Partially Composite Two-Higgs doublet model

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OUTLINE OF THE TALK

- INTRODUCTION
- MODEL
- PARTICLE SPECTRUM
- LOW ENERGY PHENOMENOLOGY
- CONCLUSION

Introduction

- Dynamical Symmetry Breaking

Bardeen-Hill-Lindner (BHL), PRD**41**,1647 (1990) (Nambu, Yamawaki...)

· New strong dynamics which condenses $t\bar{t}$ bilinear.

· breaks the EW sym. $\rightarrow U(1)_{EM}$, dynamically.

· Heavy top mass and Higgs mass are generated dynamically, with the 'gap equation',

$$m_t = -\frac{1}{2}\, G\langle \bar{t}t\rangle = 2GN_c m_t \frac{i}{(2\pi)^4}\int d^4l\, \frac{1}{(l^2 - m_t^2)}$$

$$G^{-1} = \frac{N_c}{8\pi^2}\,\left[\Lambda^2 - m_t^2 \ln(\Lambda^2/m_t^2)\right]$$

Luty PRD**41**, 2893 (1990)

· Extension of BHL to 2 (composite) Higgs-like model.

- Two drawbacks

  · predict $m_t \gtrsim 200$ GeV ?

  · No origin of new strong dynamics

- Extra dimensional scenarios easily evades these 2 drawbacks

  · Bulk QCD can induce Nambu-Jona-Lasinio (NJL) type 4 fermion interaction, the dynamical symmetry breaking can occur.

  · In extra dimensional scenarios, EWSB can occur by fundamental Higgs boson, by boundary conditions, or by dynamical mechanism.

- Our model,

· 1 $t\bar{t}$ bilinear condensate and 1 Fundamental Higgs.

· type II 2-Higgs-doublets-model, with constraints.

· It can cure the problems of BHL and Luty scenarios, also has the good predictability, and is expected to be testable in the future experiments.

Model

- Nambu-Jona-Lasinio (NJL) type 4 fermion term is introduced at scale Λ,

$$\mathcal{L} = \mathcal{L}_{\rm SM} + G(\overline{\psi}_L t_R)(\bar{t}_R \psi_L),$$

where

$$\begin{aligned}\mathcal{L}_{\rm SM} &= \mathcal{L}_{\rm gauge} + \mathcal{L}_f + \mathcal{L}_\phi \\ &+ (y_{t0}\,\overline{\psi}_L t_R \tilde{\phi} + h.c.) + (y_{b0}\,\overline{\psi}_L b_R \phi + h.c.).\end{aligned}$$

- $\mathcal{L}_\phi$ contains the scalar potential

$$V(\phi) = m_0^2 \phi^\dagger \phi + \frac{1}{2}\lambda_0 (\phi^\dagger \phi)^2.$$

- Introducing the auxiliary field Φ, NJL term can be rewritten

$$\mathcal{L} = \mathcal{L}_{\rm SM} + g_{t0}(\overline{\psi}_L t_R \tilde{\Phi} + h.c.) - M^2 \Phi^\dagger \Phi,$$

where $G = g_{t0}^2 / M^2$.

$\longrightarrow$ Integrating out Φ, we can reproduce the 4 fermion vertex as induced interaction.

$\longrightarrow$ Generically $M \sim \Lambda$ and positive M^2, implying the attractive interaction.

- Low Energy Effective Lagrangian With the discrete symmetry

$$\phi \longrightarrow -\phi, \;\; D_R \longrightarrow -D_R,$$
$$\Phi, \; \psi_L, \; U_R \longrightarrow \Phi, \; \psi_L, \; U_R,$$

· For the suppression of FCNC

· $(g_{t0}\, \overline{\psi}_L t_R \phi + h.c.)$ is forbidden

· ϕ (fundamental) couples to d-type quark

· Φ (composite) couples to u-type quark

$\longrightarrow$ Type II 2-Higgs-doublets model

- The effective Lagrangian, far below Λ,

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm gauge} + \mathcal{L}_f + (D_\mu\phi)^\dagger(D^\mu\phi) + (D_\mu\Phi)^\dagger(D^\mu\Phi) \\ &\quad +(g_b\overline{\psi}_L b_R\phi + {\rm h.c}) + (g_t\overline{\psi}_L t_R\tilde{\Phi} + {\rm h.c}) - V(\phi,\Phi),\end{aligned}$$

where the most general Higgs potential is given by

$$\begin{aligned}V(\phi,\Phi) &= \mu_1^2\phi^\dagger\phi + \mu_2^2\Phi^\dagger\Phi + \mu_{12}^2(\phi^\dagger\Phi + h.c.) \\ &\quad +\frac{1}{2}\lambda_1(\phi^\dagger\phi)^2 + \frac{1}{2}\lambda_2(\Phi^\dagger\Phi)^2 \\ &\quad +\lambda_3(\phi^\dagger\phi)(\Phi^\dagger\Phi) + \lambda_4|\phi^\dagger\Phi|^2 + \frac{1}{2}\lambda_5((\phi^\dagger\Phi)^2 + {\rm h.c}).\end{aligned}$$

Note: Soft breaking term of the discrete symmetry μ_{12} is introduced, which will not induce dangerously large FCNC at loop level.

