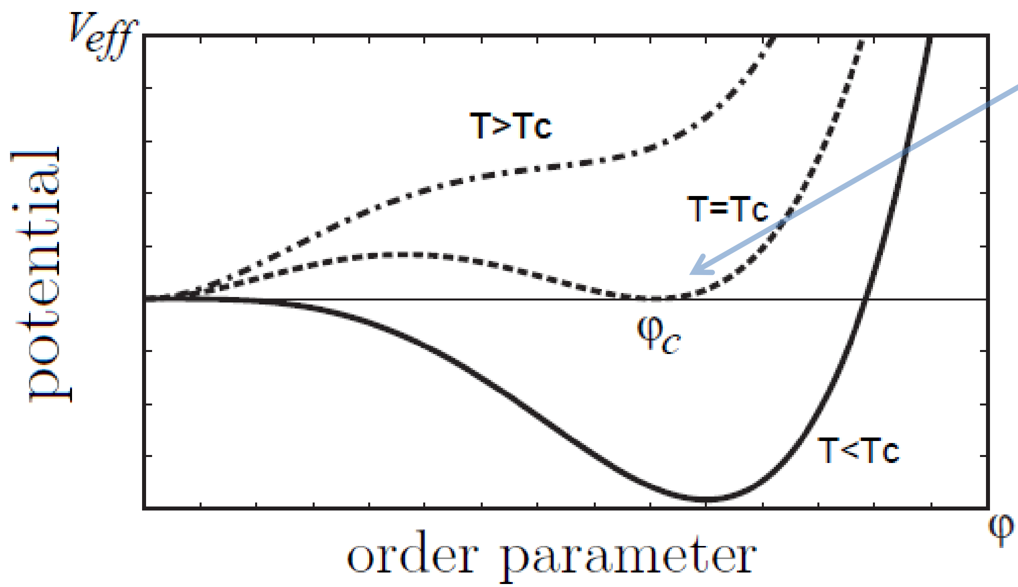

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Lessons from Two Higgs Doublet Model

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

(Non-SUSY) two Higgs doublet model is the simplest model that can realize strongly first order phase transition.

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

$\Phi_1,\ \Phi_2$: Higgs doublets

SM Higgs-like scalar h + Extra scalars $H,\ A,\ H^\pm$.

Thermal loop corrections involving extra scalars, $H,\ A,\ H^{\pm}$, enhance the cubic term in the effective potential at finite temperature,

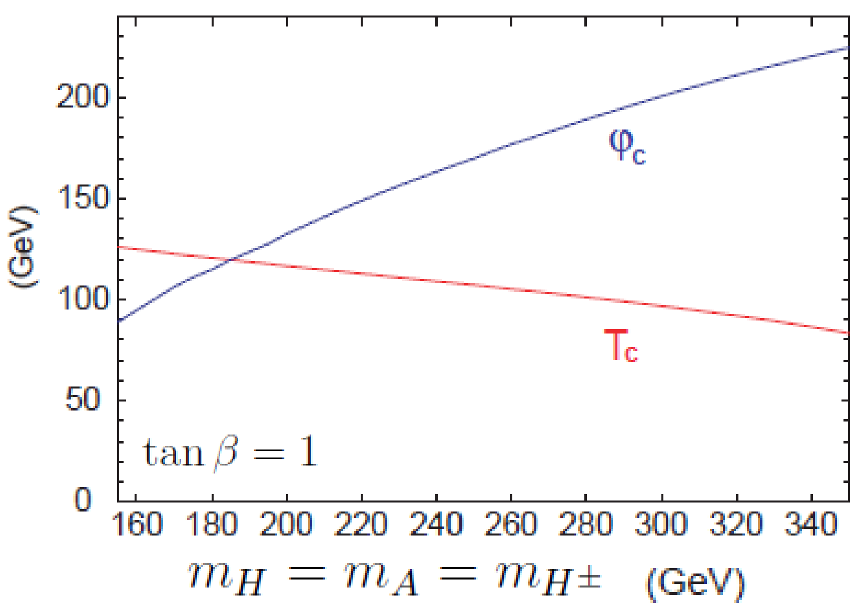
$$V_{\rm eff}(\varphi,T) \simeq D(T^2-T_0^2)\varphi^2 - ET|\varphi|^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots \quad .$$

When the decoupling parameter is zero (*i.e.* masses come exclusively from Higgs VEV), the cubic term is given by

$$E \;=\; \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3 + m_H^3 + m_A^3 + 2m_{H^\pm}^3) \quad .$$

Large cubic term makes strongly first order phase transition possible.

