A Light Higgs Scenario from TeV-scale SUSY Strong Dynamics

Toshifumi Yamada

(Univ. of Tokyo)

In collaboration with

S. Kanemura (*Toyama),* T. Shindou (*Kogakuin)*

based on *Phys.Rev. D86 (2012) 055023*

Introduction

Implications of 126 GeV Higgs

Higgs (?) has been discovered at $m_h = 126\ \mathrm{GeV}$.

Higgs self-coupling is $\lambda_h(Mz) \simeq \frac{m_h^2}{4v^2} = 0.13$.

No Landau pole.

Higgs sector seems described by

a **weakly-coupled** theory in UV.

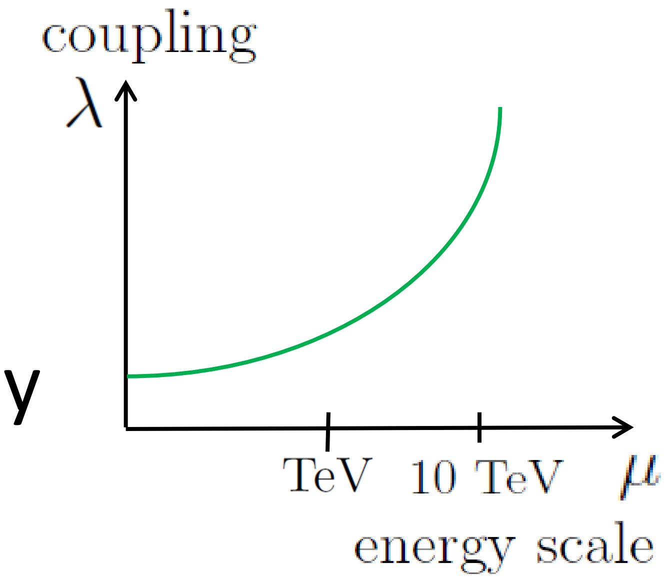
However, some models of extended Higgs sector, *e.g.*, models realizing **Electroweak Baryogenesis**, have new large couplings that blow up at 10 TeV-100 TeV scale.

e.g., In the model in the previous talk, superpotential couplings among MSSM Higgs and exotic Higgs fields, λ in $W = \lambda\ H_u \Phi_u \Omega^- + \ldots$, are as large as $\lambda(M_Z) \sim 2$ at the electroweak scale.

MSSM Higgs (H_u), Exotic doublet (Φ_u), Exotic charged singlet (Ω^-)

Landau pole at 10 TeV-100 TeV

Higgs sector may be described by a **strongly-coupled** theory in UV.



However, some models of extended Higgs sector, *e.g.*, models realizing **Electroweak Baryogenesis**, have new large couplings that blow up at 10 TeV-100 TeV scale.

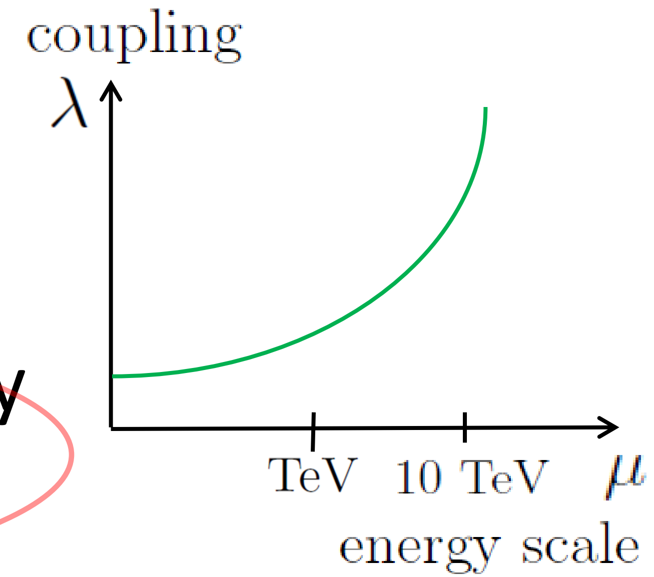
e.g., In the model in the previous talk,
superpotential couplings among MSSM Higgs and exotic Higgs fields, λ in $W = \lambda\, H_u \Phi_u \Omega^-$ +..., are as large as $\lambda(M_Z) \sim 2$ at the electroweak scale.