Matching the Lagrangian at Λ

The renormalized Lagrangian at low energy,

$$\begin{aligned}\mathcal{L} &= Z_\phi (D_\mu \phi)^\dagger (D^\mu \phi) + Z_\Phi (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\sqrt{Z_\phi}\phi, \sqrt{Z_\Phi}\Phi) \\ &+ \sqrt{Z_\Phi} g_t (\overline{\psi}_L t_R \tilde{\Phi} + \mathrm{h.c}) + \sqrt{Z_\phi} g_b (\overline{\psi}_L b_R \phi + \mathrm{h.c}),\end{aligned}$$

Matching conditions,

$$\begin{aligned} &\sqrt{Z_\phi} \to 1, \qquad \sqrt{Z_\Phi} \to 0, \\ &Z_\phi \mu_1^2 \to m_0^2, \qquad Z_\Phi \mu_2^2 \to M^2, \\ &Z_\phi \lambda_1 \to \lambda_{10}, \qquad Z_\Phi^2 \lambda_2 \to 0, \\ &Z_\phi Z_\Phi (\lambda_{3,4,5}) \to 0 \end{aligned}$$

as the scale $\mu \to \Lambda$.

Particle Spectrum

- The matching conditions can be rewritten,

$$g_t \longrightarrow \infty, \qquad g_b \longrightarrow g_{b0},$$
$$\mu_1^2/g_b^2 \longrightarrow \mu_{10}^2/g_{b0}^2, \qquad \mu_2^2/g_t^2 \longrightarrow \Lambda^2/g_{t0}^2,$$
$$\lambda_1/g_b^4 \longrightarrow \lambda_{10}/g_{b0}^4, \qquad \lambda_{2,3,4,5} \longrightarrow 0,$$

with the conventional normalization of couplings, by the field redefinition,

$$\phi \rightarrow Z_\phi^{-1/2}\phi, \qquad \Phi \rightarrow Z_\Phi^{-1/2}\Phi.$$

Constraints

1) g_t, g_b and $\tan\beta$ should provide the measured m_t, and m_b at EW scale, $i.e.$,

$$m_t = \frac{1}{\sqrt{2}} g_t v \sin\beta \;\; (m_t(m_Z) = 178.1\,\mathrm{GeV})$$
$$m_b = \frac{1}{\sqrt{2}} g_b v \cos\beta \;\; (m_b(m_Z) = 2.8\,\mathrm{GeV}).$$

2) To break the symmetry $SU(2)_L \times U(1)_Y \to U(1)_{EM}$, Higgs feilds should have vev's,

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 e^{i\delta} \end{pmatrix},$$

3) For bounded-belowness of the scalar potential, we require that $\lambda_{1,2} > 0$ and

$$\begin{aligned} \sqrt{\lambda_1 \lambda_2} &> -\lambda_3 - \lambda_4 + |\lambda_5| \quad \text{if} \;\; \lambda_4 < |\lambda_5|, \\ \sqrt{\lambda_1 \lambda_2} &> -\lambda_3 \quad \text{if} \;\; |\lambda_5| < \lambda_4. \end{aligned}$$

Minimizing the Higgs potential at v_1 and v_2,

$$\begin{aligned} \mu_1^2 + \mu_{12}^2 \tan\beta + \frac{1}{2}\lambda_1 v_1^2 + \frac{1}{2}\lambda_{345} v_2^2 &= 0, \\ \mu_2^2 + \mu_{12}^2 \cot\beta + \frac{1}{2}\lambda_2 v_2^2 + \frac{1}{2}\lambda_{345} v_1^2 &= 0, \end{aligned}$$

