Strongly coupled fourth family and electroweak phase transition

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Based on work with
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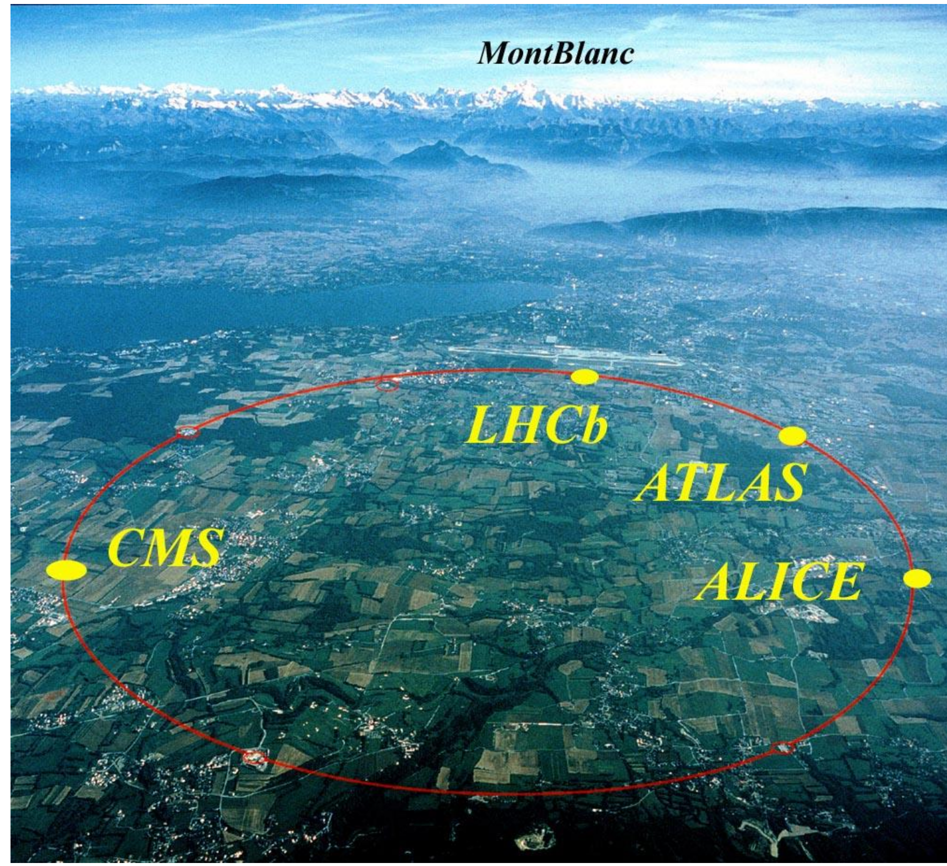
The era of LHC

One of main task is to uncover

Higgs sector

origin of Electroweak symmetry breaking

(origin of particle masses)



Electroweak phase transition

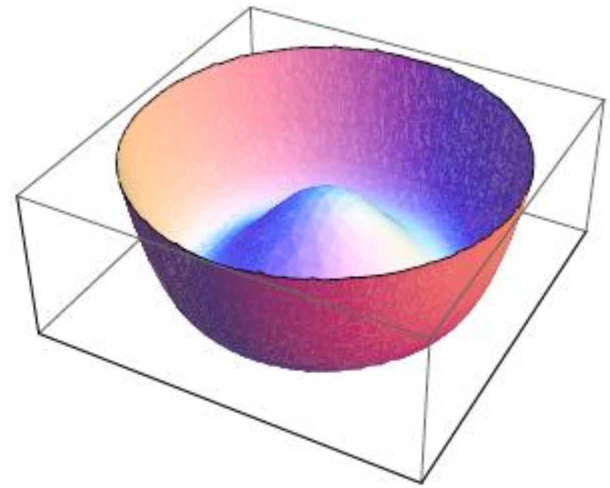
How Electroweak symmetry was broken in early universe?

(maybe related to origin of matter in the universe)

Spontaneous Symmetry Breaking of EW gauge symmetry

$SU(3)c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)c \times U(1)_{EM}$

--> W, Z acquire masses (Higgs mechanism)



Higgs sector : fields and interactions which trigger this SSB

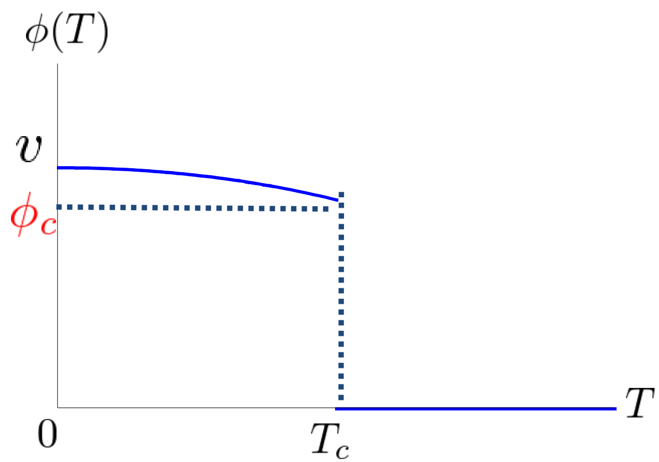
In SM, SU(2) doublet-Higgs field H
--> SSB is realized by nonzero VEV of Higgs <H>

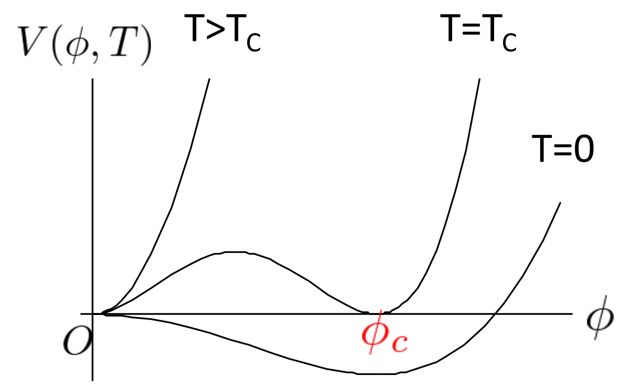
- At finite T, EW symmetry is expected to be restored
  [Kirzhnitz and Linde (1972)]
  - pointed out based on analogy with superconductor
  - early stage of universe is in unbroken phase

ElectroWeak Phase Transition

◆breaking of SU(2)×U(1) at finite T : <H>=0 → <H>≠0

◆ EW baryogenesis requires 1st order phase transition





◆ For EW baryogenesis, phase transition should be also strongly 1st order (explain later): $$\frac{\phi_c}{T_c} \gtrsim 1$$

◆In standard model, this condition is not satisfied

◆ In this talk, consider 4th family fermions

Outline of my talk

1. **Introduction**
   - Baryogenesis in SM, current status of 4th family
2. **EW phase transition in SM**
   - one-loop analysis based on finite temp. effective potential
3. **Strongly coupled 4th family**
   - 4th family as origin of EW symmetry breaking
   - setup of our model
4. **EWPT with strongly coupled 4th family**
   - numerical results for EWPT
   - strongly 1st order PT ?
5. **Summary and discussion**

1. Introduction

Baryon Asymmetry of the Universe

- In current Universe: N(baryon) >> N(antibaryon)
- The universe is asymmetric between baryon and antibaryon
- Degree of baryon asymmetry

$$\eta \equiv \frac{n_B}{n_\gamma} = (4.7 - 6.5) \times 10^{-10}$$ [PDG 2008]

- required for big-bang nucleosynthesis
- also measured through Cosmic Microwave Background

Conditions for baryogenesis

$$\eta \equiv \frac{n_B}{n_\gamma} = (4.7 - 6.5) \times 10^{-10}$$

◆Our goal is to explain this value based on particle physics and cosmology

◆ dynamical creation of baryon asymmetry in early universe (Baryogenesis)

$n_B = 0$ ⇒ $n_B \neq 0$

◆ Sakharov's conditions for baryogenesis

(1) B non-conservation (2) C, CP violation (3) Out of equilibrium

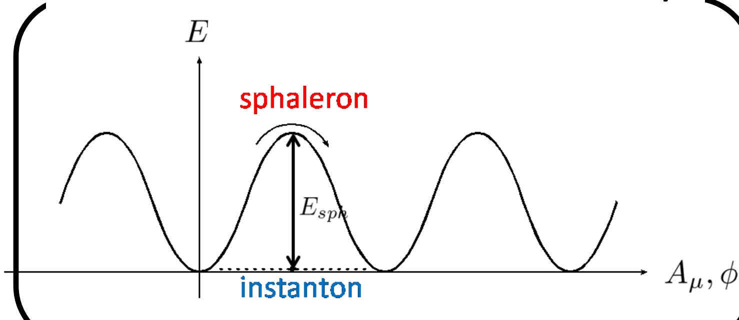
SM and Sakharov's conditions (1)

◆ SM can fulfill all Sakharov's conditions, in principle

(1) B non-conservation

◆ B is violated by quantum anomaly

Vacuum structure of EW theory



Reaction rates of B-violating processes

➢ T = 0 : *instanton* transition

$$\Gamma_{\not B} \sim \quad e^{-2S_{instanton}} = e^{-4\pi/\alpha_2} \sim 10^{-170} << 1$$

⇒ consistent with experiments

➢ T > 0 : *sphaleron* transition

$$\Gamma_{\not B} \sim \begin{cases} T e^{-E_{sph}/T} & \text{for } T < T_c \ (\langle H \rangle \neq 0) \\ T & \text{for } T > T_c \ (\langle H \rangle = 0) \end{cases}$$

•sphaleron energy : $E_{sph} = \frac{4\pi\langle H\rangle}{g_2} \times (1.5 - 2.7)$

⇒ large B violation for T > Tc ∼ O(100) GeV !

SM and Sakharov's conditions (2)

(2) C and CP violation

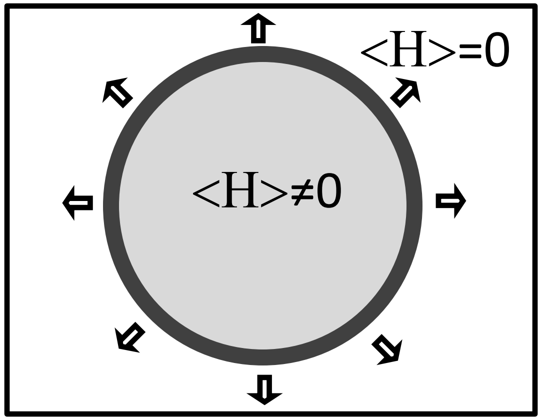
- ◆ SU(2)xU(1) gauge interaction is chiral ⇒ C violation
- ◆ Kobayashi-Maskawa phase ⇒ CP violation

  (nicely explaining B,K physics)

(3) Out of equilibrium

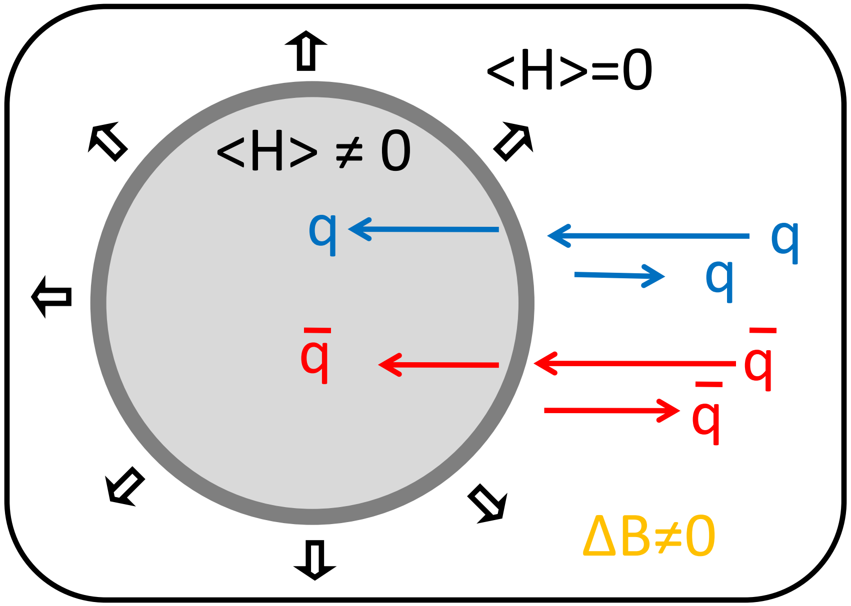
- ◆ At T > Tc, all gauge int. and sphaleron processes are in eq.
- ◆ EWPT --> masses change suddenly
- ◆ If 1st order
  - ➢ expanding bubble of broken phase

    ⇒ out of eq.



⇨ **Electroweak baryogenesis**

EW Baryogenesis in SM (1)



[Farrar and Shaposhnikov (1993)]

- CP violating scattering of quarks with bubble wall
- Transmission rate is CP asymmetric
  ⇒ B≠0 is stored in broken phase
- B in symmetric phase is erased by rapid sphaleron process

- To avoid washout of generated baryon asymmetry, sphaleron processes should **decouple inside bubble**

$$\Gamma_{\not B} \sim e^{-E_{sph}/T}|_{T=T_c} \lesssim H(T_c) \qquad E_{sph} = \frac{4\pi\phi}{g_2} \times (1.5 - 2.7)$$

--> $\frac{\phi_c}{T_c} \gtrsim 1$ --> strongly 1st order EWPT is required

EW Baryogenesis in SM (2)

◆ EW baryogenesis does not work in SM, because of two reasons :

(1) CP violation from *KM phase is not sufficient*

$$\left|\frac{n_B}{s}\right| < 10^{-26}$$

from Huet and Sather (1995)

[Similar bound by Gavela et al. (1994)]

15 orders of magnitude smaller than $\left(\frac{n_B}{s}\right)_{obs.} \sim 10^{-11}$

(2) For *m_h >114 GeV (LEP), EWPT is not 1st order* *(explained later)*

--> To explain baryon asymmetry, *physics beyond SM* is required!