MSSM Higgs (H_u), Exotic doublet (Φ_u), Exotic charged singlet (Ω^-)

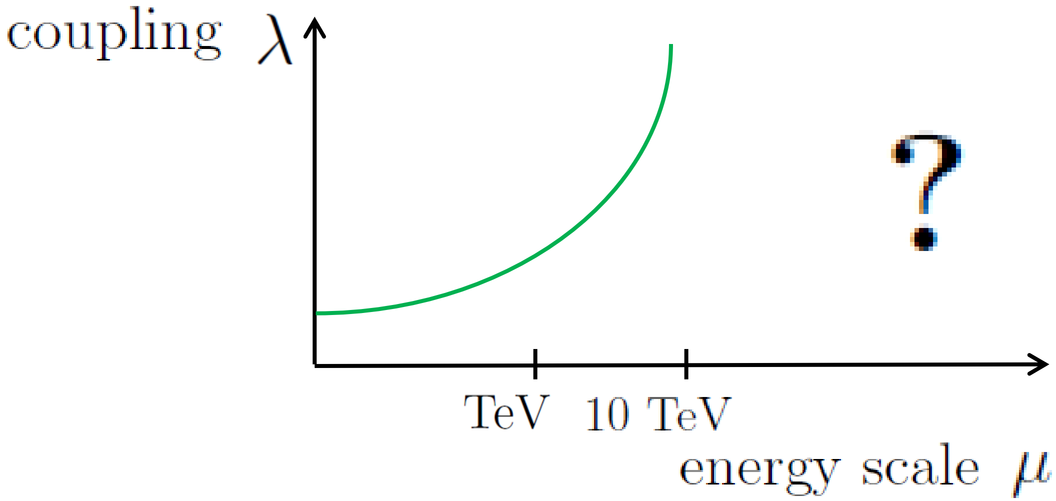
Landau pole at 10 TeV-100 TeV

↓

Higgs sector may be described by a **strongly-coupled** theory in UV.



What is the **fundamental theory** beyond Landau pole?



Here we consider **SUSY SU(2) gauge theory**
as the UV theory of the **extended SUSY Higgs model**
discussed in the previous *Dr. Shindou's talk*,
which realizes 1^{st} order electroweak phase transition.

Strongly-coupled Theory vs. Light (126 GeV) Higgs boson

In general, strongly-coupled theory predicts a large Higgs self-coupling and a heavy Higgs boson :

➡ $m_h \sim \lambda v \sim \text{several } 100 \text{ GeV}$.

In our model, **SUSY** + **approximate flavor symmetry** forbid a large Higgs self-coupling, and the self-coupling comes only from D-terms.

➡ Higgs boson is naturally light,

$$m_h^2 \simeq M_Z^2 + (\text{loop corrections})$$

Model

Fundamental Theory

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

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	$-1/2$	$-$
S	1	0	+

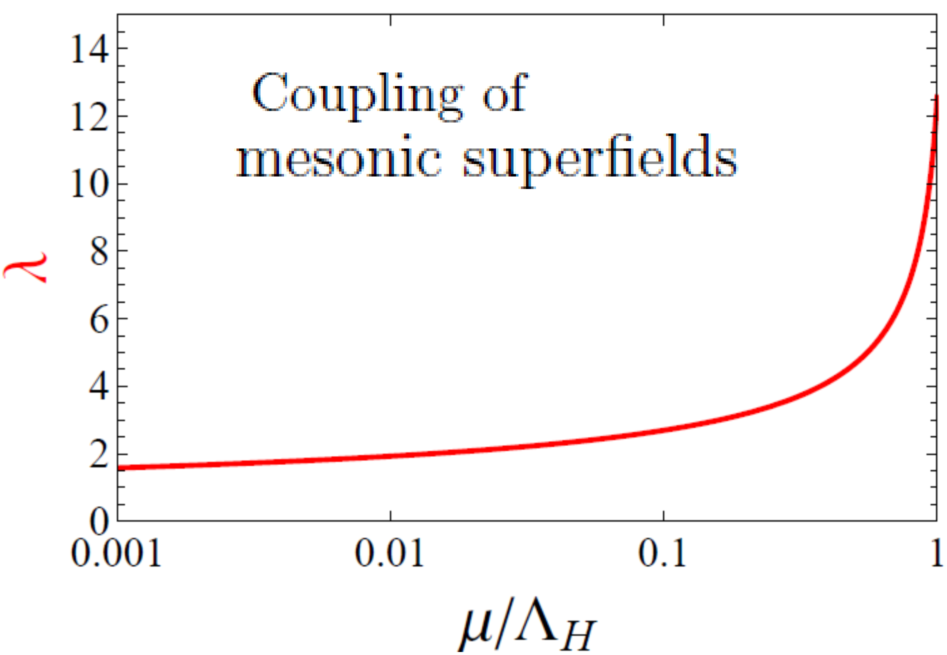
Mass term ("current mass"): $W_m = m_1 T_1 T_2 + m_3 T_3 T_4 + m_5 T_5 T_6$