where $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$

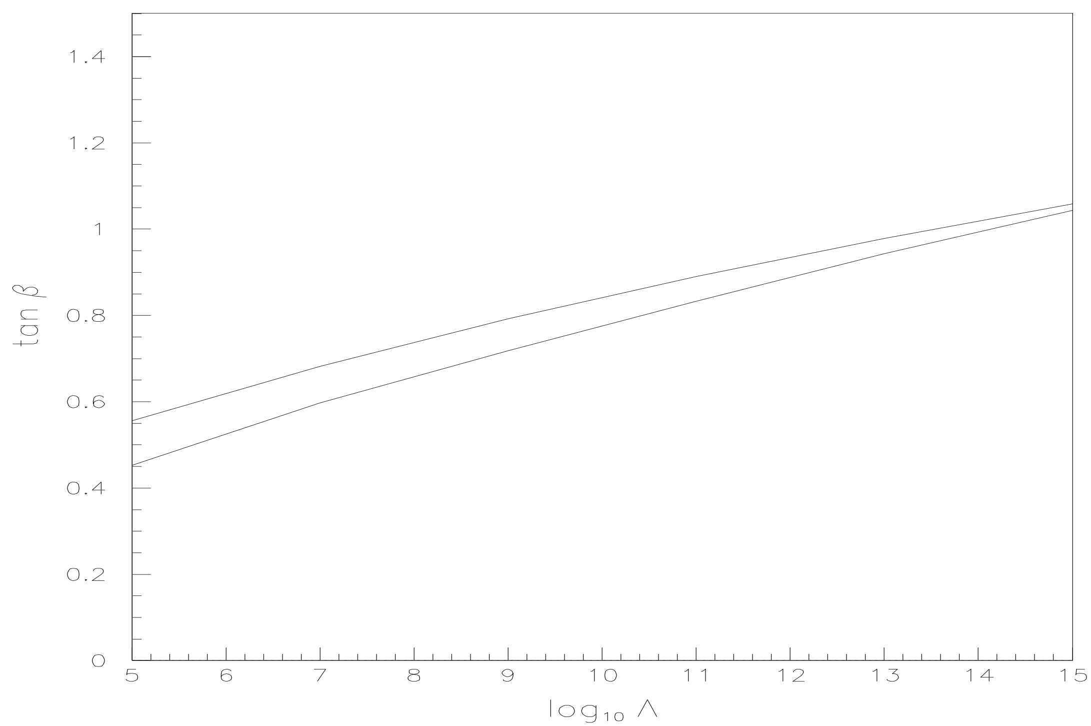
- The input parameters for model are,

  · g_{b0}, λ_{10} at compositeness scale Λ,
  · $\tan\beta$ at EW scale.
- $\lambda_{2,3,4,5}$ should be zero at Λ.
- g_{t0} should be infinity, but we take finite value for it because of infra-red fixed point nature of g_t.
- μ_{12}^2 can be traded to m_A, because of the relation

$$m_A^2 = -\frac{2\mu_{12}^2}{\sin 2\beta} - \lambda_5 v^2$$

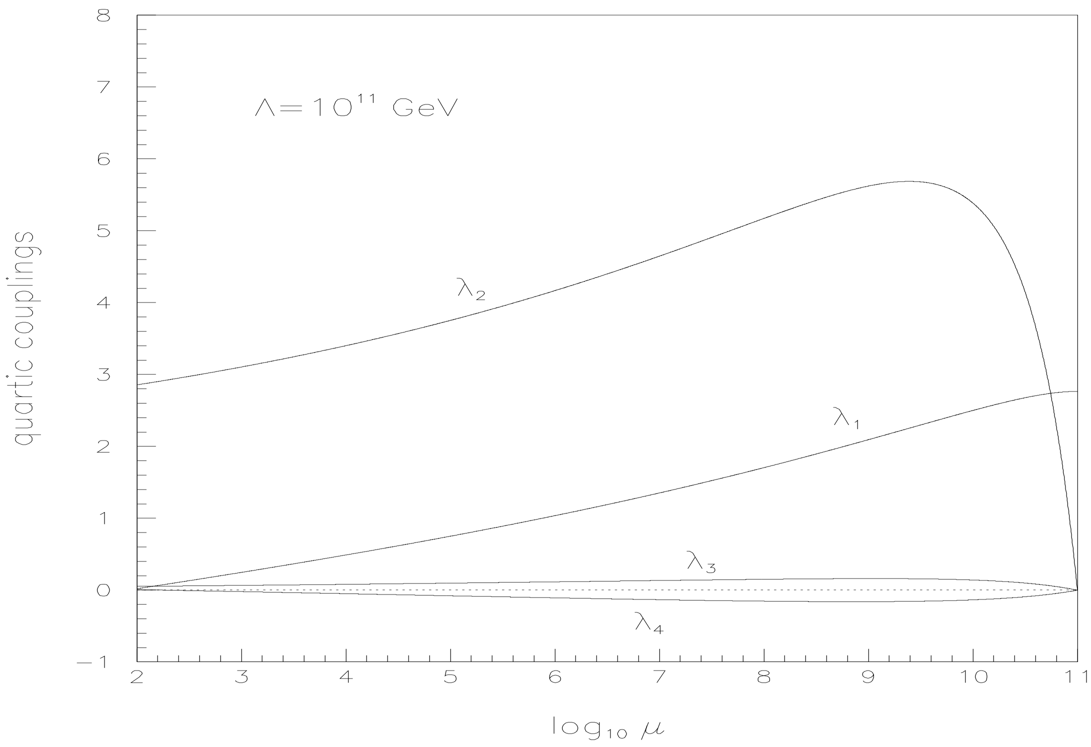
λ_5 is always zero in our model, since its 1-loop RG equation is proportional to itself.