4th family revive EW Baryogenesis ?

4th family fermions : t', b', ν', τ'

(1) **extra CP violating phases** appear in 4 × 4 CKM matrix

4th family enhances CP asymmetry

[Shaposhnikov (1987); W.-S. Hou (2008)]

- ◆ smallness of CPV in SM

➢ Jarlskog invariant: nonzero if and only if CPV exists

$$J = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)2A$$

A: area of unitarity triangle

➢ size of CPV at $T_C \sim 100\text{GeV}$ $\frac{J}{T_c^{12}} \sim 10^{-20}$ <-- too small to explain BAU

- ◆ In 4th family case, similar quantity for 2-3-4 generation

$$J_{(2,3,4)}^{sb} = (m_{t'}^2 - m_t^2)(m_{t'}^2 - m_c^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_b^2)(m_{b'}^2 - m_s^2)(m_b^2 - m_s^2)2A_{234}^{sb}$$

$$\sim \frac{m_{t'}^4}{m_t^2 m_c^2} \frac{m_{b'}^4}{m_b^2 m_s^2} \frac{A_{234}^{sb}}{A} J$$

--> 10^{15} enhancement is possible for $m_{t'} \sim m_{b'} \sim 600\text{GeV}$!

4th family revive EW Baryogenesis ?

4th family fermions : t', b', ν', τ'

(1) **extra CP violating phases** appear in 4 × 4 CKM matrix

◆ dimensional analysis suggests large enough enhancement

4th family revive EW Baryogenesis ?

4th family fermions : t’, b’, ν’, τ’

(1) **extra CP violating phases** appear in 4 × 4 CKM matrix

◆ dimensional analysis suggests large enough enhancement

(2) In this talk, I will concentrate on another problem of EWBG

◆4th family fermions can induce strongly 1st order EWPT?

Experimental constraints on 4th family

Nν ∼ 3 $Z \not\to \nu' \bar{\nu}'$

- from measurement of Z decay width --> $m_{\nu'} > m_z/2$

Direct search experiments [Particle Data Group 2010]

$m_{t'} > 256$ GeV, $m_{b'} > 199$ GeV, $m_{\tau'} > 102$ GeV, $m_{\nu'} > 90$ GeV

--> $m_{t'} > 335$ GeV (CDF@4.6fb^{-1}), $m_{b'} > 372$ GeV (CDF@4.8fb^{-1})

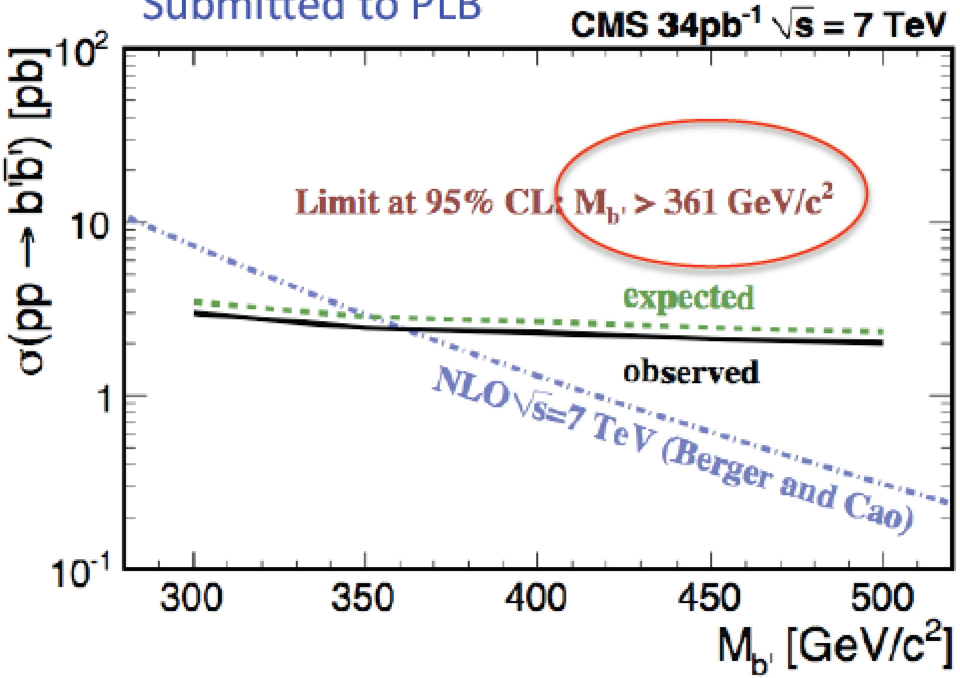
LHC already gives constraint on 4th family

◆ CMS b' search

- **Pair produced b'→tW→WWb**
- Like-sign dilepton and trilepton (e,μ) decays + jets (BR=7.3%)
- $N_{background}$ = 0.3 +/- 0.2 events (tt+jets)
- 0 events observed

Similar to a new CDF limit of 372 GeV, arXiv:1101.5728 (4.8 fb^{-1})

arXiv:1102.4746, Submitted to PLB



From Santanastasio's talk slide @ Moriond2011

Already comparable to Tevatron bound!

Experimental constraints on 4th family

Nν ∼ 3 $Z \not\to \nu'\bar{\nu}'$

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EW presision data (indirect measurement)

◆ ρ-parameter constraint

$$\delta\rho \sim 0 \Rightarrow |m_{t'} - m_{b'}| \lesssim m_W \qquad \rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W}$$

◆ also consistent with other EW data (by S,T-parameter analysis)

[Kribs , Plehn, Spannowsky and Tait (2007)]

4th family is still consistent with experiments!

2. EW phase transition in SM

Finite Temperature Effective Potential

- tool for analyzing phase transition
- FTEP = free energy density
- obtained from partition function

$$V(\phi, T) = -\frac{1}{V} T \log Z \quad \begin{cases} \text{partition function}: \ Z = Tr[e^{-\beta H}] \ \ \beta \equiv 1/T \\ \text{order parameter}: \ \langle H(x) \rangle_T = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \phi \end{pmatrix} \end{cases}$$

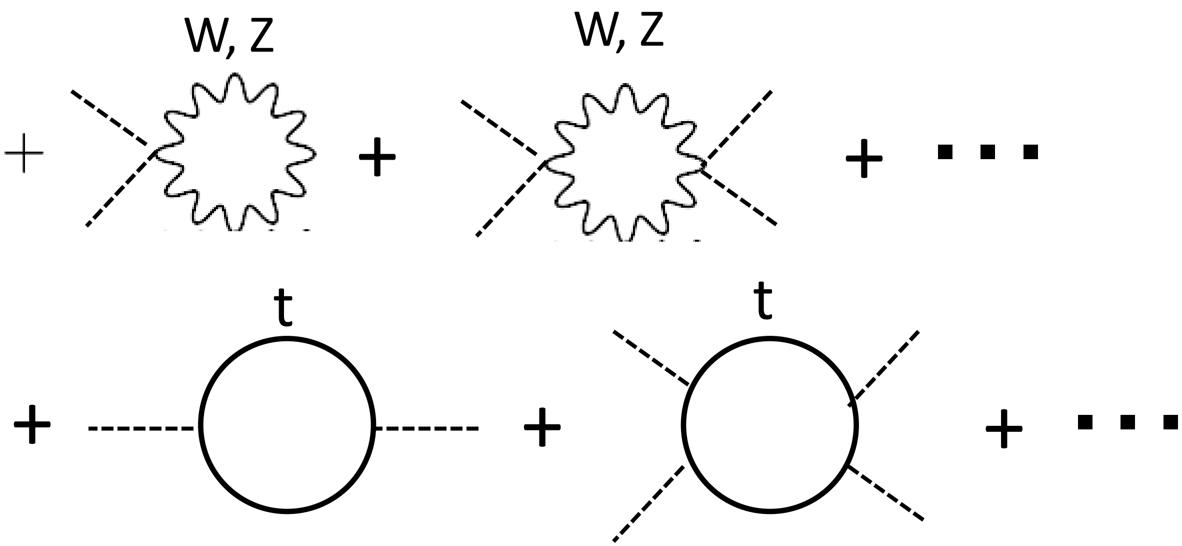
- calculated based on the finite-temperature field theory

One-loop FTEP in SM (1)

◆ FTEP at one loop

tree level effective potential : $V_0(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$

$V(\phi, T) = V_0(\phi) +$



One-loop FTEP in SM (2)

- FTEP at one loop

$$V(\phi, T) = V_0(\phi) + \underline{V_1^{(0)}(\phi)} + \underline{V_1^{(T)}(\phi, T)} + \dots$$

1. T-independent correction (Coleman-Weinberg potential)

$$V_1^{(0)}(\phi) = \sum_{i=W,Z,t} \frac{m_i^4(\phi)}{64\pi^2} \left[\ln \frac{m_i^2(\phi)}{\mu^2} + const. \right]$$

2. T-dependent correction

$$V_1^{(T)}(\phi, T) = \frac{T^4}{2\pi^2} (6J_B[m_W^2(\phi)/T^2] + 3J_B[m_Z^2(\phi)/T^2] - 6J_F[m_t^2(\phi)/T^2])$$

$$J_{B,F}(m^2/T^2) \quad = \int_0^\infty dx \; x^2 \log[1 \mp e^{-\sqrt{x^2 + m^2/T^2}}]$$

One-loop FTEP in SM (3)

$$J_{B,F}(m^2/T^2) \quad = \int_0^\infty dx\ x^2 \log[1 \mp e^{-\sqrt{x^2+m^2/T^2}}]$$

- high temperature expansion : m(ϕ)/T << 1

$$\begin{cases} J_B(m^2/T^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}\frac{m^2}{T^2} - \frac{\pi}{6}\left(\frac{m^2}{T^2}\right)^{3/2} + \mathcal{O}\left(\frac{m^4}{T^4}\right) \\ J_F(m^2/T^2) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}\frac{m^2}{T^2} + \mathcal{O}\left(\frac{m^4}{T^4}\right) \end{cases}$$

- For T > m_W(ϕ), m_Z(ϕ), m_t (ϕ), $m_i^2(\phi) \sim \phi^2$

$$V(\phi, T) \simeq \left[\left(\frac{2m_W^2 + m_Z^2 + 2m_t^2}{8v^2}\right) T^2 - \frac{\mu^2}{2}\right]\phi^2 - ET|\phi|^3 + \frac{\lambda_T}{4}\phi^4$$

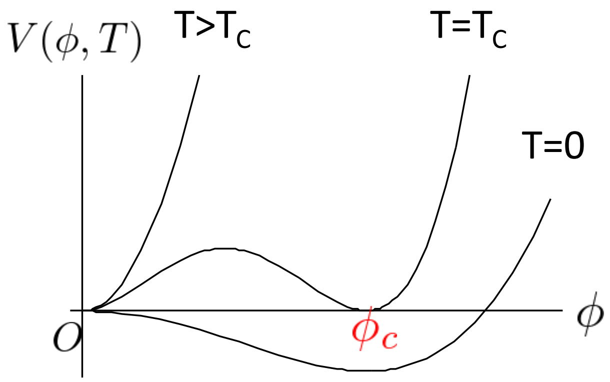
$$\begin{cases} E = \frac{2m_W^3 + m_Z^3}{4\pi v^3} \sim 10^{-2} \\ \lambda_T = \lambda + \text{log-terms} \end{cases}$$

EW phase transition in SM (1)

Behavior of EWPT

$$V(\phi,T) \simeq \left[\left(\frac{2m_W^2+m_Z^2+2m_t^2}{8v^2}\right)T^2-\frac{\mu^2}{2}\right]\phi^2 - ET|\phi|^3+\frac{\lambda_T}{4}\phi^4$$

- For high T, quadratic term > 0 --> restoration of EW symmetry
- cubic term induce 1st order phase transition



EW phase transition in SM (2)

Behavior of EWPT

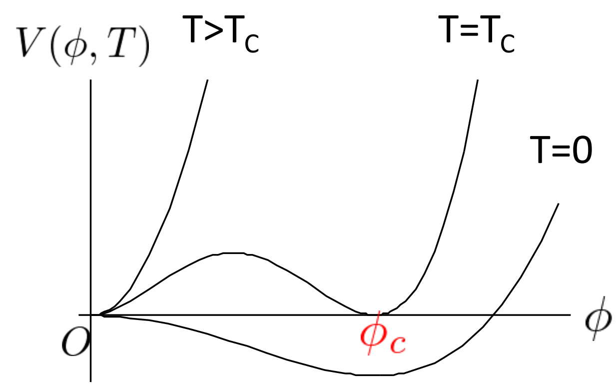
$$V(\phi,T) \simeq \left[\left(\frac{2m_W^2+m_Z^2+2m_t^2}{8v^2}\right)T^2-\frac{\mu^2}{2}\right]\phi^2 - ET|\phi|^3+\frac{\lambda_T}{4}\phi^4$$

- For high T, quadratic term > 0 --> restoration of EW symmetry
- cubic term induce 1st order phase transition

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

$\frac{\phi_c}{T_c} \gtrsim 1$ → $m_h \lesssim \sqrt{4Ev} \sim 49\text{GeV}$

⇔ LEP bound : $m_h > 114\text{GeV}$



⇒ EWPT is not strongly 1st order in SM

- Lattice : crossover for $m_h \gtrsim 80\text{GeV}$

[Kajantie et al. (1996)]

How to strengthen EWPT

- Introduce new bosons strongly coupled to Higgs

  ⇒ $\Delta V \sim \Delta E T \phi^3$

  ⇒ strengthen 1st order phase transition

  ex. light stop scenario in MSSM

- 4th family fermions themselves do not play role

- Extra bosons are required

  - SUSY 4th family model [Fok and Kribs(2008)]

- Naturally realized when 4th family is responsible for EW symmetry breaking (strongly coupled 4th family scenario)

3. Strongly coupled 4th family

4th family and EW symmetry breaking [Holdom (1984)]

4th family fermions : t′, b′, ν′, τ′

- extremely heavy : m $\gtrsim$ 246 GeV

- can be origin of EW symmetry breaking

order parameters

$$\langle H \rangle \longrightarrow \langle \bar{t}' t' \rangle, \ \langle \bar{b}' b' \rangle, \ \langle \bar{\tau}' \tau' \rangle, \ \langle \bar{\nu}'_\tau \nu'_\tau \rangle$$

➢ Higgs sector : 4th family fermions w/ new int.