S.Kanemura, Y.Okada and E.Senaha (2005)



Strongly first order phase transition, $\varphi_C/T_C \gtrsim 1$, occurs for

$$m_H = m_A = m_{H^\pm} \gtrsim 180\ \mathrm{GeV}$$

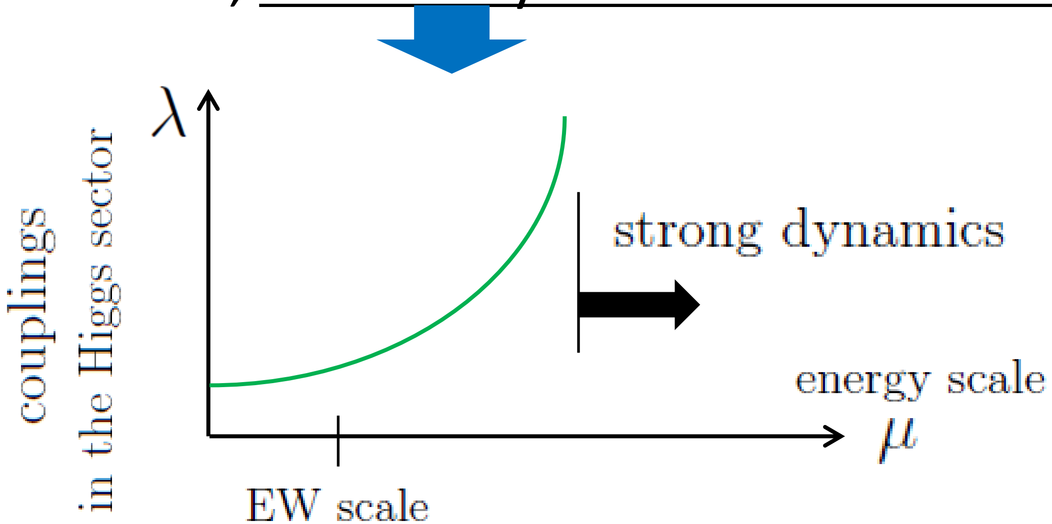
when the decoupling parameter is zero and $\tan\beta = 1$.

The two Higgs doublet model may not be the fundamental theory because

- The gauge hierarchy problem is not discussed.
- $m_H = m_A = m_{H^\pm} \gtrsim 180\ \mathrm{GeV}$ with zero decoupling parameter means that some of the coupling constants in the Higgs sector are so large that they blow up below the Planck scale.