- $m_t = \frac{1}{\sqrt{2}}\, g_t v \sin\beta, \quad m_b = \frac{1}{\sqrt{2}}\, g_b v \cos\beta$



Allowed values of $\tan\beta$ with respect to the compositeness scale Λ.

- The positiveness condition for $\lambda_{1,2}$ plays an crucial role when determine the allowed parameter space.



Evolution of the Higgs quartic coupling λ_i with respect to $\log_{10}\mu$.

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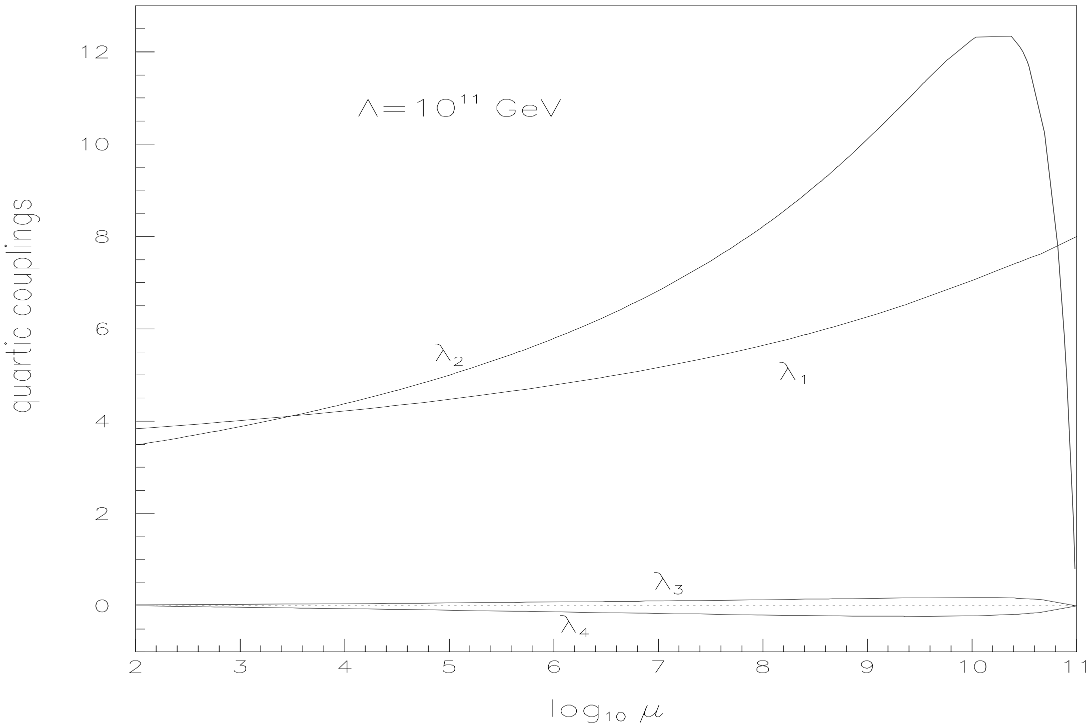
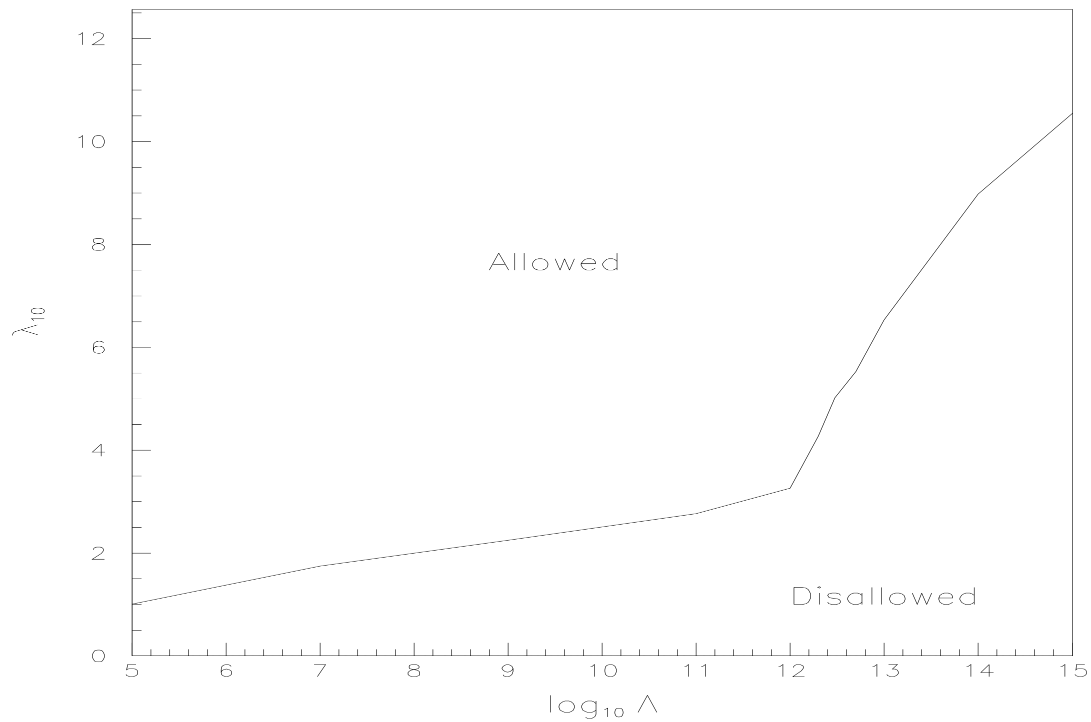


Evolution of the Higgs quartic coupling λ_i with respect to $\log_{10} \mu$.