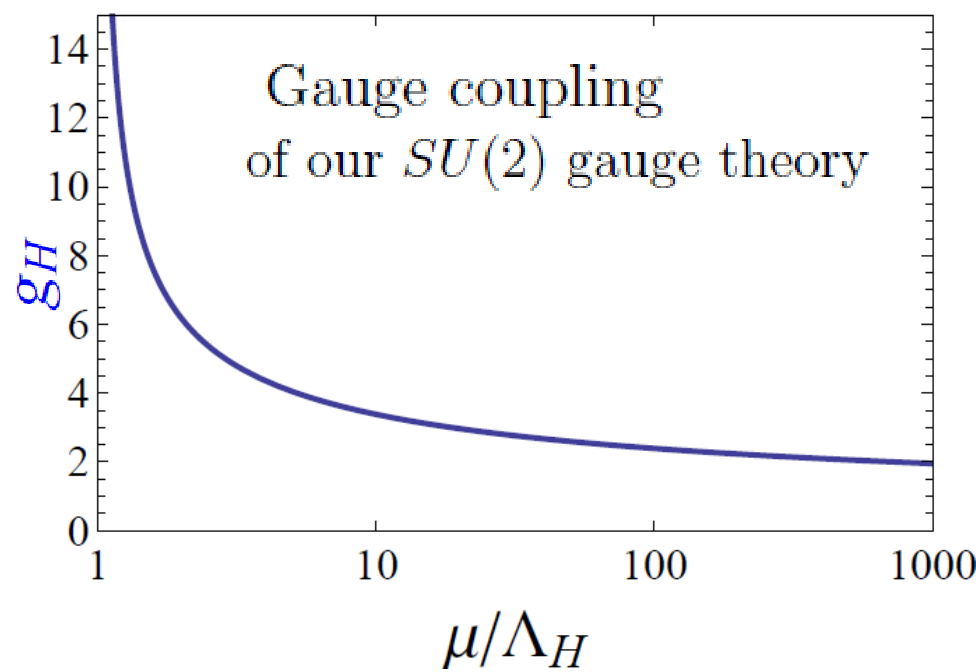
Yukawa term: $W_y = (\ y_1 T_1 T_2 + y_3 T_3 T_4 + y_5 T_5 T_6\ )\ S$

Confinement

- Our SUSY gauge theory becomes strongly-coupled and confines at a low-energy scale Λ_H .
- Below the confinement scale, Λ_H , the theory is described in terms of **mesonic superfields**.

These mesons have a large coupling λ among themselves.





Mesons = Higgses

- We have fifteen mesonic superfields whose form is constrained by SUSY as $M_{ij} \propto T_i T_j \quad (i, j = 1, 2, \ldots, 6)$.
- We identify them with MSSM Higgses and exotic fields:

	Field	$SU(2)_L$	$U(1)_Y$	Z_2
MSSM Higgs doublets	H_u	2	$+1/2$	$+$
MSSM Higgs doublets	H_d	2	$-1/2$	$+$
Exotic fields: Extra Higgs doublets	Φ_u	2	$+1/2$	$-$
Exotic fields: Extra Higgs doublets	Φ_d	2	$-1/2$	$-$
Exotic fields: Charged singlets	Ω^+	1	$+1$	$-$
Exotic fields: Charged singlets	Ω^-	1	-1	$-$
Exotic fields: Z_2-even Neutral singlets	N, N_Φ, N_Ω	1	0	$+$
Exotic fields: Z_2-odd Neutral singlets	ζ, η	1	0	$-$