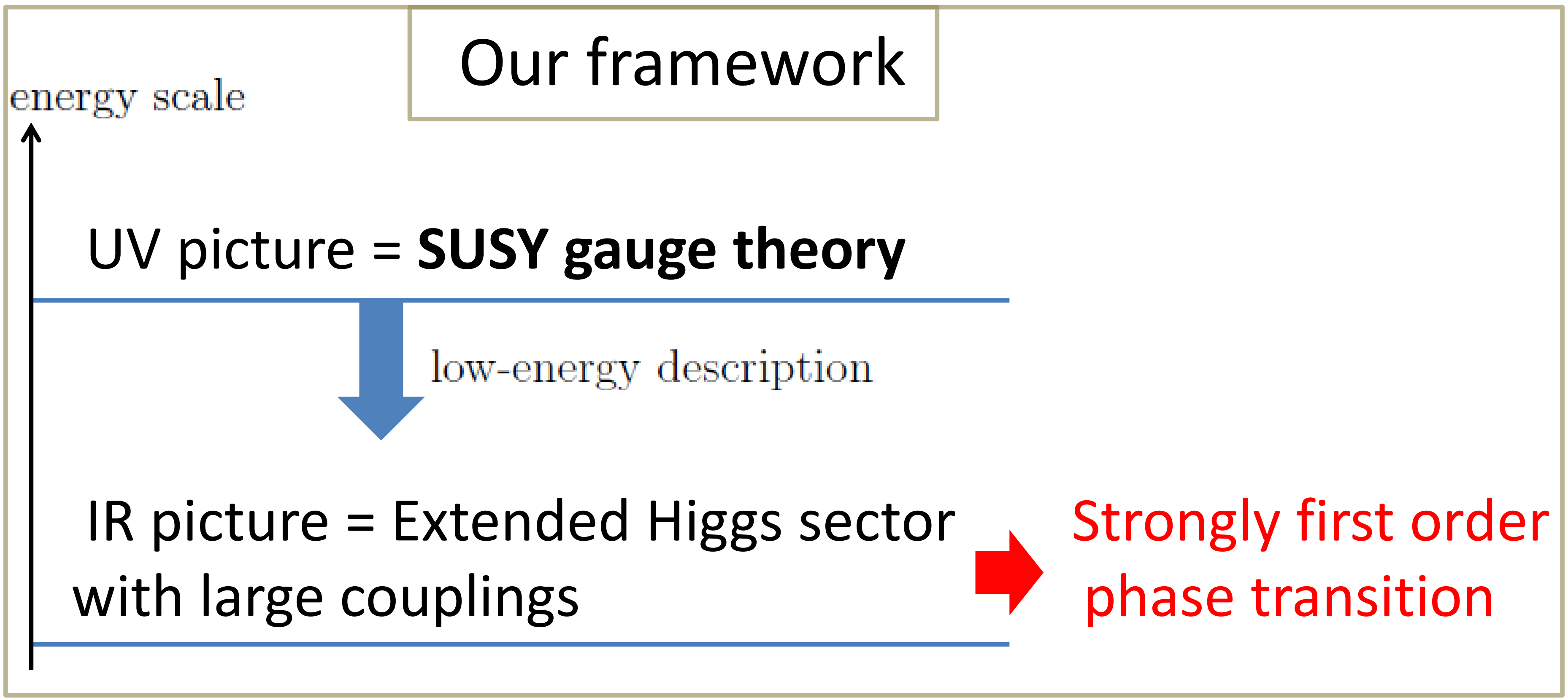
But we learn that

1. extra scalars with zero or small decoupling parameter
2. large coupling constants among the SM-like Higgs and the extra scalars, which may be related to some strong dynamics



are essential for strongly first order phase transition.

Here we build a **UV complete model** based on **SUSY strongly-coupled gauge theory** whose low-energy theory contains extra scalars and large coupling constants that make strongly first order phase transition possible.



Motivation for SUSY

We will work on **SUSY Higgs sector** because

- SUSY solves the gauge hierarchy problem.
- Some of the quantities in strongly-coupled theory are calculable in softly-broken SUSY models.

  In particular, we have an elegant mechanism for deriving the top quark Yukawa.

Model based on
SUSY SU(2) Gauge Theory

UV Picture

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

Also introduce a Z_2 -parity for phenomenological reasons.

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	$-1/2$	$-$

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)

- The SUSY gauge theory becomes strongly-coupled and the doublets are confined at an IR scale Λ_H .
- Below the scale Λ_H, the theory is described in terms of **mesonic superfields**, $M_{ij} = T_i T_j$, with the 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*, we obtain the following superpotential with canonically normalized fields $\hat{M}_{ij}$:

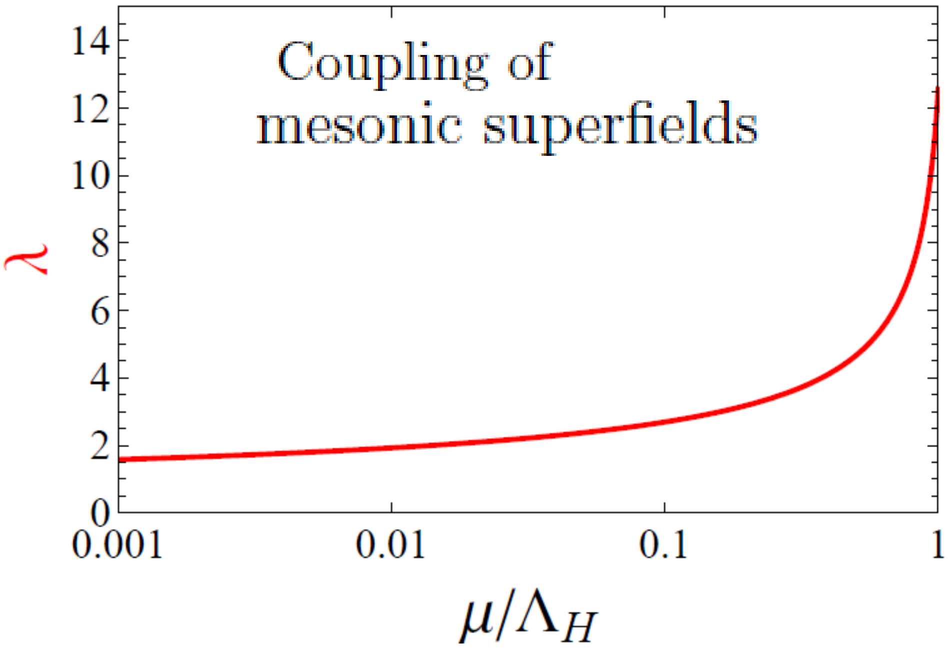
$$W_{eff} \simeq \lambda\, \epsilon_{ijklmn} \hat{M}_{ij} \hat{M}_{kl} \hat{M}_{mn} + \frac{m_1 \Lambda_H}{4\pi}\hat{M}_{12} + \frac{m_3 \Lambda_H}{4\pi}\hat{M}_{34} + \frac{m_5 \Lambda_H}{4\pi}\hat{M}_{56}$$