- 1-loop beta funtion of λ_5 is proportional to itself.
- With the vanishing initial condition for λ_5, λ_5 remains zero at all scale down to M_Z.
- λ_1 decreases with the decrease of the energy scale, so for positiveness of it at low energy, rather large initial value of λ_{10} is required.
- $\mathbf{Im}(\mu_{12}^2) = -\frac{1}{2}\mathbf{Im}(\lambda_5)v_1 v_2$
  $\rightarrow$ No CP violation in our model in the Higgs sector.

- We can determine the allowed range of parameters for varying compositeness scale Λ.



Allowed values of the quartic coupling λ_{10} at Λ with respect to the compositeness scale Λ.

- Mass relations

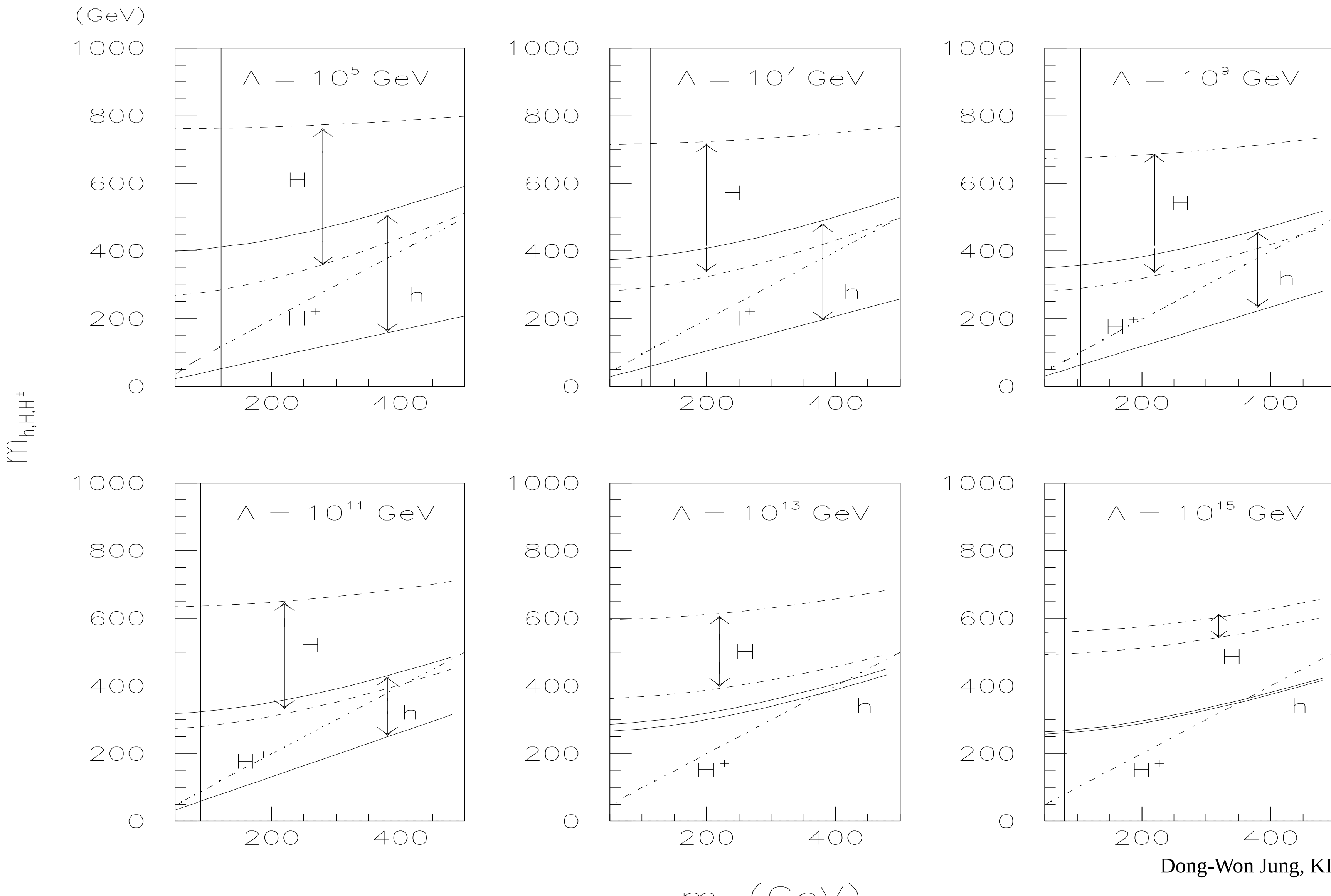
$$m_A^2 = -\frac{2\mu_{12}^2}{\sin 2\beta} - \lambda_5 v^2$$
$$m_{H^\pm}^2 = m_A^2 - \frac{1}{2}(\lambda_4 - \lambda_5)v^2.$$