$\Leftrightarrow M_{ij}$

(*c.f.* “Fat Higgs Model” (2003) by R. Harnik *et al.*)

Parameter Choice

- Add the mass term for S, $\Delta W = \frac{M_S}{2} S^2$, with $\Lambda_H \sim M_S$.
- Assume the following hierarchy of the "Yukawa couplings":

$$1 \sim y_5 \gg y_1, \; y_3 \quad .$$

- Implement "conformal enhancement" that enhances the Yukawa couplings by $\sim 4\pi$, to derive the top Yukawa.

1. S gains the large mass of order Λ_H .
2. Integrating S out, we obtain the effective mass term for N,

$$W_{eff} = \frac{M_N}{2} N^2 \quad \text{with} \quad M_N \sim \Lambda_H \; .$$

3. Below Λ_H, we may integrate N out.

Low-energy Model

Integrating N out, we obtain the following superpotential :

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

- No three-point superpotential coupling for H_uH_d .

➡ **Higgs self-coupling remains small**.

By taking $\Lambda_H \; > \; m_5 \; \gg \; m_1, \; m_3$, we can have O(100) GeV μ -terms for (H_u, H_d), $(\Phi_u, \; \Phi_d)$, (Ω^+, Ω^-) from the VEVs of N, N_Ω, N_Φ , which originally comes from their tad-pole terms.

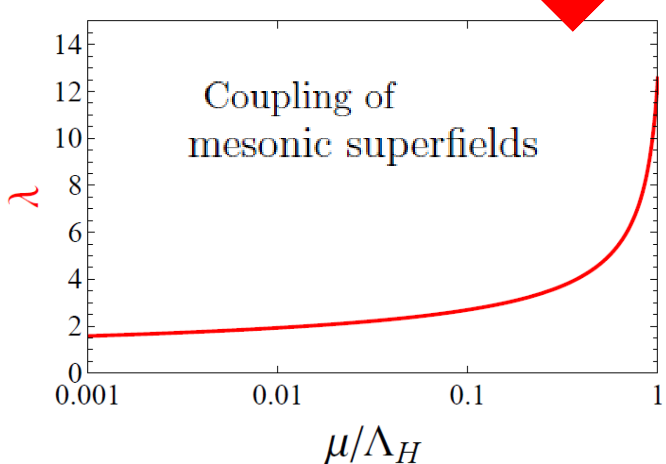
With the VEVs of N, N_Ω, N_Φ we arrive at the following model, which is basically the same as the model in the previous *Dr. Shindou's talk*.

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

Large, $\lambda(M_Z) \sim 2$

Our UV theory, namely, SUSY $SU(2)$ gauge theory **uniquely determines** the field content and the coupling !

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	$-$

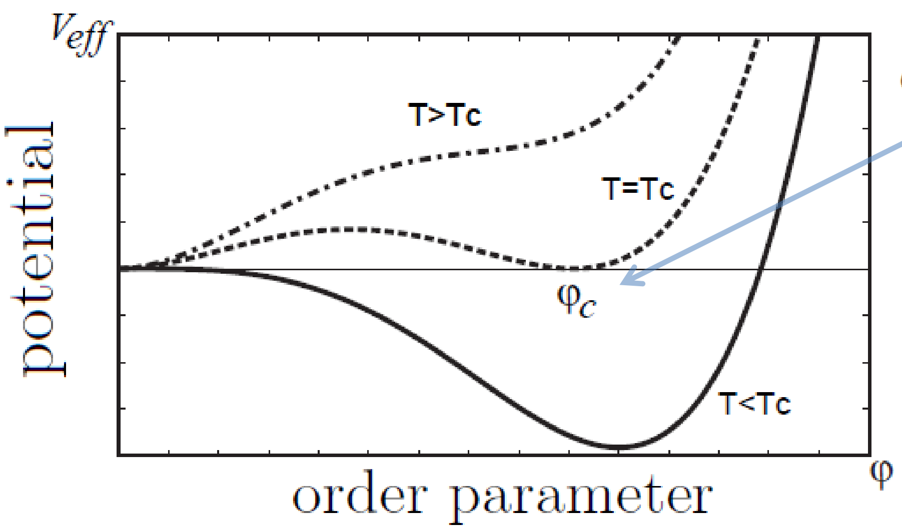


Phenomenology

Let's take **our UV-complete extended Higgs model** as a benchmark model.