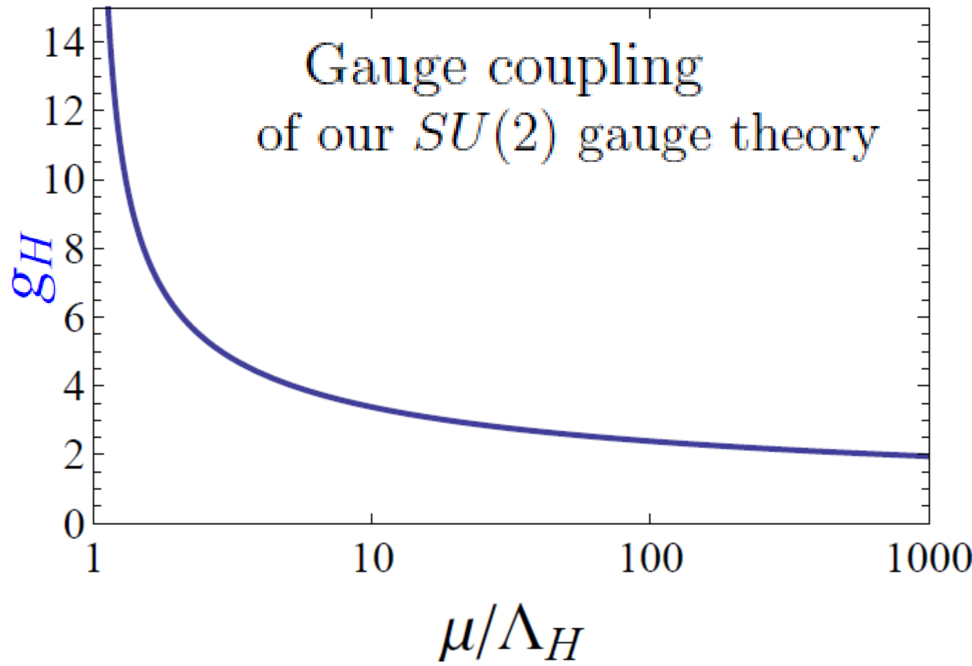
where the coupling λ becomes non-perturbative at the scale Λ_H ,

i.e., $\lambda(\mu = \Lambda_H) \simeq 4\pi$.

Meaning of *Naïve Dimensional Analysis*

- *Naïve Dimensional Analysis* is just an assumption that the IR description in terms of mesons breaks down **at the same scale** where the UV description of the gauge theory breaks down.





IR Picture

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

		Field	$SU(2)_L$	$U(1)_Y$	Z_2
	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	$-$
	Z_2-even Neutral singlets	$N,\ N_\Phi,\ N_\Omega$	1	0	$+$
	Z_2-odd Neutral singlets	$\zeta,\ \eta$	1	0	$-$

$\Leftrightarrow M_{ij}$

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

The superpotential is rewritten as

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

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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}
$$

Tadpole terms

Higgs couples to exotic fields with large coupling λ.

- The tadpole terms for N, N_Φ, N_Ω induce the VEVs of their scalar components, which give effective μ-terms.

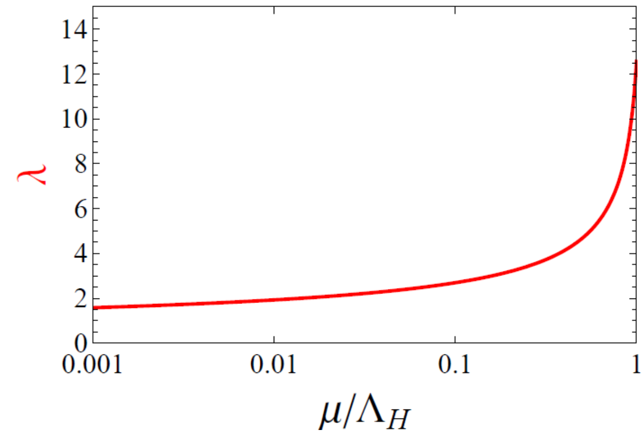
  The superpotential can be rewritten as

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

$\boxed{\text{physical component of } N}$

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

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



- Electroweak symmetry breaking is triggered by soft SUSY breaking terms, as in MSSM and NMSSM.

  The mass of the SM-like Higgs boson follows the same formula as that in NMSSM.

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.

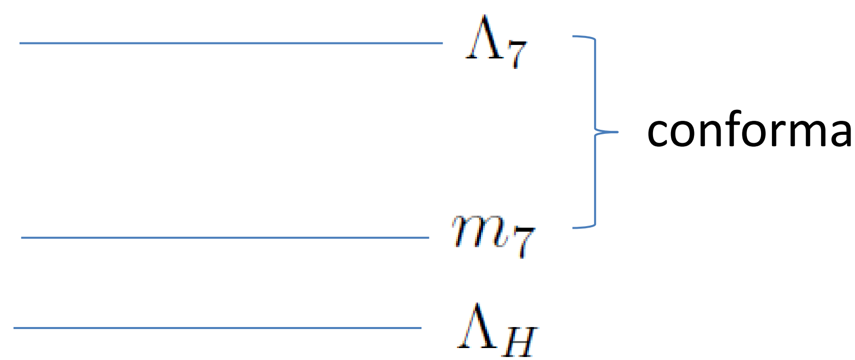
“Conformal enhancement”

H. Murayama (2003)

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 .

Electroweak Phase Transition in the Model

We have built a **UV complete model** of an extended Higgs sector that contains large coupling constant λ between MSSM Higgs fields $H_u,\ H_d$ and exotic fields $\Phi_u,\ \Phi_d,\ \Omega^+,\ \Omega^-$.