- Since λ_4 is almost positive in our model, the mass of the charged Higgs boson is always less than that of the pseudo-scalar Higgs boson.

$\longrightarrow$ It is the generic feature of our model.

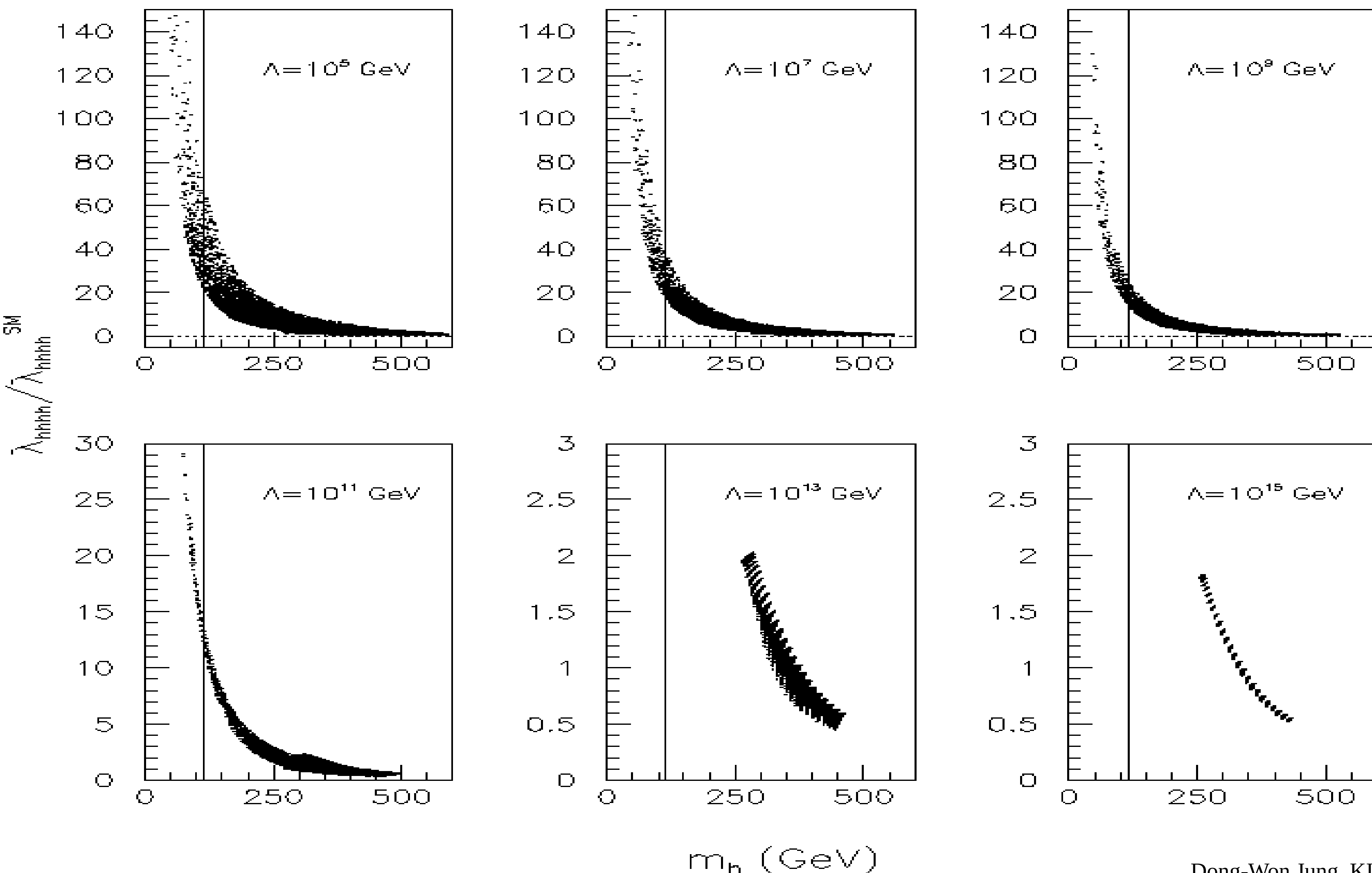
$cf.\ m_{H^\pm}^2 = m_A^2 + m_W^2$, in the MSSM.