Loop corrections involving exotic fields that strongly couple with MSSM Higgs fields have important phenomenological consequences.

❶ Thermal loop corrections affect the Higgs triple coupling in thermal bath, and can realize **strongly first order Electroweak phase transition** in the early Universe.



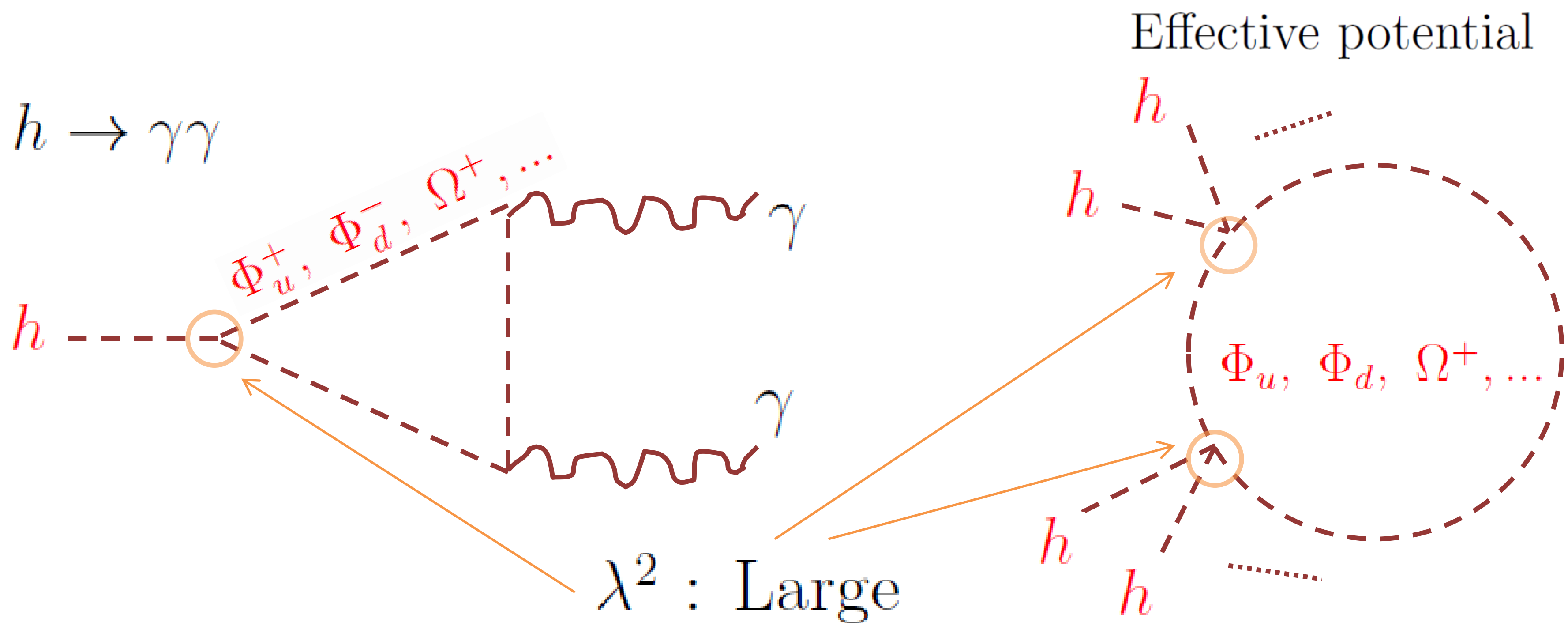
$\phi_C \gtrsim T_C$

Essential condition for **Electroweak Baryogenesis**.

As to collider physics,

❷ Higgs to $\gamma\ \gamma$ branching ratio, $Br(h \to \gamma\gamma)$, dramatically changes.

❸ Triple coupling of SM-like Higgs boson, $-\mathcal{L} \supset \lambda_{hhh}\, v\, h^3$, significantly deviates from the SM value.