Strongly first order phase transition is possible due to thermal loop corrections involving the scalar components of $\Phi_u,\ \Phi_d,\ \Omega^+,\ \Omega^-$.

(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 .

$$m^2_{\Phi_d} + \mu^2_\Phi = m^2_{\Omega_+} + \mu^2_\Omega = m^2_\zeta + \mu^2_\Omega = (1000 \text{ GeV})^2 .$$

Stops and sbottoms are almost decoupled.

n (physical component of N) is decoupled.

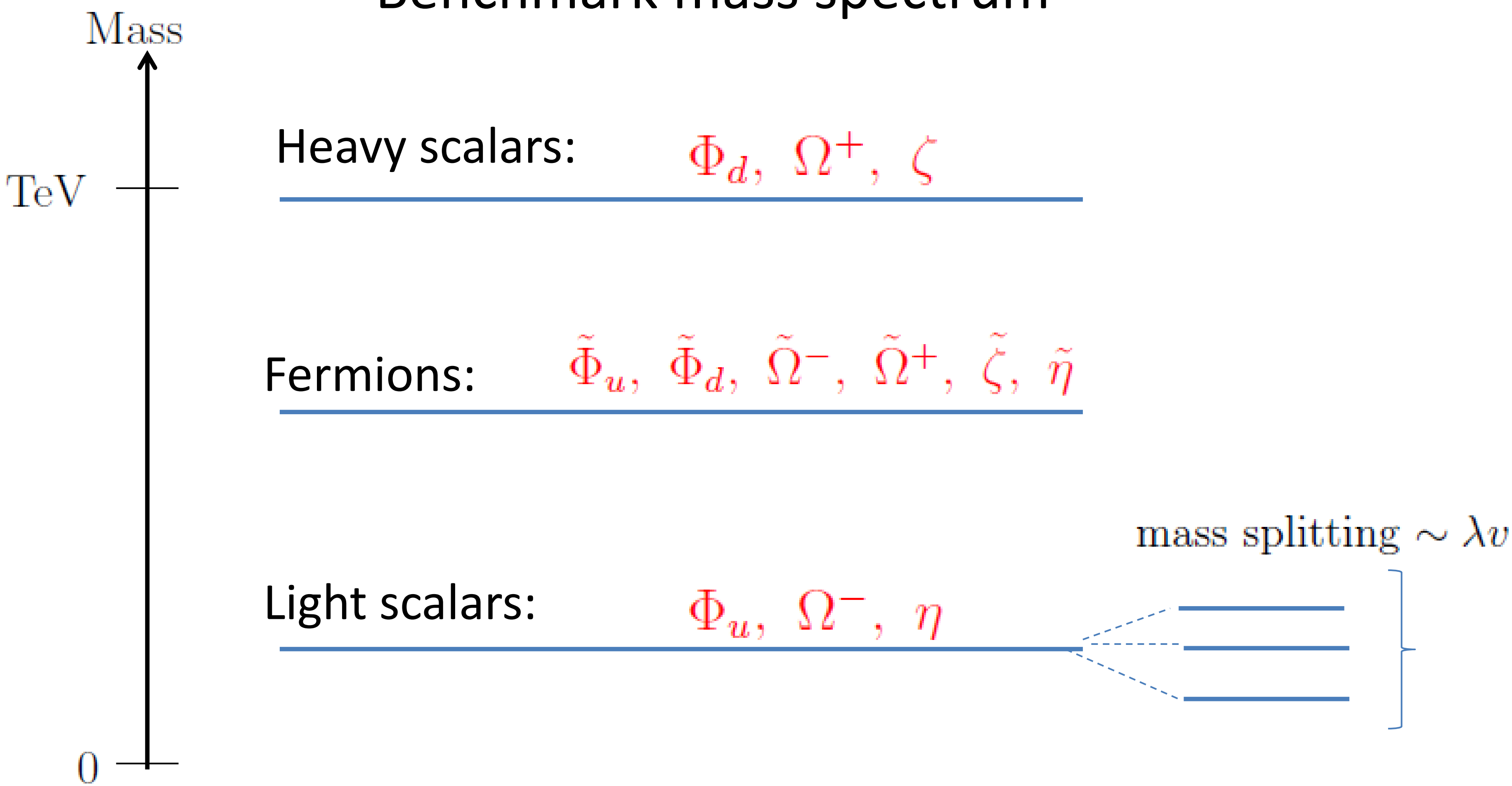
(Free parameters)

$\underline{m^2_{\Phi_u} = m^2_{\Omega_-} = m^2_\eta}$, λ .