- 4th family version of top-quark condensate model

Nambu – Jona-Lasinio model of 4th family (1)

- SM without Higgs field + 4th family
- introduce 4-Fermi operator among 4th family quarks

$$\mathcal{L}_{4\mathrm{f}} = G_{q'}(\bar{q}'_{Li} q'_{Rj})(\bar{q}'_{Rj} q'_{Li}) \qquad q'_i = \begin{pmatrix} t' \\ b' \end{pmatrix}$$

with cutoff $\Lambda_{4\mathrm{f}}$

- If $G_{q'} > G_{q',c} = 8\pi^2/(N_c \Lambda_{4\mathrm{f}}^2)$

$$\langle \bar{t}' t' \rangle = \langle \bar{b}' b' \rangle \neq 0$$

⇒ break EW symmetry; $m_{t'} = m_{b'} \neq 0$

- 2 Higgs doublets appear as the bound state of 4th quarks

$$\phi_1 = \begin{pmatrix} \phi_1^0 \\ \phi_1^- \end{pmatrix} \sim \begin{pmatrix} \bar{t}'_R t'_L \\ \bar{t}'_R b'_L \end{pmatrix} \qquad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \sim \begin{pmatrix} \bar{b}'_R t'_L \\ \bar{b}'_R b'_L \end{pmatrix}$$

3NGBs + 5 physical Higgs bosons --> can induce 1st EWPT!

Nambu – Jona-Lasinio model of 4th family (2)

Other 4 Fermi operators

- among 4th family leptons $\ell' = (\nu', \tau')$

  ex.) $G_{\ell'}\bar{\ell'}_L\ell'_R\bar{\ell'}_R\ell'_L$

  ⇒ extra 2 Higgs doublet is generated (4 doublet Higgs in total)

- between 4th family and first 3 family fermions

  ex.) $G_{t't}\bar{t'}_L t'_R \bar{t}_R t_L$ --> mass of top

◆ For simplicity,

- ➢ assume that only 4th family quarks condense
- ➢ neglect effects from τ', ν' and top
- ➢ switch off SU(2) × U(1) gauge couplings

Low-energy effective model of NJL (1)

◆The effects of composite Higgs should be included

- low-energy effective model at μ_{EW} =246 GeV

- Lagrangian --Yukawa theory of 4th quarks and 2HD--

$$\mathcal{L} = \mathcal{L}_{\rm kin} - y(\bar{q}'_L \phi_1 t'_R + \bar{q}'_L \phi_2 b'_R + h.c.) - V(\phi_1, \phi_2)$$

$\mathcal{L}_{\rm kin}$: kinetic term of 4th family quarks and Higgs

$V(\phi_1, \phi_2)$: Higgs potential

- assume $\Lambda_{4f} >> \mu_{EW}$ ⇒ higher dim. operator can be neglected
  can use renormalizable Lagrangian

Low-energy effective model of NJL (2)

$$\mathcal{L} = \mathcal{L}_{\rm kin} - y(\bar{q}'_L \phi_1 t'_R + \bar{q}'_L \phi_2 b'_R + h.c.) - V(\phi_1, \phi_2)$$

- to satisfy δρ ∼ 0 ,

  assume $m_{t'} = m_{b'}$ and impose $SU(2)_R$ symmetry

- symmetry of this model: $SU(2)_L \times SU(2)_R \times U(1)_A$

  $U(1)_A$: $q'_L \to e^{-i\theta} q'_L \;,\quad q'_R \to e^{i\theta} q'_R \;,\quad \phi_{1,2} \to e^{-2i\theta} \phi_{1,2}$

- use matrix notation for Higgs fields

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (2, 2^*)$$

Low-energy effective model of NJL (3)

Higgs potential for bi-fundamental Higgs $\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$

$$V(\Phi) = m_\Phi^2 \,\mathrm{tr}(\Phi^\dagger \Phi) + \frac{\lambda_1}{2} \mathrm{tr}(\Phi^\dagger \Phi)\, \mathrm{tr}(\Phi^\dagger \Phi) + \frac{\lambda_2}{2} \mathrm{tr}(\Phi^\dagger \Phi \Phi^\dagger \Phi)$$

- This model is equivalent to NJL model [Bardeen, Hill and Lindner (1990)]
  - If running coupling satisfy boundary condition

    $\bar{\lambda}_1(\mu) \to 0\,, \quad \bar{\lambda}_2(\mu) \to \infty\,, \quad \bar{y}(\mu) \to \infty$ when $\mu \to \Lambda_{4\mathrm{f}}$

    (compositeness condition)

    at some high energy scale Λ_{4f} (composite scale)
- One can obtain value of λ1, λ2 corresponding to NJL by RG
- In following analysis, we first consider whole of parameter space without compositeness condition, and then discuss about effects of compositeness

Low-energy effective model of NJL (4)

Higgs potential

$$V(\Phi) = m_\Phi^2 \,\mathrm{tr}(\Phi^\dagger \Phi) + \frac{\lambda_1}{2}\,\mathrm{tr}(\Phi^\dagger \Phi)\,\mathrm{tr}(\Phi^\dagger \Phi) + \frac{\lambda_2}{2}\,\mathrm{tr}(\Phi^\dagger \Phi \Phi^\dagger \Phi)$$

bi-fundamental Higgs : $\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$

- massless NG boson of $U(1)_A$ symmetry breaking
  - add explicit $U(1)_A$ (soft) breaking mass term

$$\Delta V(\Phi) = -c(\det \Phi + h.c.)$$

  - examine effect of nonzero pseudo NG boson mass

Low-energy property of model (1)

- scalar sector is special case of 2 Higgs doublet model
- $SU(2)_R$ symmetry ⇒ $\langle\Phi\rangle = \frac{1}{2}\begin{pmatrix}\phi & 0 \\ 0 & \phi\end{pmatrix}$ ⇒ $\tan\beta = 1$
- tree-level effective potential

$$V_0(\phi) = \frac{1}{2}(m_\Phi^2 - c)\phi^2 + \frac{1}{8}\left(\lambda_1 + \frac{\lambda_2}{N_f}\right)\phi^4$$

Nf = 2 :
# of 4th family quark flavors

  - (λ1+λ2/Nf) corresponds to λ in SM
  - For the stability of potential : $\lambda_1 + \lambda_2/N_f > 0$

- 4 free parameters

  scalar self couplings : λ1, λ2, Yukawa coupling : y

  $U(1)_A$ breaking mass : c

Low-energy property of model (2)

◆ mass spectra of Higgs bosons ($\phi_0 = 246\mathrm{GeV}$)

h : SM like Higgs

$$m_h = \sqrt{\lambda_1 + \lambda_2/N_f}\,\phi_0$$

ξ = (H^0, $H^{\pm}$): extra Higgs

$$m_\xi = \sqrt{2c + (\lambda_2/N_f)\phi_0^2}$$

➢ degenerate due to $SU(2)_R$

η : pseudo scalar Higgs

$$m_\eta = \sqrt{2c}$$

⇒ pNGB of $U(1)_A$ breaking

π : would be NG bosons

$$m_\pi = 0$$

⇒ eaten by W,Z

◆ experimental bound on Yukawa coupling

$$m_{q'} \gtrsim 256\mathrm{GeV} \quad \Rightarrow \quad y \gtrsim 2.1$$

cf. $m_{q'} = \dfrac{y}{\sqrt{2N_f}}\phi_0$

Cutoff scale of effective model

◆ We define cutoff as energy scale where one of running coupling

-- diverges

or ⇒ suggest breakdown of theory

-- becomes negative

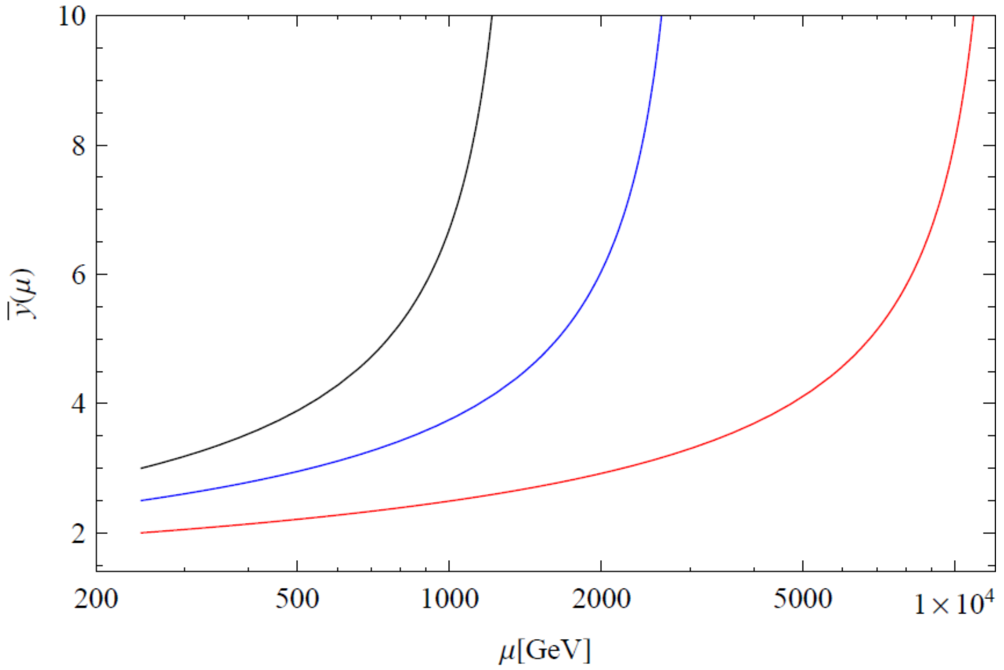
➢ Yukawa coupling

•1-loop RGE

$$\mu\frac{\partial}{\partial\mu}\bar{y} = \frac{1}{16\pi^2}(N_f + N_c)\bar{y}^3$$

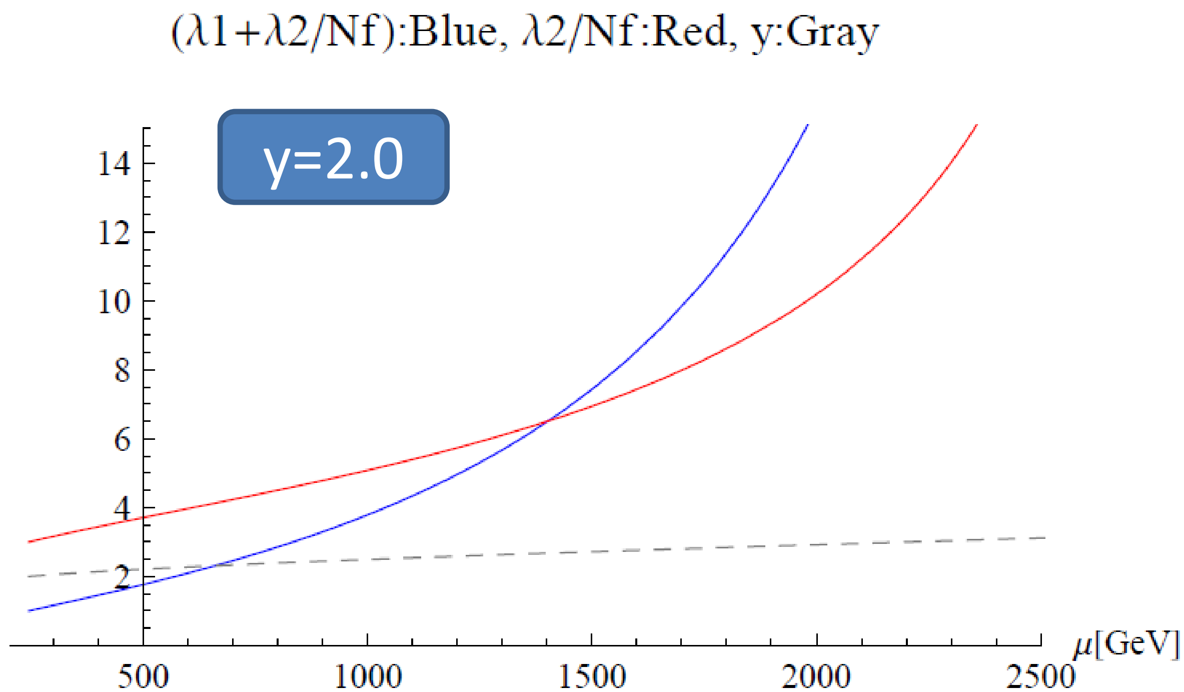
•boundary condition:
y >2.1 at μ=246 GeV