Based on our model, we have calculated

❶ ϕ_C/T_C in the early Universe.

Temprature at electroweak phase transition

Higgs expectation value at electroweak phase transition

❷ $Br(h \to \gamma\gamma)$.

❸ Triple coupling of SM-like Higgs boson, λ_{hhh} .

Benchmark Mass Spectrum

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

We further introduce soft SUSY breaking terms.

(Fixed parameters)

$m_h = 126$ GeV:

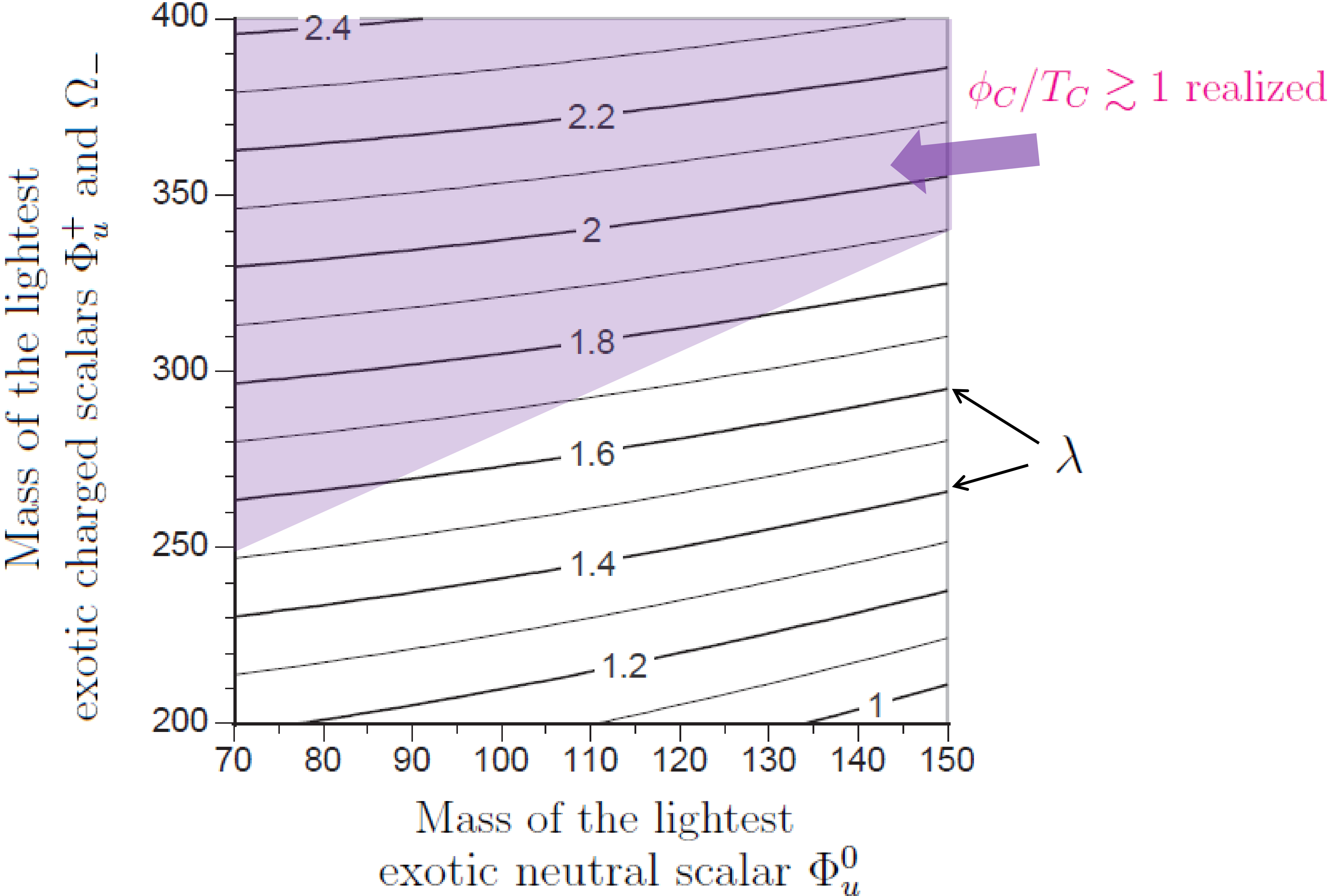
- MSSM Higgs parameters: $\tan\beta = 3, \quad m_{H^\pm} = 400$ GeV .
- μ-terms for exotic superfields: $\mu_\Phi = \mu_\Omega = 250$ GeV .
- Soft SUSY breaking terms: $m_{\tilde{t}_{L,R}} = m_{\tilde{b}_{L,R}} = 2000$ GeV .
  $X_t = 1.22 - 2.8$ TeV .
  $m^2_{\Phi_d} + \mu^2_\Phi = m^2_{\Omega_+} + \mu^2_\Omega = m^2_\zeta + \mu^2_\Omega = (1000 \text{ GeV})^2$.
  (A, B terms for exotic fields) = 0 .