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

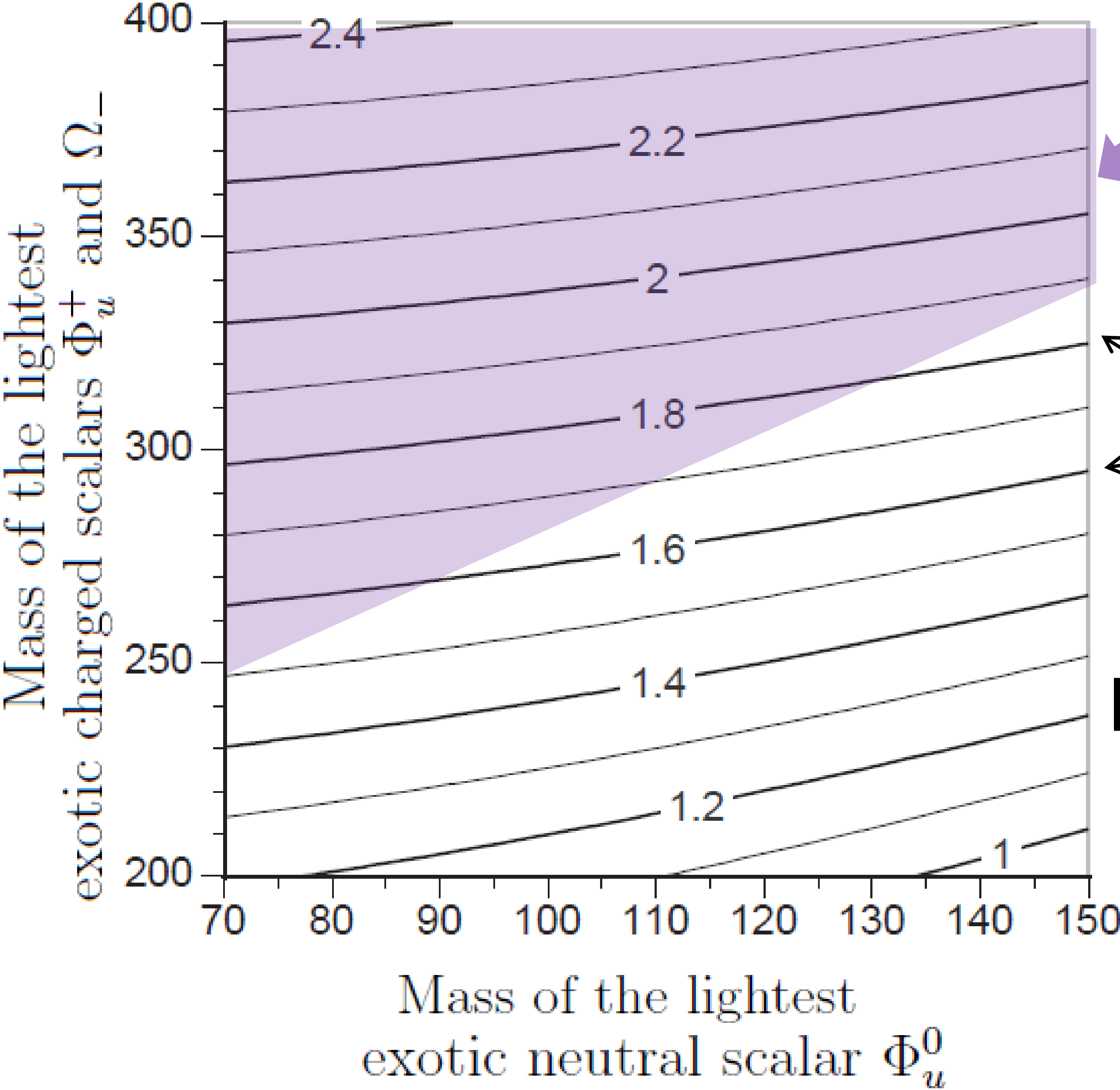
(∵ Some of the scalars must be lighter than the fermions.)

Benchmark mass spectrum



- 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.