•blow up around 1〜10 TeV

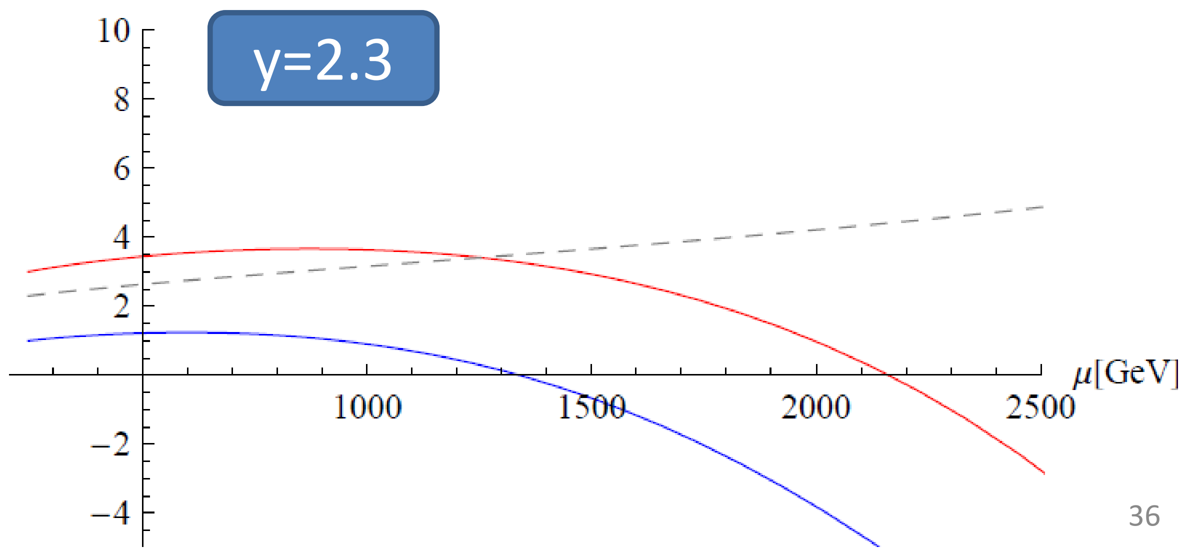


➢ Higgs self-couplings

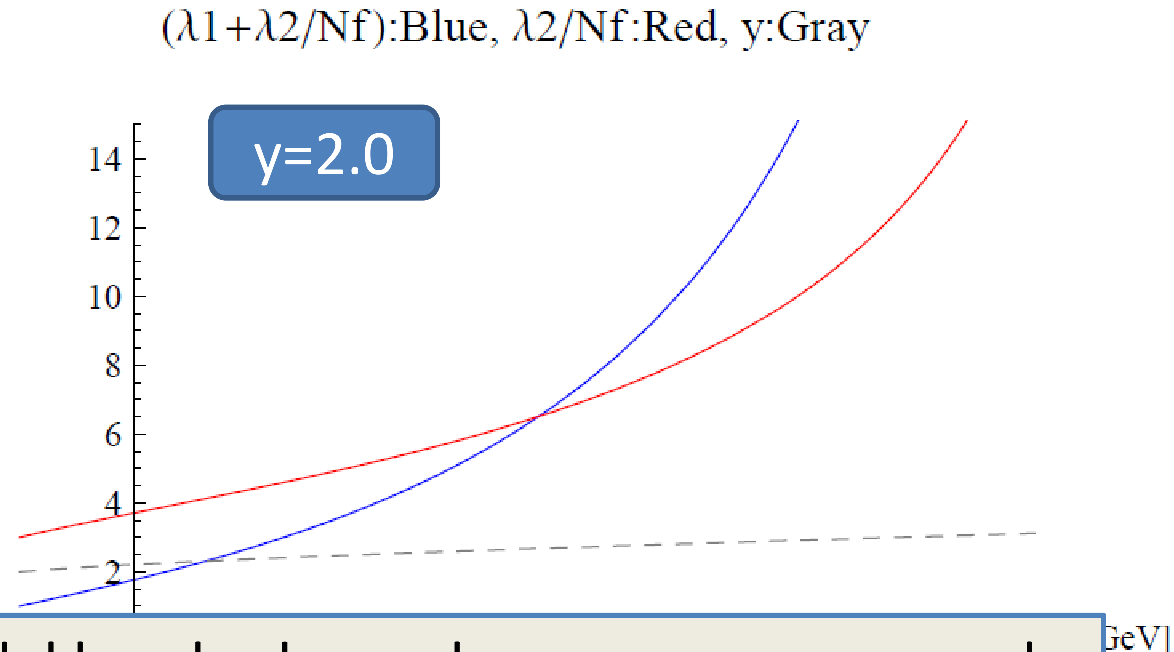
Case 1.
Higgs self-couplings blow up
(Landau pole)



Case 2.
Higgs self-couplings are pulled down to negative
(vacuum instability)

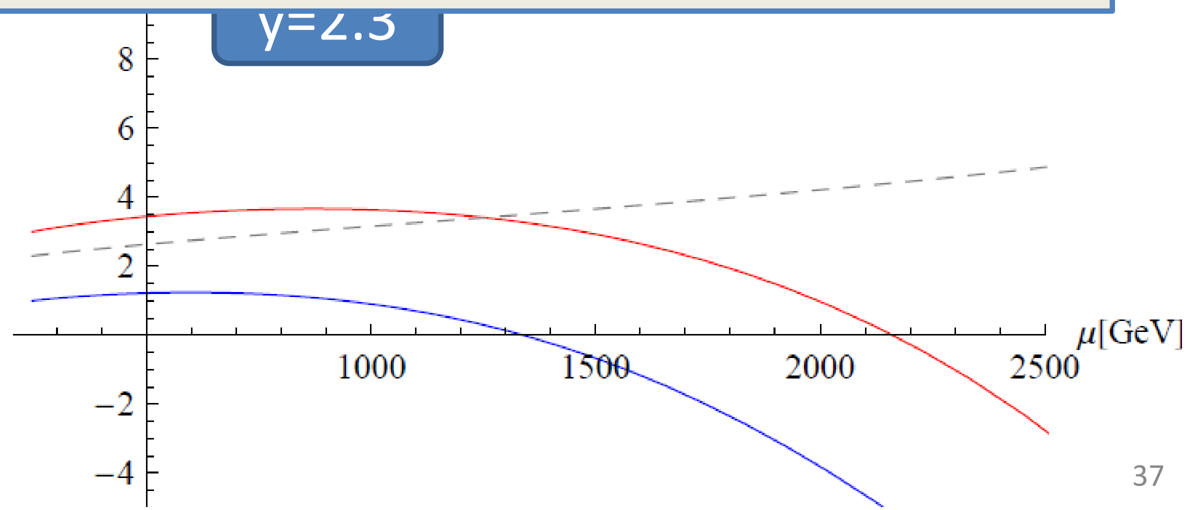


➢ Higgs self-couplings



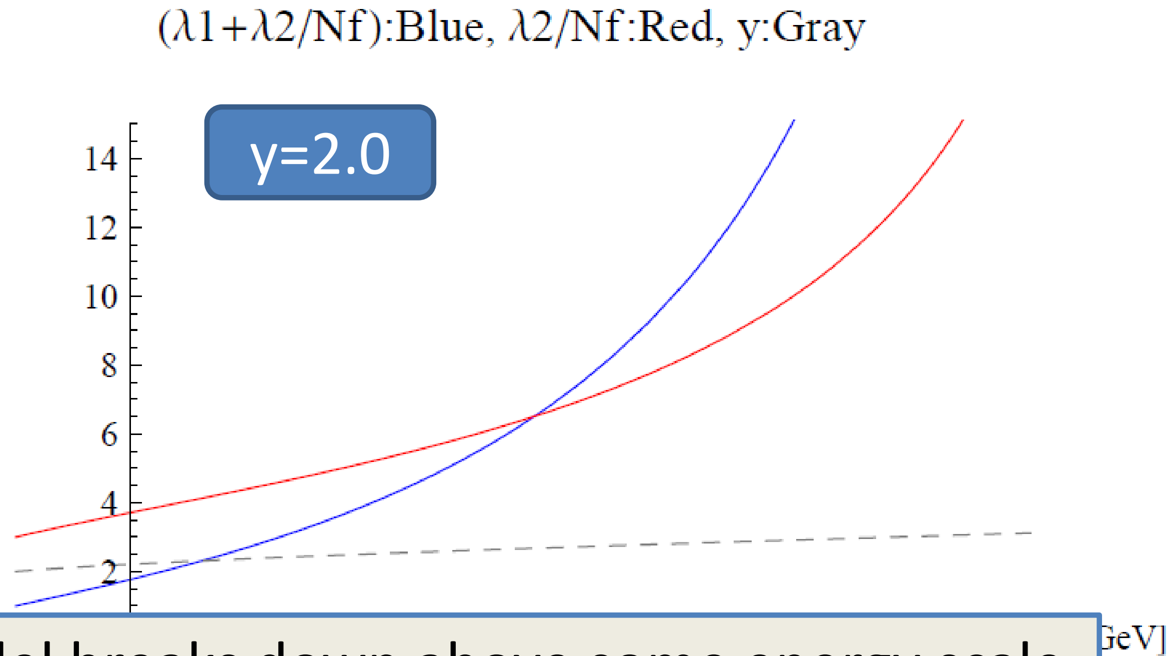
<u>Case 1.</u>
Higgs self-couplings blow up
(Landau pole)

The effective model breaks down above some energy scale
Cutoff Λ should be introduced



<u>Case 2.</u>
Higgs self-couplings are pulled down to negative
(vacuum instability)

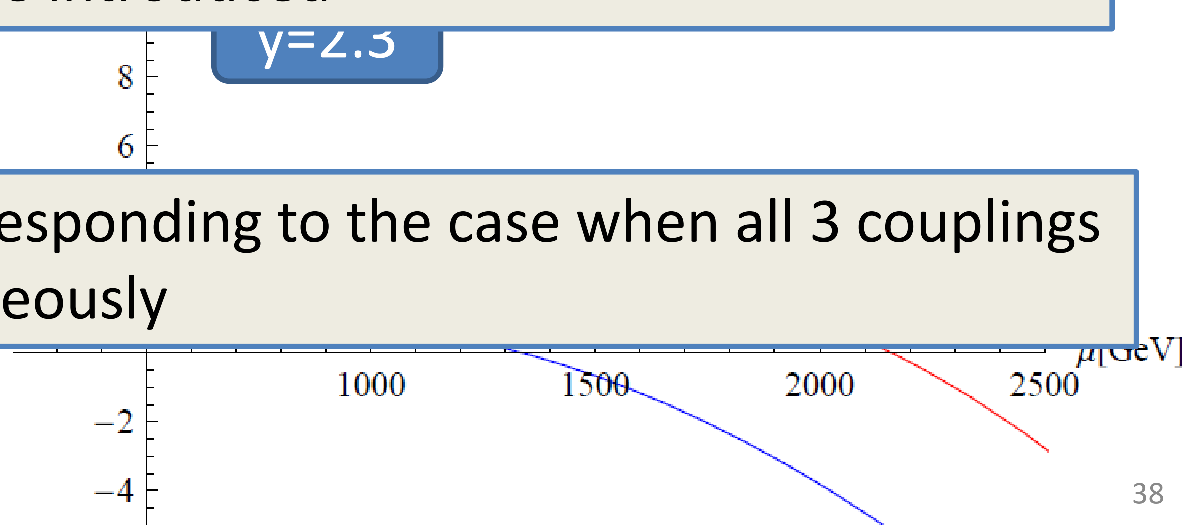
- Higgs self-couplings



<u>Case 1.</u>
Higgs self-couplings
blow up
(Landau pole)