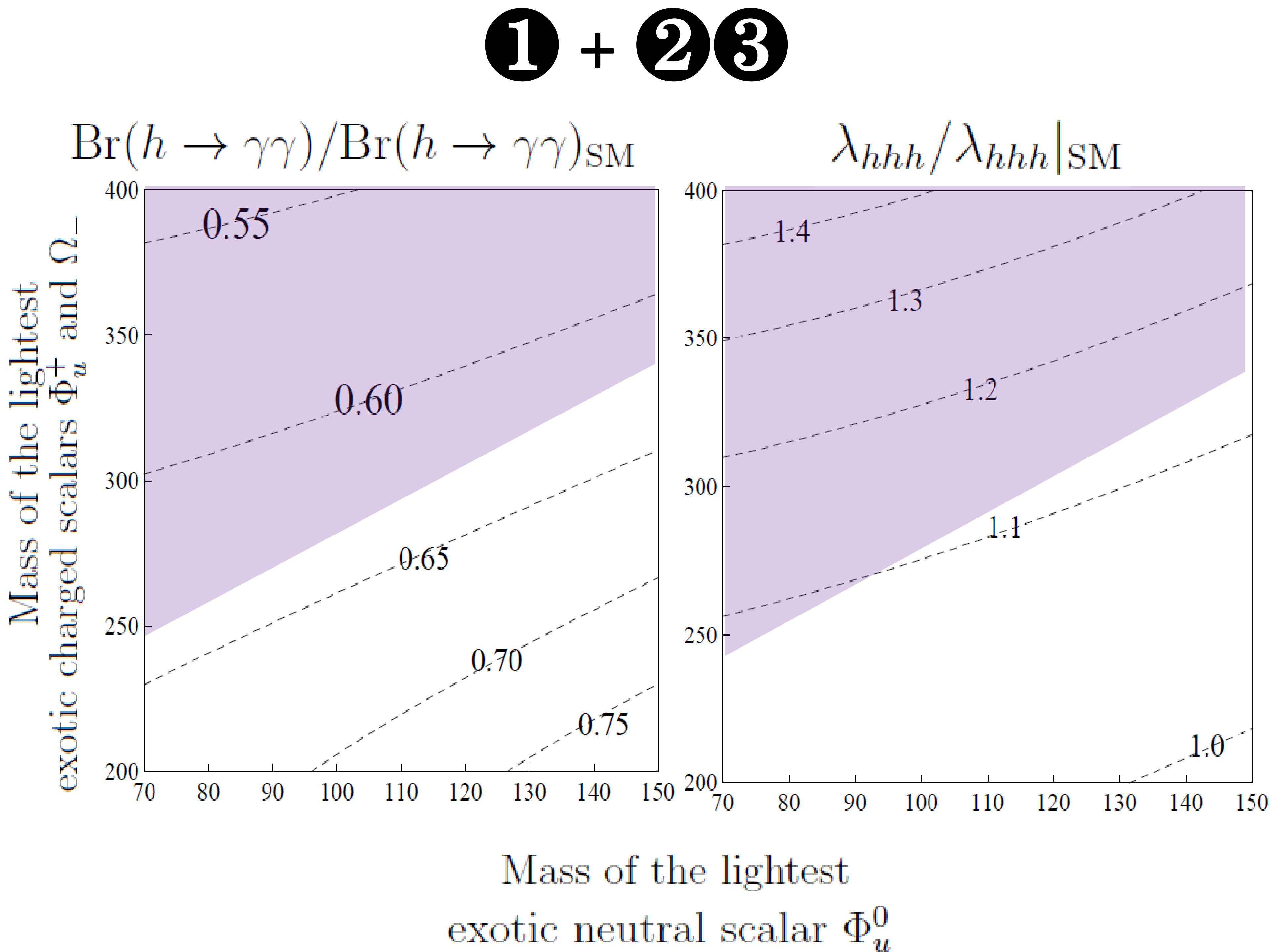
(Free parameters)

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

We take **negative** values for these.