Result



$\varphi_C/T_C \gtrsim 1$ realized

λ

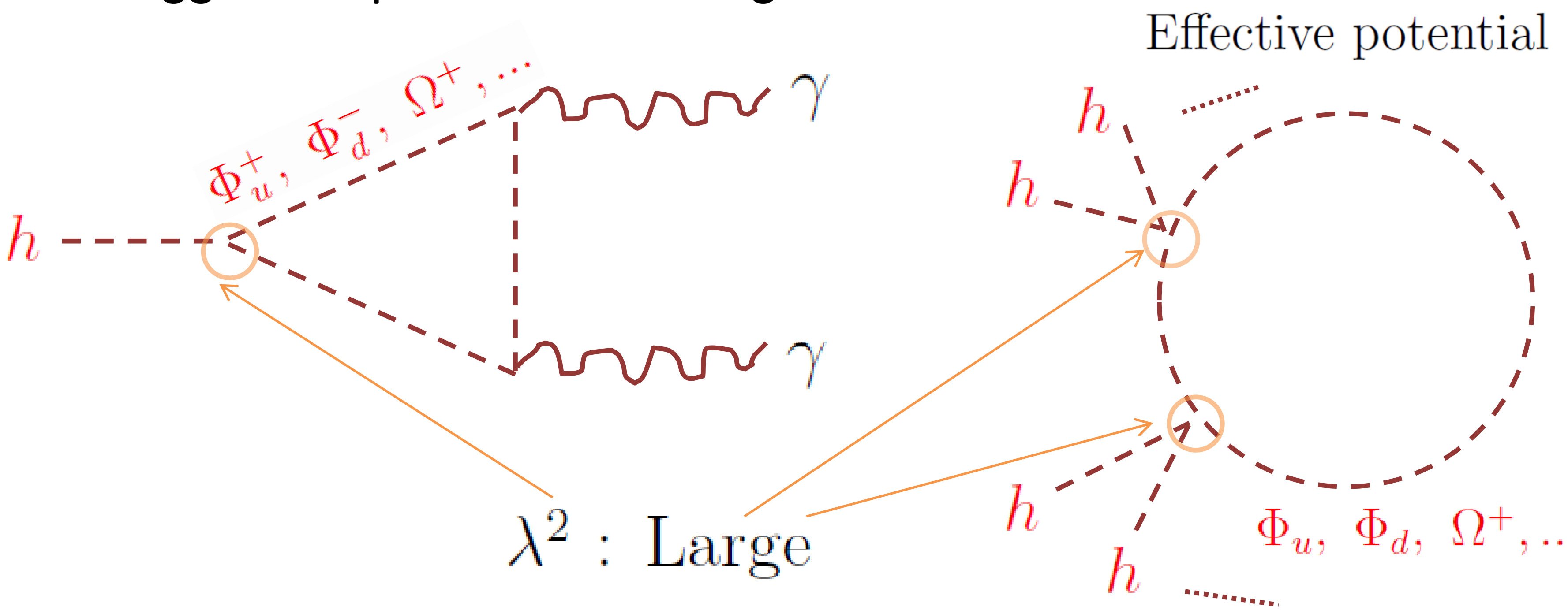
$\lambda \gtrsim 1.5$ is needed.

$\Updownarrow$

$\Lambda_H \lesssim 15$ TeV.

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



Deeply connected with φ_C/T_C .

Reflect large coupling constant λ^2 .

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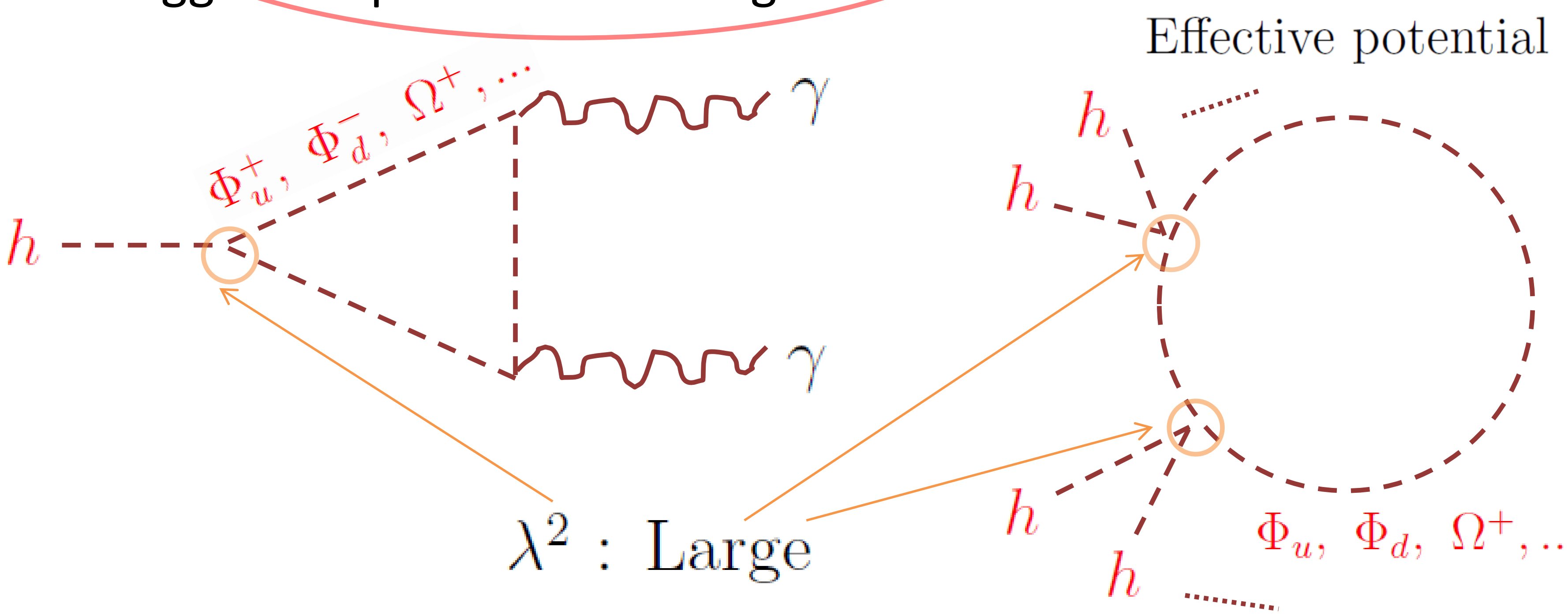