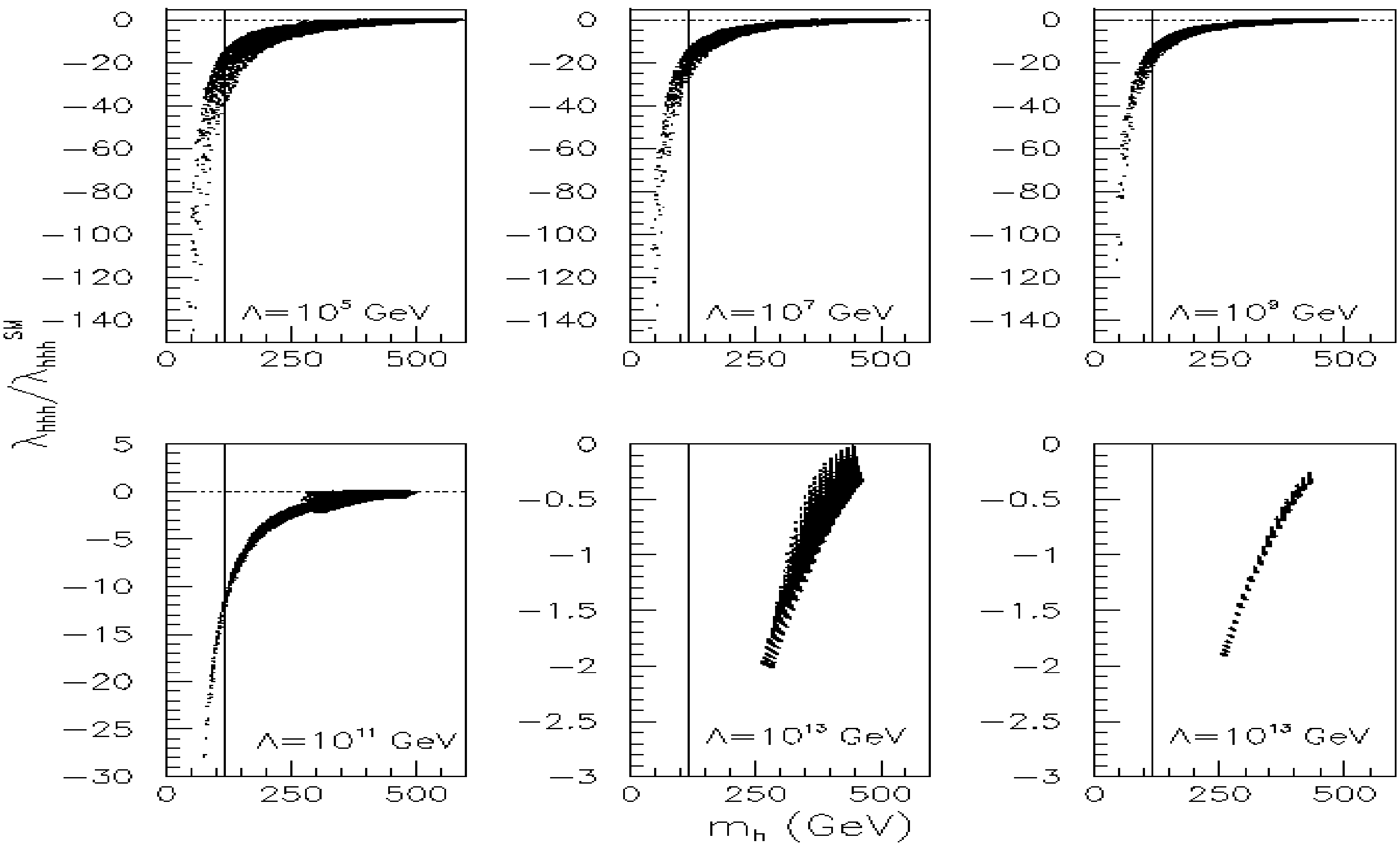
- The range of the masses of the Higgs particle, m_h, m_H.



Low Energy Phenomenology

- The Higgs self couplings : sensitive probe to the new Physics





$\Lambda=10^5$ GeV
$\Lambda=10^7$ GeV
$\Lambda=10^9$ GeV
$\Lambda=10^{11}$ GeV
$\Lambda=10^{13}$ GeV
$\Lambda=10^{13}$ GeV
$\lambda_{hhh}/\lambda_{hhh}^{SM}$
m_h (GeV)

Collider Signatures

a) LHC : 2007 and luminosity $\sim 100\ fb^{-1}$.