❶ ϕ_C/T_C in the Early Universe





❶ + ❷❸
$\mathrm{Br}(h \to \gamma\gamma)/\mathrm{Br}(h \to \gamma\gamma)_{\mathrm{SM}}$
$\lambda_{hhh}/\lambda_{hhh}|_{\mathrm{SM}}$
Mass of the lightest exotic charged scalars Φ_u^+ and Ω_-
Mass of the lightest exotic neutral scalar Φ_u^0
0.55
0.60
0.65
0.70
0.75
1.4
1.3
1.2
1.1
1.0

Note:

When $\mu_\Phi/\mu_\Omega < 0$,

$\mathrm{Br}(h \to \gamma\gamma)/\mathrm{Br}(h \to \gamma\gamma)_{\mathrm{SM}}$ becomes larger than 1,

while $\lambda_{hhh}/\lambda_{hhh}|_{\mathrm{SM}}$ remains larger than 1.

Conclusions

Conclusions

- We consider strongly-coupled extended Higgs models where couplings are large (*i.e.* they blow up at 10-100 TeV scale), but the SM-like Higgs boson is naturally light.

Such models may realize electroweak baryogenesis. *(Dr. Shindou's talk)*

- We have constructed a UV theory for such models based on **SUSY** $SU(2)$ **gauge theory**.

  Our UV theory **uniquely determines** the field content and the coupling of the extended Higgs sector.

- We have shown that the low-energy model derived from our UV theory successfully realizes strongly 1st order electroweak phase transition in the early Universe,
  while predicting large deviations in the Higgs to $\gamma\gamma$ branching ratio and the Higgs triple coupling, which **are observable at the ILC !**

Back up

Scale of Λ_H

- "SUSY tadpole problem" puts a constraint on Λ_H .
- Soft SUSY breaking terms contribute to the tadpole terms for N, N_Ω, N_Φ :

Source of SUSY breaking

$$\int d^4\theta \, \frac{X^\dagger}{M^\dagger} M_{56} + \ldots \quad \Rightarrow \quad \int d^2\theta \, M_{soft} \frac{\Lambda_H}{4\pi} N + \ldots$$

- In order that these contributions do not spoil the SUSY's solution to the gauge hierarchy problem,

$$\frac{\Lambda_H}{4\pi} \lesssim 1 \text{ TeV} \quad .$$

- (Another way to evade SUSY tadpole problem

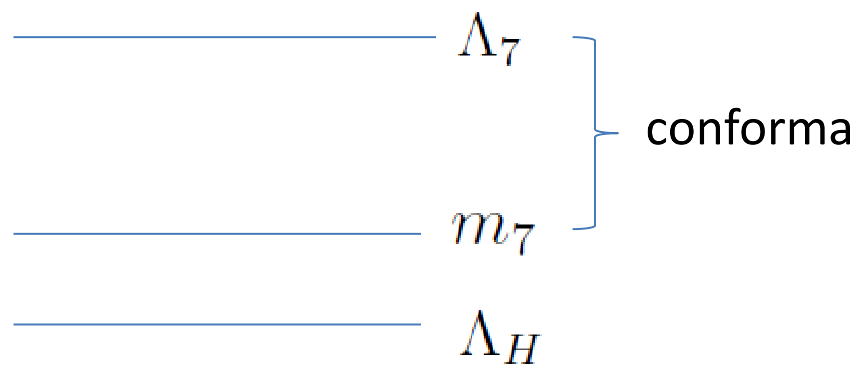
  ⇒ assigning Z_6-parity to $T_1, T_2, \ldots, T_6$. (as in NMSSM))

“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 $\Lambda_7\ (> m_7)$.



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

This is necessary to derive the O(1) top Yukawa coupling, anyway.