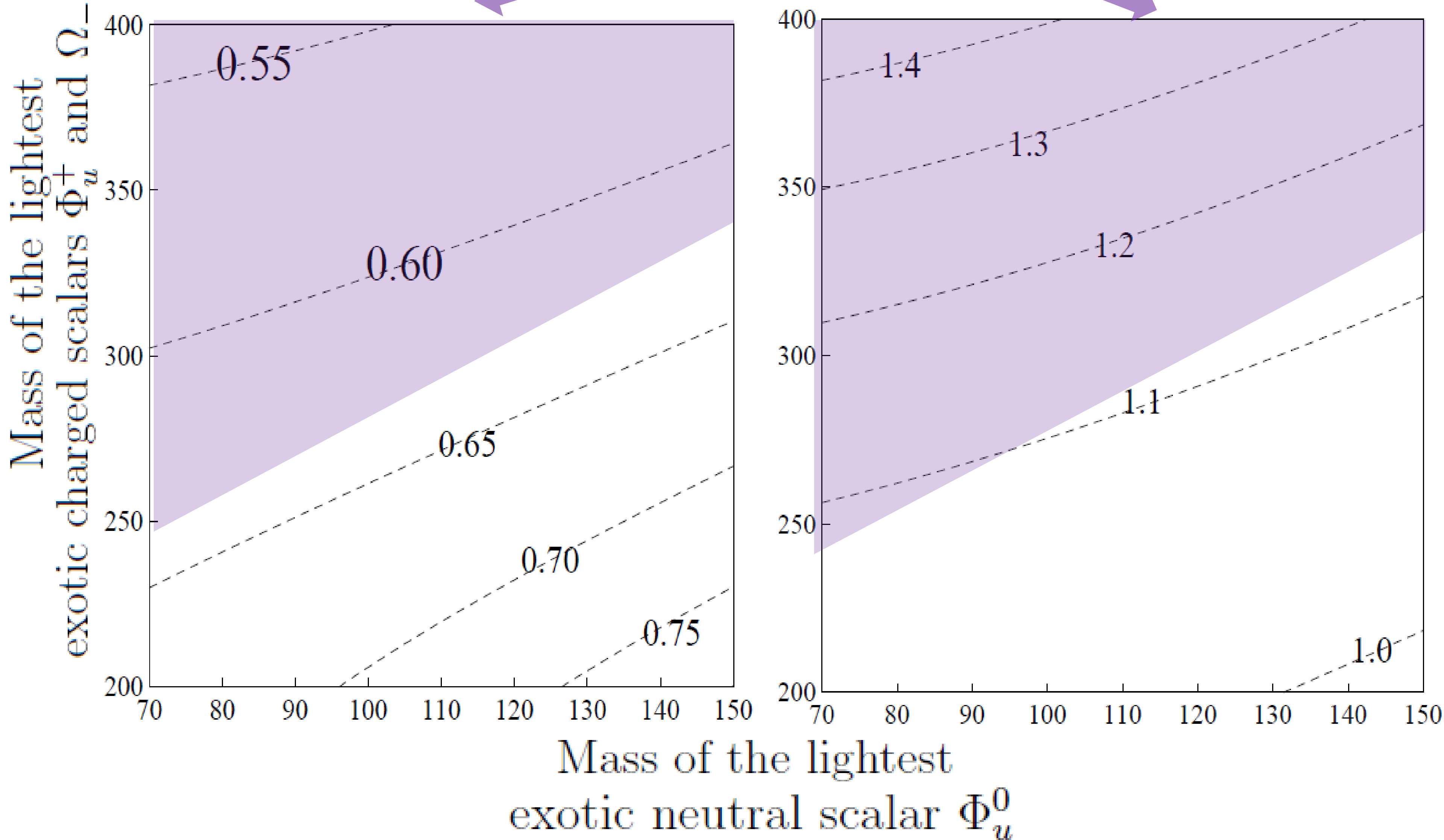
Deeply connected with φ_C/T_C .

Reflect large coupling constant λ^2 .

Same benchmark mass spectrum as before

$\boxed{\mathrm{Br}(h \to \gamma\gamma)/\mathrm{Br}(h \to \gamma\gamma)_{\mathrm{SM}}}$ $\boxed{\lambda_{hhh}/\lambda_{hhh}|_{\mathrm{SM}}}$

$\varphi_C/T_C \gtrsim 1$ realized



Conclusions

- We have proposed a **UV-complete model** of SUSY extended Higgs sector containing **extra scalars** with **large couplings** to the SM-like Higgs boson.
- We have confirmed that thermal loop corrections involving these **extra scalars with large couplings** can realize strongly first order phase transition.
- Large deviations in Higgs to di-photon branching ratio and the Higgs triple coupling are predicted.