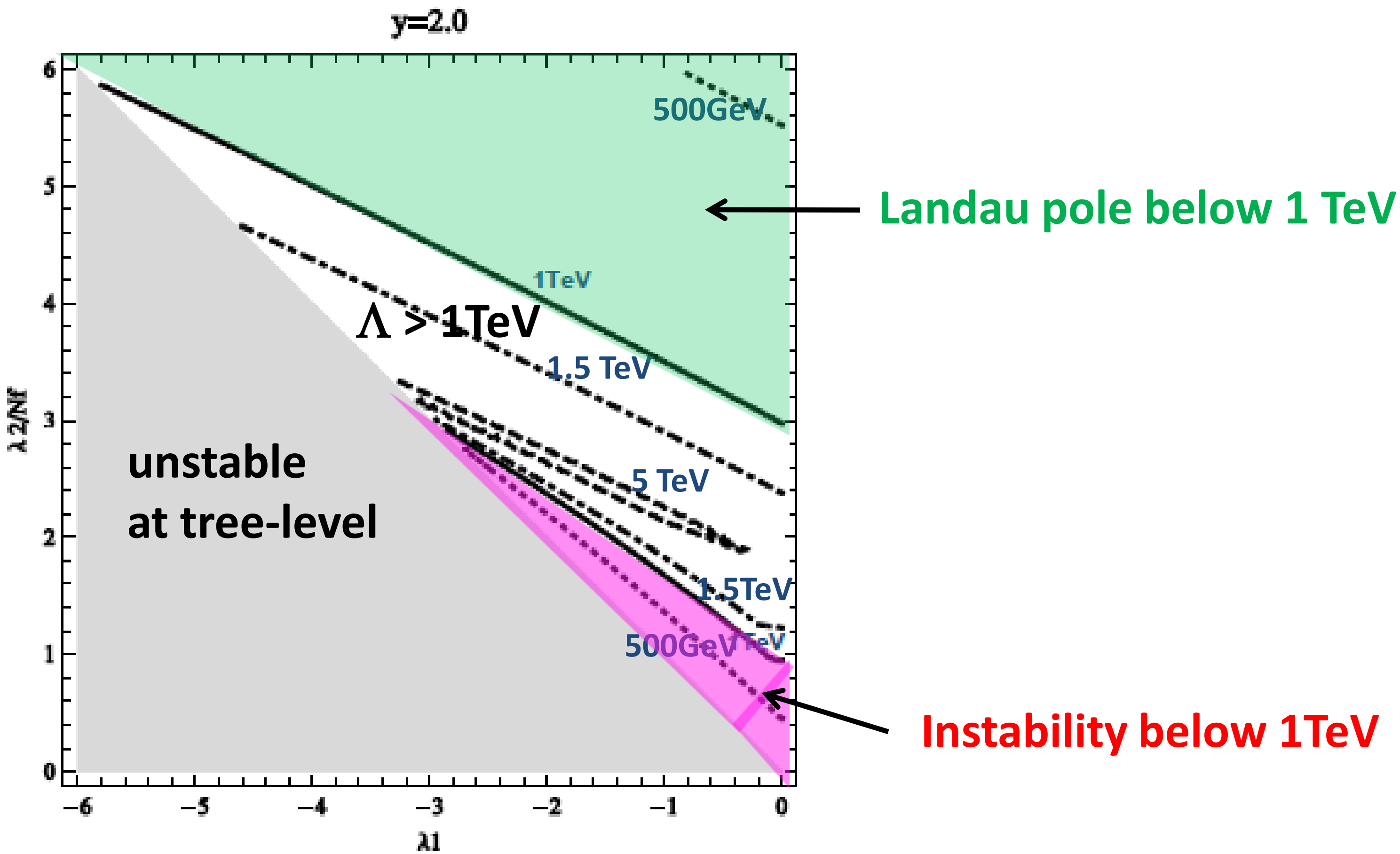
The effective model breaks down above some energy scale
Cutoff Λ should be introduced

<u>Case 2.</u>
Higgs self-couplings
are p
negat
(vacu



NJL model is corresponding to the case when all 3 couplings
blow up simultaneously

◆contour plot of cutoff Λ



To ensure renormalizability → Λ >> mh, Tc ∼ O(100)GeV

➢ In the following, we require Λ > 1TeV

<--> $y < 3.0$ ($m_{q'} < 480$ GeV (on-shell))

4. EWPT with strongly coupled 4th family

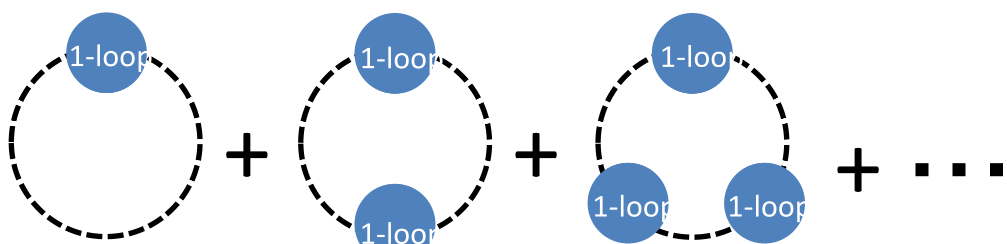
Y. Kikukawa , M.K., J.Yasuda, Prog. Theor. Phys. 122, No. 2, 2009

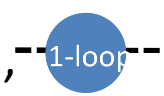
One-loop effective potential (with ring improvement)

$$
\begin{aligned}
V(\phi,T) =& \frac{1}{2}(m_\Phi^2 - c)\phi^2 + \frac{1}{8}\left(\lambda_1 + \frac{\lambda_2}{N_f}\right)\phi^4 \\
&+ \sum_{i=h,\xi,\eta,\pi,q'} n_i \frac{\mathcal{M}_i^4(\phi,T)}{64\pi^2}\left[\ln\frac{\mathcal{M}_i^2(\phi,T)}{\mu^2} - \frac{3}{2}\right] + \frac{1}{2}A\phi^2 \\
&+ \sum_{i=h,\xi,\eta,\pi,q'} n_i \frac{T^4}{2\pi^2}\int_0^\infty dx\, x^2 \ln\left[1 \mp \exp\left(-\sqrt{x^2 + \mathcal{M}_i^2(\phi,T)/T^2}\right)\right]
\end{aligned}
$$

$$
\begin{cases}
\mathcal{M}_i^2(\phi,T) = m_i^2(\phi) + [(N_f^2+1)\lambda_1 + 2N_f\lambda_2 + y^2]\dfrac{T^2}{12} \\
\mathcal{M}_{q'}^2(\phi,T) = m_{q'}^2(\phi)
\end{cases}
$$

•including higher order contributions (ring diagram)

$V_{\rm ring}(\phi,T) =$ 

At high T , 

$\sim \lambda_i T^2$

High temperature expansion

◆ extra Higgs ξ induce cubic term ($m_\xi >> m_h$)

$$\Delta V \sim \Delta E T \phi^3 \qquad \Delta E \sim (\lambda_2/N_f)^{3/2} \sim m_\xi^3$$

⇒ $$\frac{\phi_c}{T_c} \sim \frac{(\lambda_2/N_f)^{3/2}}{(\lambda_1 + \lambda_2/N_f)} \sim \frac{m_\xi^3}{m_h^2}$$

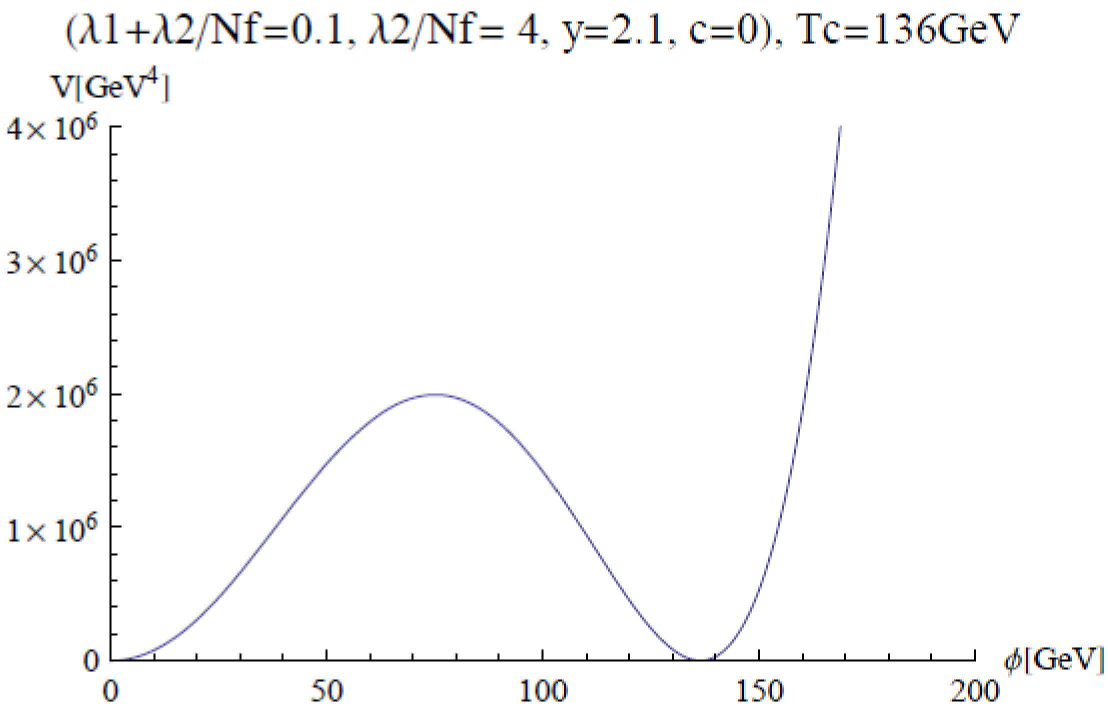
⇒ strongly 1st order for $m_\xi >> m_h$

◆ make sense for λi , y << 1

◆ cannot rely on high-T expansion for 4th family quarks

⇒ estimate T-dependent loop integral numerically

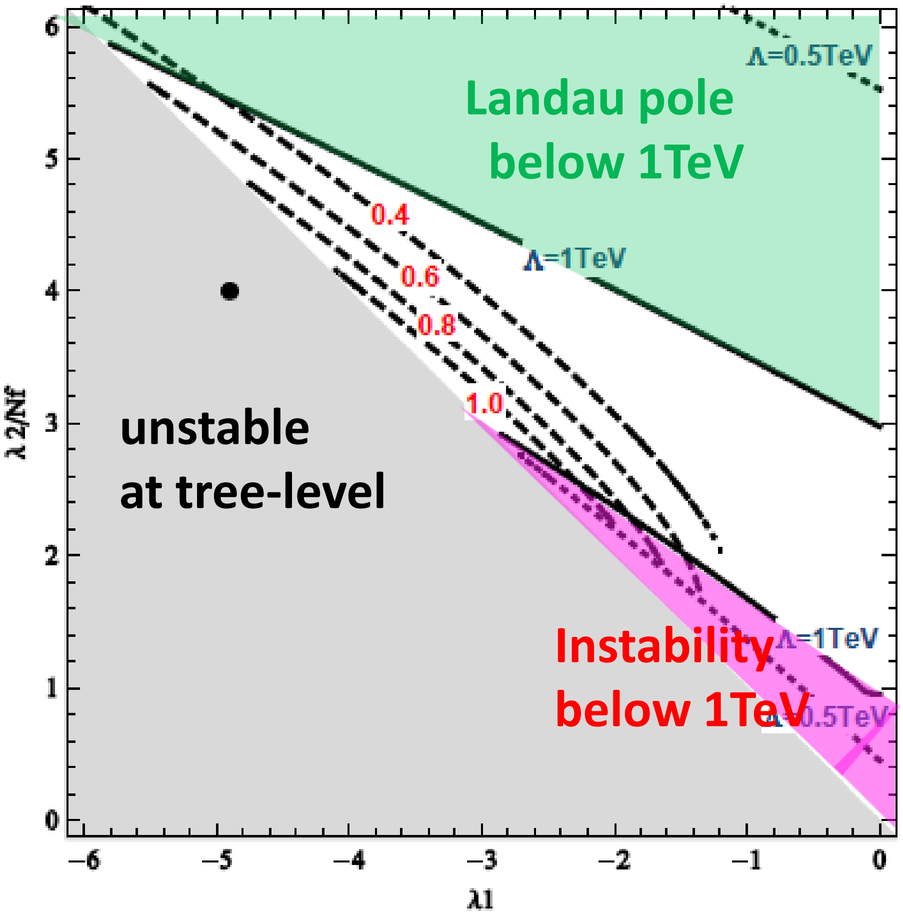
Effective potential at Tc



Numerical results (1)

◆ Contour plot for ϕ_c/T_c on λ_1-λ_2/N_f plane

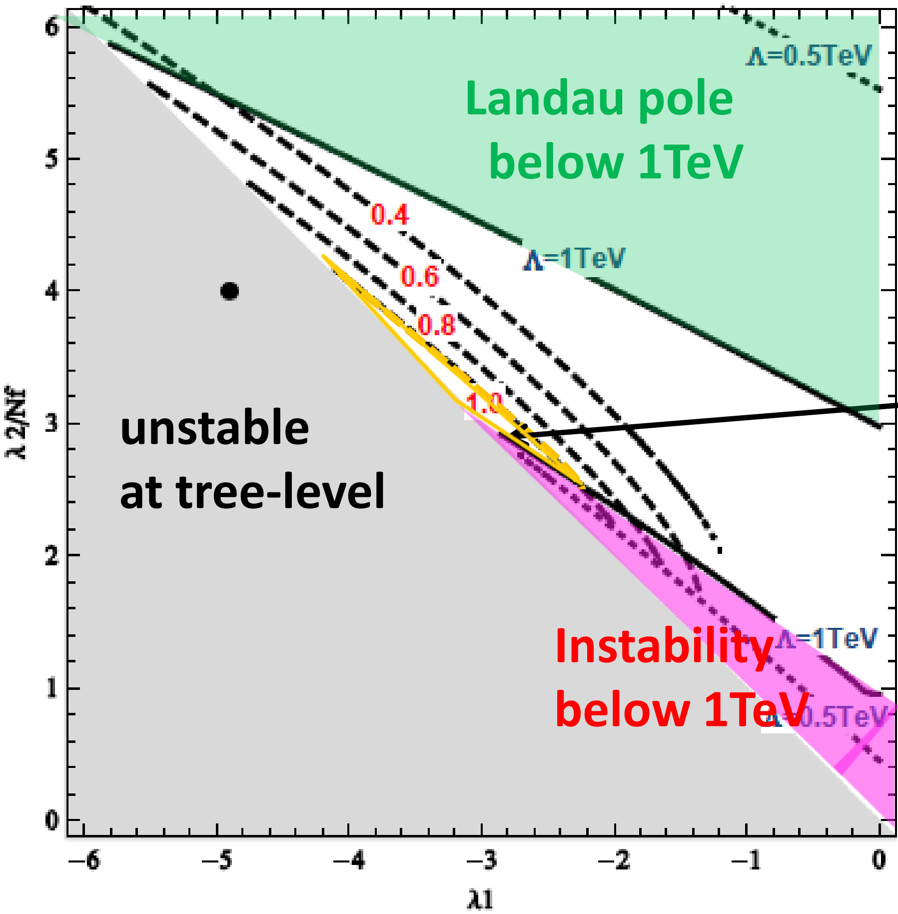
$y=2$ ($m_{q'}=246$ GeV) and $m_\eta=0$



Numerical results (1)