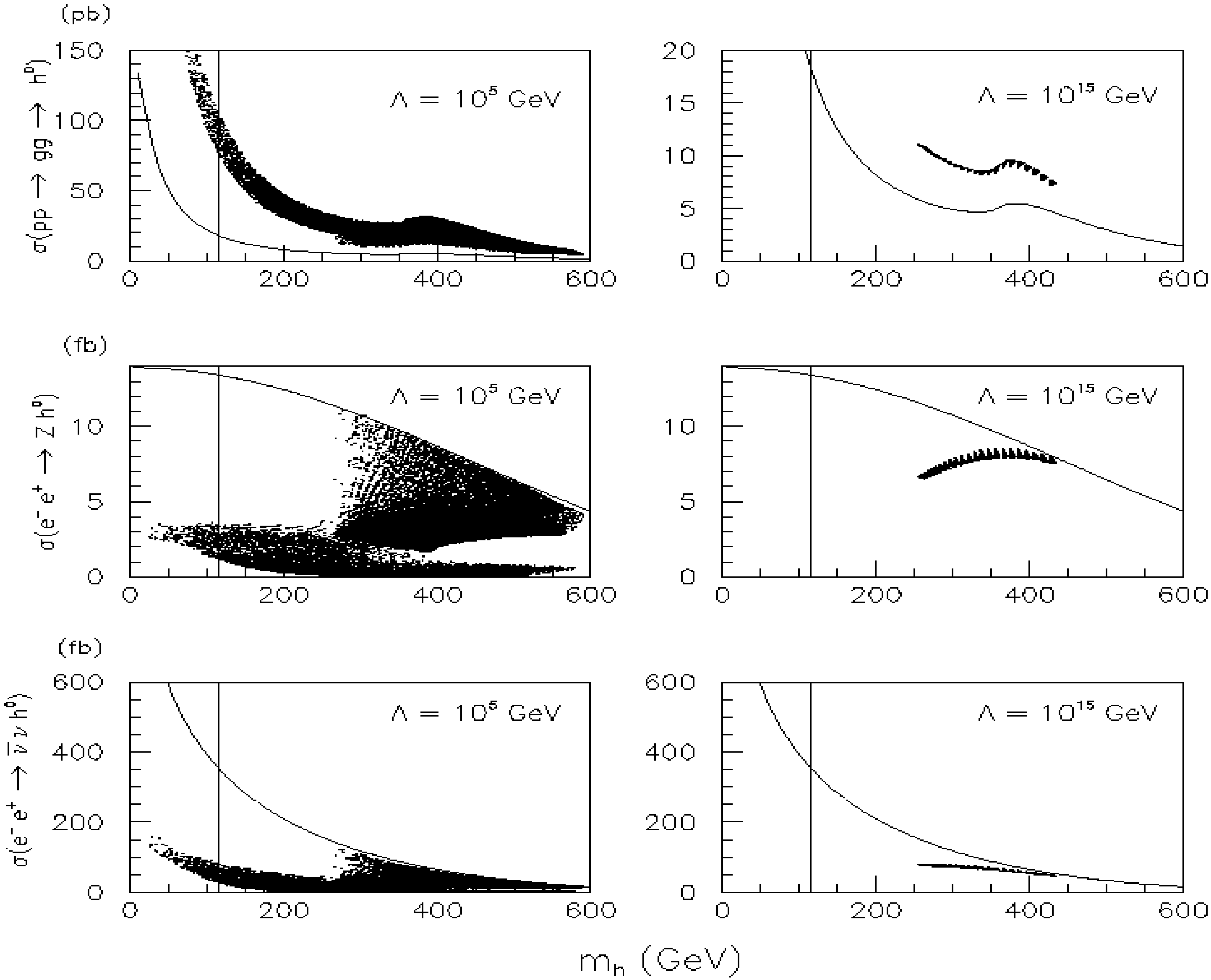
· $pp \longrightarrow gg \longrightarrow h$ dominant.

$$\sigma(pp \longrightarrow gg \longrightarrow h^0) = \left(\frac{\cos\alpha}{\sin\beta}\right)^2 \sigma_{SM}(pp \longrightarrow gg \longrightarrow h^0),$$

b) The future e^-e^+ linear collider (ILC).

· Higgs-strahlung and WW fusion,

$$\begin{aligned} \sigma(e^+e^- \longrightarrow Z + h^0) &= \sin^2(\beta - \alpha)\sigma_{\rm SM}(e^+e^- \longrightarrow Z + h^0), \\ \sigma(e^-e^+ \longrightarrow \bar{\nu}_e\nu_e + h^0) &= \sin^2(\beta - \alpha)\sigma_{\rm SM}(e^-e^+ \longrightarrow \bar{\nu}_e\nu_e + h^0). \end{aligned}$$



Production Xsection of the neutral Higgs boson at the LHC and ILC. Solid cruves are SM values.

Conclusion

- Simple model with both fundamental and composite Higgs bosons are studied.
- This type of model can be realized by embedding the SM in the higher dimensions with bulk gauge interactions.
- Contrary to the BHL and Luty's scenarios, this model can fit both the top and bottom quark masses well, and give the very restricted prediction for $\tan\beta$.
- It also give stringent ranges for the Higgs boson masses according to the compositeness scale Λ.
- Future experiments, especially ILC is expected to be able to confirm/exclude our model.