- Contour plot for ϕc/Tc on λ1-λ2/Nf plane

y=2 ($m_{q'}$=246 GeV) and m_η=0

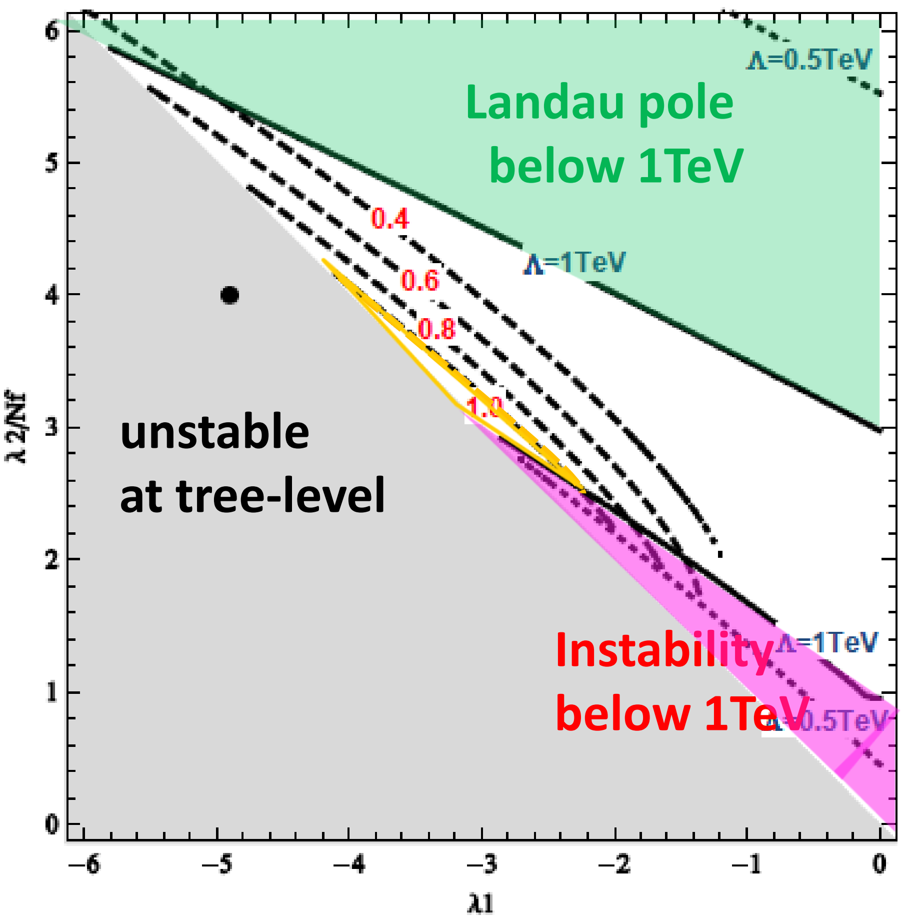


$$\phi_c/T_c \geq 1$$

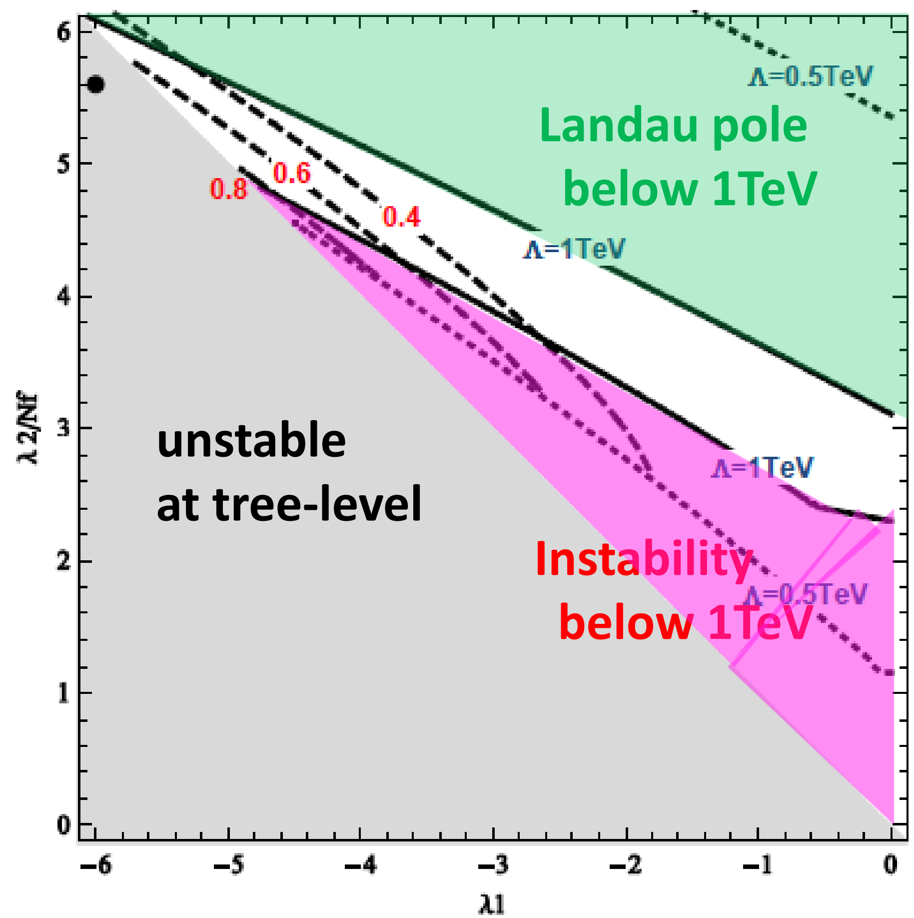
Numerical results (1)

- Contour plot for φc/Tc on λ1-λ2/Nf plane

y=2 ($m_{q'}$=246 GeV) and m_η=0



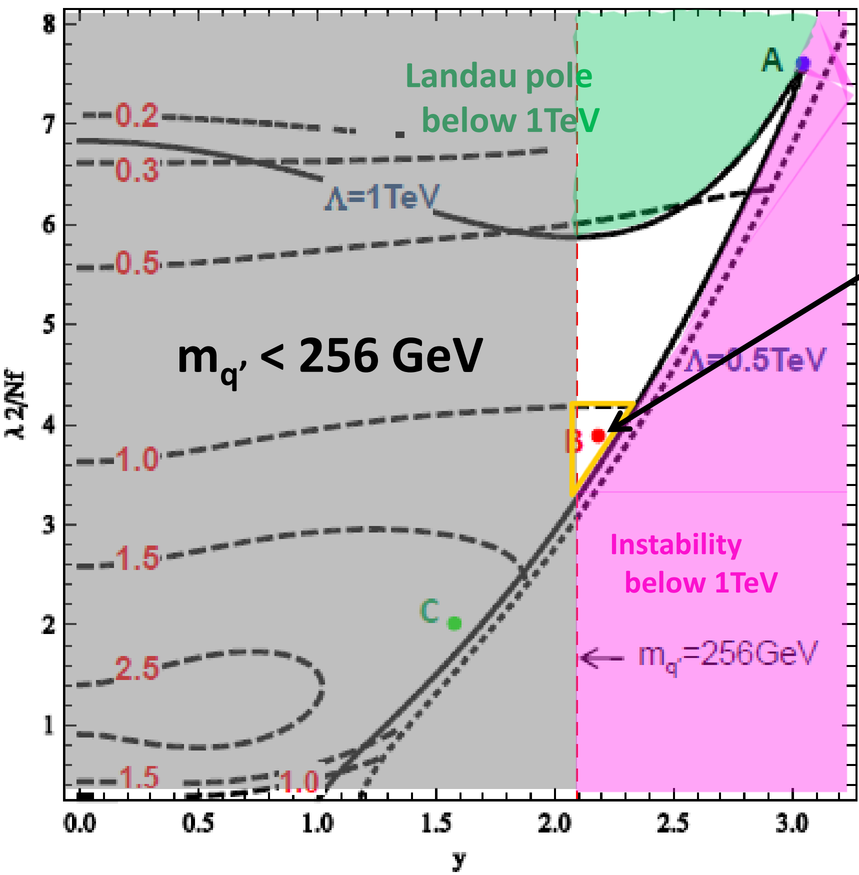
y=2.5 ($m_{q'}$=310 GeV) and m_η=0



Numerical results (2)

◆ Contour plot for ϕc/Tc on y-λ2/Nf plane

λ1+λ2/Nf ∼ 0 and m_η=0



$$\phi_c/T_c \geq 1$$

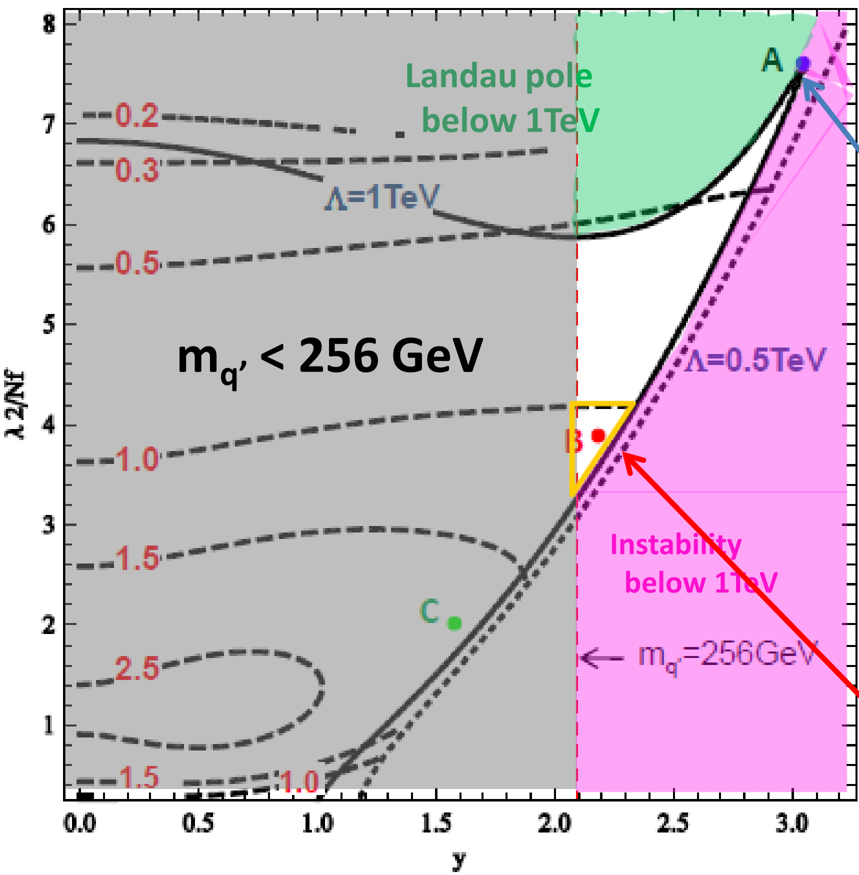
➢ upper bound on λ2/Nf and y
⇒ upper bound on m_ξ and $m_{q'}$

256 GeV < $m_{q'}$ < 290 GeV
430GeV < m_ξ < 500 GeV
200 GeV < m_h(1-loop) < 300 GeV

Numerical results (2) --Prediction of NJL model--

◆ Contour plot for ϕc/Tc on y-λ2/Nf plane

λ1+λ2/Nf ∼ 0 and m_η=0



compositeness condition

$$\bar{\lambda}_1(\Lambda_{4f}) = 0, \quad \bar{\lambda}_2(\Lambda_{4f}) = \frac{16\pi^2}{N_f}, \quad \bar{y}(\Lambda_{4f})^2 = \frac{16\pi^2}{N_c}$$

Λ_{4f} = 1 TeV

⇒ ϕc/Tc ∼ 0

$$\bar{\lambda}_1(\Lambda_{4f}) = 0, \quad \bar{\lambda}_2(\Lambda_{4f}) = \frac{8\pi^2}{N_f}, \quad \bar{y}(\Lambda_{4f})^2 = \frac{8\pi^2}{N_c}$$

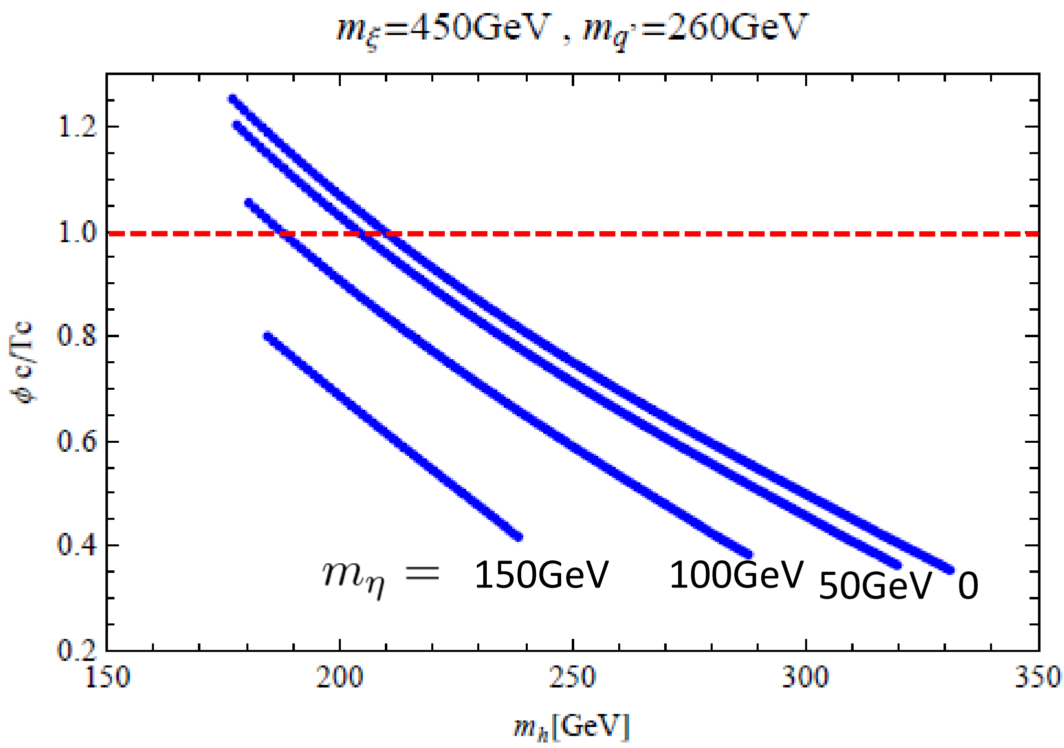
Λ_{4f} = 4 TeV

⇒ ϕc/Tc > 1

Prediction is not so definite

Numerical results (3)

◆ effect of nonzero pseudo scalar Higgs mass : m_η



- for larger m_η , ϕc/Tc becomes smaller
- for strongly 1st order PT, $m_\eta \lesssim$ 100 GeV

Summary of effective theory's results

- NJL prediction for low energy parameters are not definite

- In order to realize $\phi c/Tc > 1$, there are upper bounds on masses

$$m_{q'} < 290\ \text{GeV},\quad m_{\xi} < 500\ \text{GeV},\ m_{\eta} < 100\ \text{GeV}$$

<-- already excluded by recent data by CDF, CMS

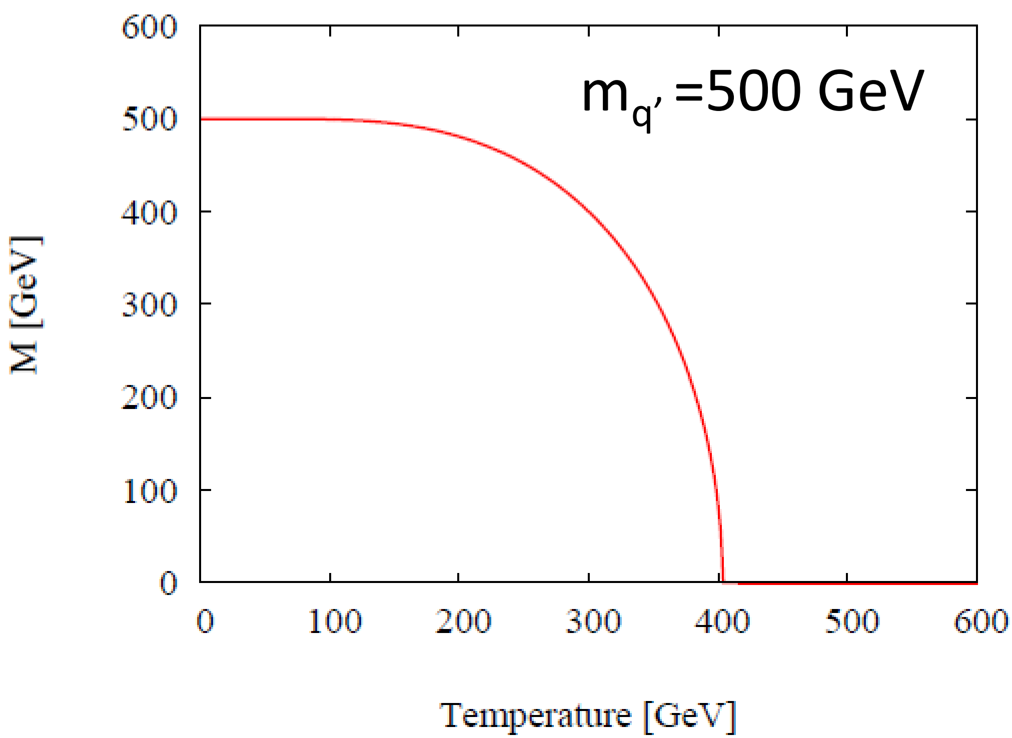
- Our effective theory is valid for $\Lambda < 1\text{TeV}$
  --> $m_{q'} <$ 480 GeV (on-shell)

- Need alternative method for $m_{q'} > 500$ GeV

Direct analysis of NJL not relying on effective theory

M.K., H. Kohyama

- NJL was originally invented in hadron physics
  - Usually PT is investigated by using gap equation with 1/Nc -expansion



2nd order for $m_{q'} > 500$ GeV

⇒ Two complemental results suggest EWPT is not strong 1st order

5. Summary and discussion

◆ In the strongly coupled 4th family model, EWPT can be strongly 1st order due to the loop effects of the extra composite Higgs

◆ However, there is upper bound on 4th quark mass $m_{q'} < 300$ GeV

<-- excluded by recent experimental data

◆ Result from 1/Nc expansion suggests EWPT is 2nd order for $m_{q'} > 500$ GeV

◆ 4-fermion interaction of 4th quarks can not cause strongly 1st order EWPT for experimentally allowed $m_{q'}$

◆ Possible way out: 4-fermion int. of 4th leptons
- bound states of τ’, ν’ provide extra 2 Higgs doublets
- enhance 1st order?

Back Up Slides

Direct search measurements (quarks)

[Particle Data Group 2008]

t' (4^{th} Generation) Quark, Searches for

Mass $m >$ 256 GeV, CL = 95% ($p\overline{p}$, $t'\overline{t}'$ prod., $t' \to Wq$)

b' (4^{th} Generation) Quark, Searches for

Mass $m >$ 190 GeV, CL = 95% ($p\overline{p}$, quasi-stable b')

Mass $m >$ 199 GeV, CL = 95% ($p\overline{p}$, neutral-current decays)

Mass $m >$ 128 GeV, CL = 95% ($p\overline{p}$, charged-current decays)

Mass $m >$ 46.0 GeV, CL = 95% (e^+e^-, all decays)

Direct search measurements (leptons)

[Particle Data Group 2008]

Heavy Charged Lepton Searches

$L^{\pm}$ – charged lepton

Mass $m >$ 100.8 GeV, CL = 95% [h] Decay to νW.

$L^{\pm}$ – stable charged heavy lepton

Mass $m >$ 102.6 GeV, CL = 95%

Heavy Neutral Leptons, Searches for

For excited leptons, see Compositeness Limits below.

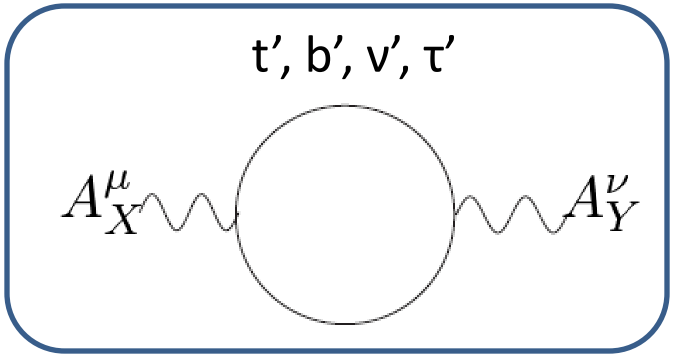
Stable Neutral Heavy Lepton Mass Limits

Mass $m >$ 45.0 GeV, CL = 95% (Dirac)
Mass $m >$ 39.5 GeV, CL = 95% (Majorana)

Neutral Heavy Lepton Mass Limits

Mass $m >$ 90.3 GeV, CL = 95%
(Dirac ν_L coupling to e, μ, τ; conservative case(τ))
Mass $m >$ 80.5 GeV, CL = 95%
(Majorana ν_L coupling to e, μ, τ; conservative case(τ))

Constraints from S, T parameter



- vacuum polarization of gauge bosons

$$\Pi_{XY}^{\mu\nu}(q^2) \equiv g^{\mu\nu}\Pi_{XY}(q^2) + (q^\mu q^\nu\text{-terms})$$

$$\Pi_{XY}(q^2) = \Pi_{XY}^{sm}(q^2) + \Pi_{XY}^{new}(q^2)$$

- definition for S and T

$$\alpha S \equiv 4e^2[\Pi'^{new}_{33}(0) - \Pi'^{new}_{3Q}(0)]$$

$$\alpha T \equiv \frac{e^2}{s_W^2 c_W^2 m_Z^2}[\Pi_{11}^{new}(0) - \Pi_{33}^{new}(0)]$$

- each doublet (N, E) contribute (when mZ << mN, mE)

$$S = \frac{1}{6\pi}\left[1 - Y\log\frac{m_N^2}{m_E^2}\right]$$

$$T = \frac{1}{16\pi s_W^2 c_W^2 m_Z^2}\left[m_N^2 + m_E^2 - \frac{2m_N^2 m_E^2}{m_N^2 - m_E^2}\log\frac{m_N^2}{m_E^2}\right]$$

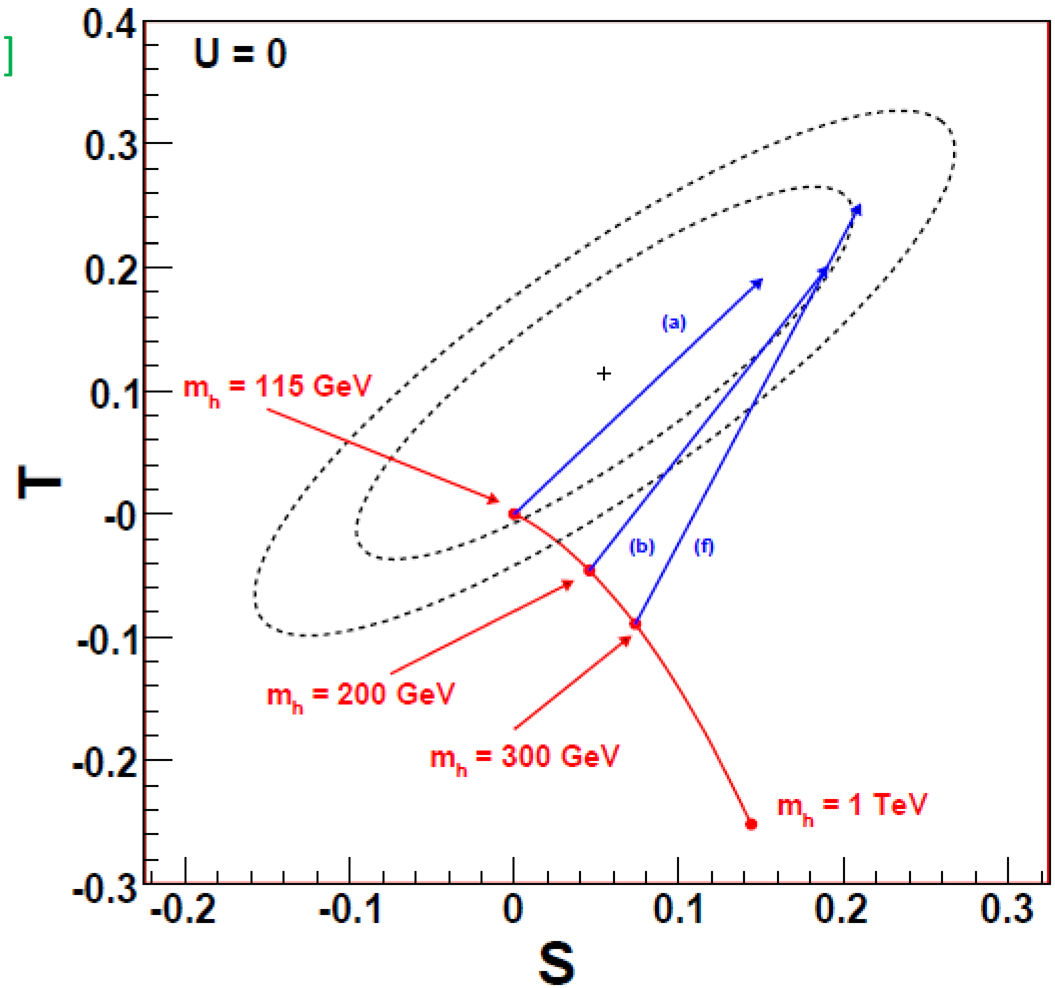
Constraints from S, T parameter (cont'd)

[Kribs , Plehn, Spannowsky and Tait (2007)]

parameter set	m_{u_4}	m_{d_4}	m_H	$\Delta S_{\rm tot}$	$\Delta T_{\rm tot}$
(a)	310	260	115	0.15	0.19
(b)	320	260	200	0.19	0.20
(c)	330	260	300	0.21	0.22
(d)	400	350	115	0.15	0.19
(e)	400	340	200	0.19	0.20
(f)	400	325	300	0.21	0.25

$$m_{\nu_4} = 100 \text{ GeV and } m_{\ell_4} = 155 \text{ GeV}$$

``relatively heavy Higgs is allowed''



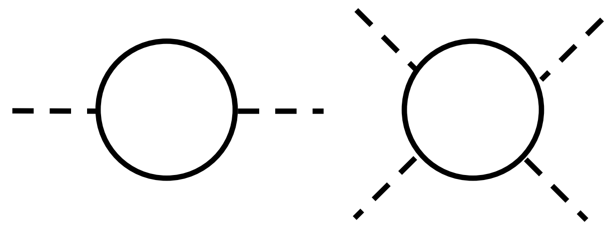
68% and 95% CL constraints by LEP Electroweak Working Group

Construction of effective theory [Bardeen, Hill and Lindner]

$\mu = \Lambda_{4\mathrm{f}}$ $\mathcal{L}_{4\mathrm{f}} = G_{q'} (\bar{q}'_{Li} q'_{Rj})(\bar{q}'_{Rj} q'_{Li})$

auxiliary field: $\Phi_{ij} \sim \bar{q}'_{Rj} q'_{Li}$

$$\mathcal{L}'_{4\mathrm{f}} = -y_0 (\bar{q}'_{Li} \Phi_{ij} q'_{Rj} + h.c.) - m^2_{\Phi 0} tr(\Phi^\dagger \Phi) \qquad G_{q'} = y_0^2 / m^2_{\Phi 0}$$



$\mu \lesssim \Lambda_{4\mathrm{f}}$

$$\mathcal{L}''_{4\mathrm{f}} = -y_0 (\bar{q}'_{Li} \Phi_{ij} q'_{Rj} + h.c.) + Z_\Phi tr(\partial^\mu \Phi^\dagger \partial_\mu \Phi) - m^2_{\Phi,0} tr(\Phi^\dagger \Phi) - \frac{\lambda_{1,0}}{2} [tr(\Phi^\dagger \Phi)]^2 - \frac{\lambda_{2,0}}{2} tr(\Phi^\dagger \Phi)^2$$

When, $\mu \to \Lambda_{4\mathrm{f}}$, $Z_\Phi \to 0$ $\lambda_{1,0} \to 0$ $\lambda_{2,0} \to 0$

◆ by rescaling the field $\Phi \to \Phi/\sqrt{Z_\Phi}$

$\mu << \Lambda_{4\mathrm{f}}$

$$\mathcal{L} = \bar{q}' i\gamma^\mu \partial_\mu q' - y(\bar{q}'_L \Phi q'_R + h.c.) + \underline{tr(\partial_\mu \Phi^\dagger \partial^\mu \Phi)} - m_\Phi^2 tr(\Phi^\dagger \Phi) - \frac{\lambda_1}{2}[tr(\Phi^\dagger \Phi)]^2 - \frac{\lambda_2}{2} tr(\Phi^\dagger \Phi)^2$$

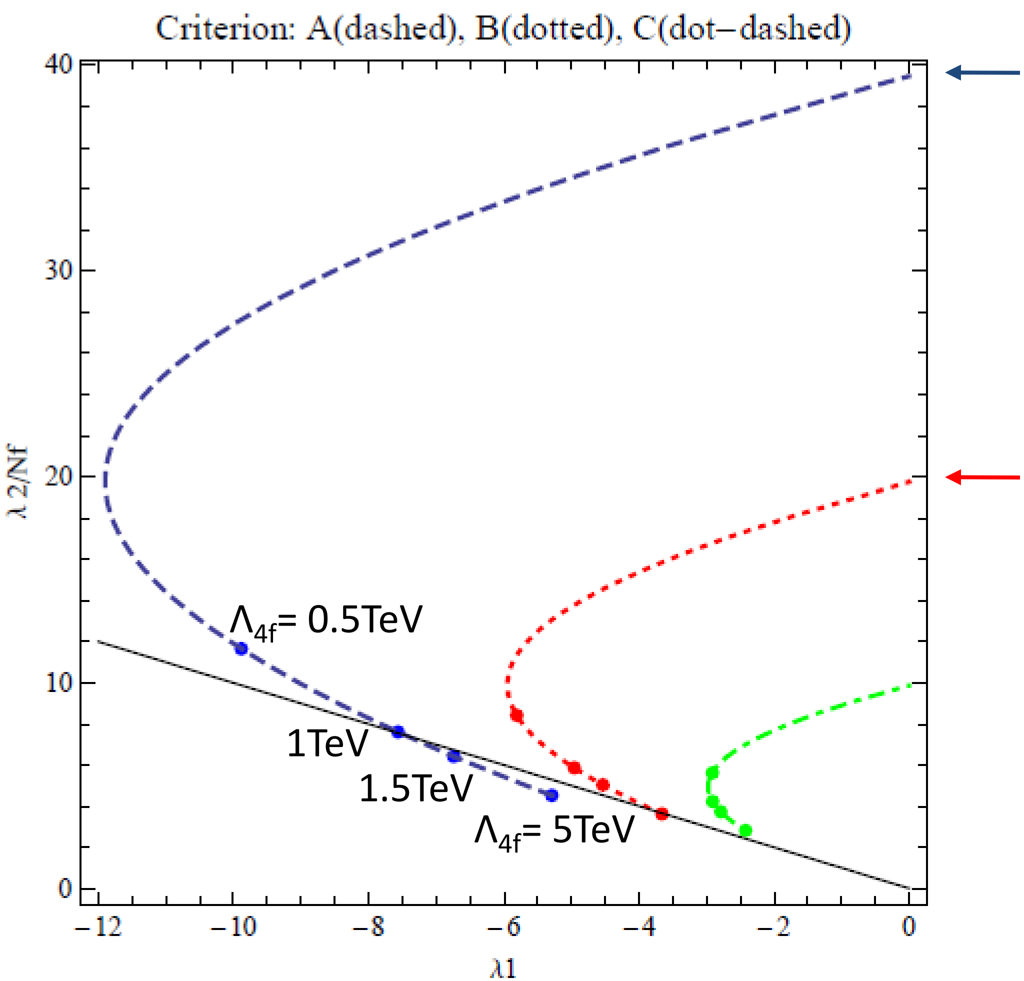
◆ compositeness condition

when $\mu \to \Lambda_{4\mathrm{f}}$

$$\lambda_1(\mu) \to 0 \qquad \lambda_2(\mu) \to \infty \qquad y(\mu) \to \infty$$

Correspondence with NJL

◆ prediction of couplings at μ_{EW} by using one-loop RGEs



compositeness conditions

$$\bar{\lambda}_1(\Lambda_{4f}) = 0, \quad \bar{\lambda}_2(\Lambda_{4f}) = \frac{16\pi^2}{N_f}, \quad \bar{y}(\Lambda_{4f})^2 = \frac{16\pi^2}{N_c}$$

another initial conditions

$$\bar{\lambda}_1(\Lambda_{4f}) = 0, \quad \bar{\lambda}_2(\Lambda_{4f}) = \frac{8\pi^2}{N_f}, \quad \bar{y}(\Lambda_{4f})^2 = \frac{8\pi^2}{N_c}$$

quite sensitive to initial cond.

→ no meaningful prediction

Strategy to define cutoff Λ of effective model

- use one-loop RGEs:

$$\mu\frac{\partial}{\partial\mu}\bar{\lambda}_1 = \frac{1}{8\pi^2}[(N_f^2+4)\bar{\lambda}_1^2 + 4N_f\bar{\lambda}_1\bar{\lambda}_2 + 3\bar{\lambda}_2^2 + 2N_c y^2\bar{\lambda}_1],$$

$$\mu\frac{\partial}{\partial\mu}\bar{\lambda}_2 = \frac{1}{8\pi^2}(6\bar{\lambda}_1\bar{\lambda}_2 + 2N_f\bar{\lambda}_2^2 + 2N_c y^2\bar{\lambda}_2 - 2N_c\bar{y}^4),$$

$$\mu\frac{\partial}{\partial\mu}\bar{y} = \frac{1}{16\pi^2}(N_f+N_c)\bar{y}^3$$

- Starting from (λ1, λ2, y) at μ=246 GeV, define cutoff Λ as scale at which one of conditions is satisfied :

(1) vacuum instability

$$\bar{\lambda}_1(\Lambda) + \bar{\lambda}_2(\Lambda)/N_f = 0, \quad \bar{\lambda}_2(\Lambda) = 0$$

(2) Landau pole

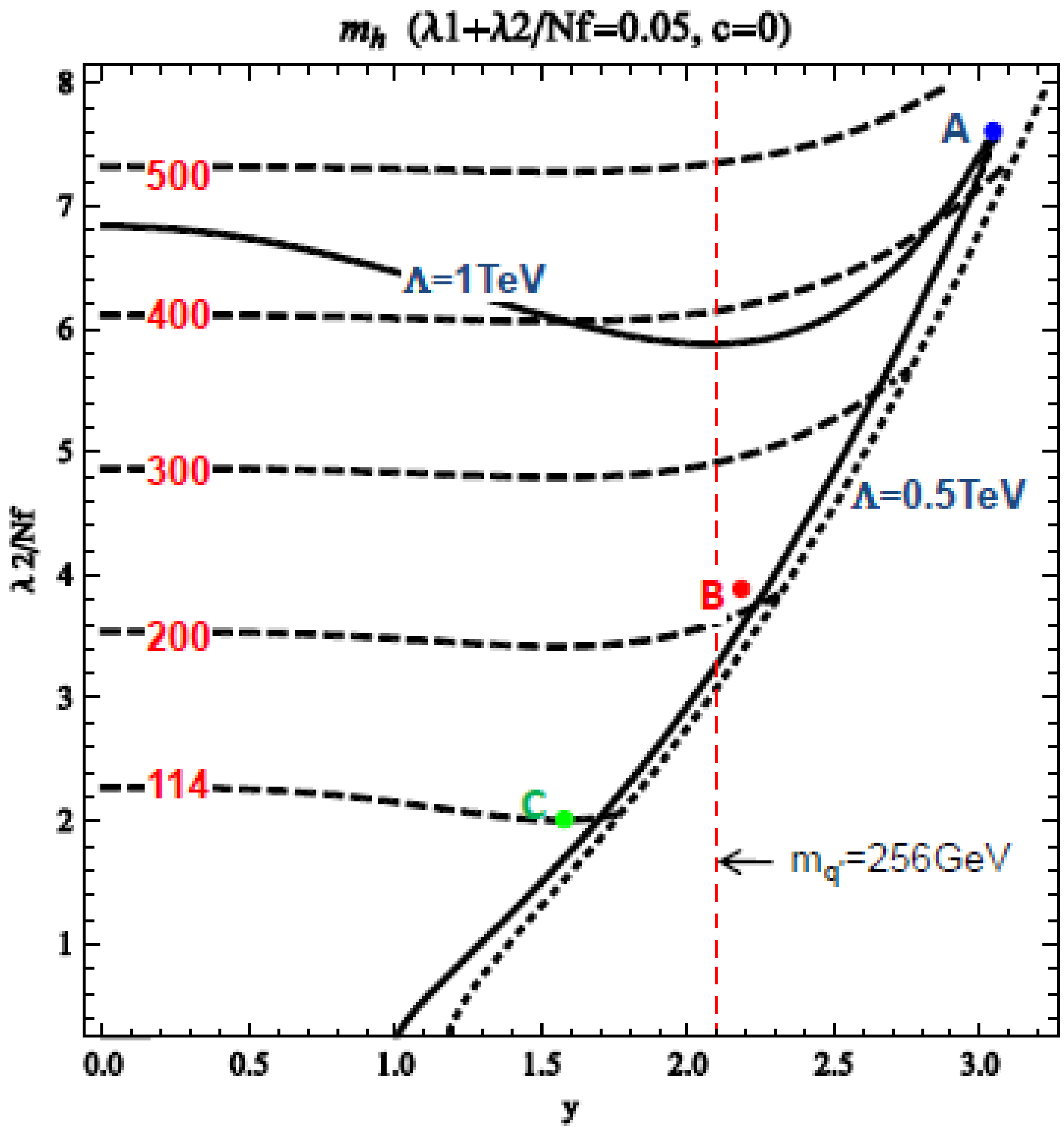
$$\bar{y}(\Lambda)^2 = \frac{16\pi^2}{N_c}, \quad \bar{\lambda}_1(\Lambda) + \bar{\lambda}_2(\Lambda)/N_f = \frac{16\pi^2}{N_f^2}, \quad \bar{\lambda}_2(\Lambda) = \frac{16\pi^2}{N_f}$$

(pertubativity bound)

one-loop Higgs mass on y-λ2/Nf plane (m_η=0)

◆define one-loop (SM-like)Higgs mass as curvature of effective potential at VEV

$$m_h^2 \equiv \left.\frac{\partial^2 (V_0 + V_1^{(0)})}{\partial \phi^2}\right|_{\phi=\phi_0}$$



ϕc and Tc --mh dependence--