UV complete model for radiative seesaw scenario electroweak baryogenesis

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S. Kanemura, T.S, and T. Yamada, PRD86,055023
S. Kanemura, N. Machida, T.S, T. Yamada,
Physics beyond the SM

Discovery of a Higgs boson & measurements of properties

Essence of the electroweak symmetry breaking

New Physics at TeV scale

It’s quite interesting, if the problems in the SM:
- Baryon asymmetry of the Universe
- Origin of the neutrino mass
- DM candidate
Solutions at TeV scale

There are examples of NP

- Baryon asymmetry of the Universe
  - Electroweak Baryogenesis
- Origin of the neutrino mass
  - Loop induced neutrino mass scenarios
- DM candidate
  - WIMP protected by some symmetry (e.g. Z
Electroweak Baryogenesis

Electroweak Baryogenesis $\rightarrow$ essence of EWSB

1st order electroweak transition $+\,$ Sphaleron

$V_{\text{eff}}(\nu; T) - V_{\text{eff}}(0, T)$

To avoid too strong washout

The strong enough first order electroweak phase transition is necessary

$\phi$

Higgs potential@EW scale
To get strong 1st order EWT

Strong 1st order EWPT requires extension of the SM

In the SM, the condition is satisfied only when $m (\phi$

Extra boson loop can enhance $\phi$

Extended Higgs sector!

e.g. 2HDM

$$L = \frac{\lambda_i}{2} h^2 |\Phi_i|^2$$

$$m_{\Phi}(\varphi) = M^2 + \lambda_i \varphi^2$$

Extra Higgs bosons as $H, A, H^{\pm}$

$\lambda = O(1)$ is required

Testable@Collider exp.

$\Delta \lambda_{hhh}/\lambda_{hhh} \geq 10\%$

$\sin(\alpha-\beta) = -1, \tan\beta = 1$

$m_h = 120 \text{ GeV}$

$m_{\Phi} = m_H = m_A = m_{H^{\pm}}$

$\phi_c/T_c = 1$

$\lambda = 2$

Kanemura, Okada, Senaha, PLB606, 361

Contour plot of $\Delta \lambda_{hhh}/\lambda_{hhh}$ and $\phi_c/T_c$ in the $m_{\Phi}$-M plane
In the MSSM, there is no such a large enough \( \phi \) with SM-like Higgs 

(The light stop scenario is the only possibility but it’s almost dead)

A scenario is SUSY 4HD+charged singlets

\( \phi \) 
\( m \) 
\( \lambda > 1.6 \)

EW baryogenesis can be realized in a SUSY model @TeV

\[ W = \lambda_1 H_u H_u' \Omega_1 + \lambda_2 H_d H_d' \Omega_2 \]

<table>
<thead>
<tr>
<th>( \lambda_2 )</th>
<th>( \Lambda_{\text{cutoff}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>2 TeV</td>
</tr>
<tr>
<td>2.0</td>
<td>10 TeV</td>
</tr>
<tr>
<td>1.5</td>
<td>100 TeV</td>
</tr>
</tbody>
</table>

What waits for us

S.K. Kanemura, E. Senaha, T.S, PLB706,40
How about neutrino mass?

Origin of the neutrino mass

Alternative to the well-known seesaw model:
Idea of loop induced neutrino mass

Especially,
Loop diagram with RH neutrinos give tiny neutrino mass

\[ \langle H \rangle \]

To avoid tree level contribution

Some new scalars are introduced!

L.M. Krauss, S. Nasri, M. Trodden, PRD67, 085002

E. Ma, PRD73, 077301
Aoki-Kanemura-Seto model

(2HD+$\mathbb{Z}_2$-odd charged and neutral singlet+$\mathbb{Z}_2$-odd RHN)

As a phenomenological model, this is quite interesting
But ...

Many extra scalars $\rightarrow$ It seems artificial
Large couplings $\rightarrow$ Landau pole at low energy scale

What is the fundamental theory of this model?
Fundamental theory?

- What is the fundamental theory of such a
  - Large coupling constant → Landau pole (cutoff)
- What is the origin of strong Higgs force?
- Where extra (non-matter) scalar fields come from?
Fundamental theory?

- What is the fundamental theory of such a
- Large coupling constant $\rightarrow$ Landau pole (cutoff)
- What is the origin of strong Higgs force?
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Our expectation:

- Higgs coupling
- New gauge coupling

$\Lambda$ cutoff $\mu$
Fundamental theory?

- What is the fundamental theory of such a large coupling constant → Landau pole (cutoff)?
- What is the origin of strong Higgs force?
- Where extra (non-matter) scalar fields come from?

Our expectation:

We have a nice candidate! SUSY SU(2)_H model
SUSY SU(2)

In SUSY QCD: \( N_f = N_c + 1 \Rightarrow \text{confinement} \)

Let us consider the simplest case \( (N_c = 2 \& N_f = 3) \)

\[ \text{SUSY SU}(2)_H \times \text{SU}(2)_L \times \text{U}(1)_Y \]

S. Kanemura, T. S, and T. Yamada, PRD86, 055023

It’s asymptotic free!

<table>
<thead>
<tr>
<th>Fields</th>
<th>( \text{SU}(2)_L )</th>
<th>( \text{U}(1)_Y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_1 ) ( T_2 )</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>( T_3 )</td>
<td>1</td>
<td>+1/2</td>
</tr>
<tr>
<td>( T_4 )</td>
<td>1</td>
<td>-1/2</td>
</tr>
<tr>
<td>( T_5 )</td>
<td>1</td>
<td>+1/2</td>
</tr>
<tr>
<td>( T_6 )</td>
<td>1</td>
<td>-1/2</td>
</tr>
</tbody>
</table>

Below the confinement scale \( \Lambda_H \), the effective theory is described by \( H_{ij} \sim T_i T_j \)

It’s the same setup as the minimal SUSY fat Higgs, where only \( H_u, H_d \), and \( N \) are made light

\( \text{R Harnik, et al., PRD70, 015002} \)
Effective theory of SU(2)H

$$W = -\mu H_u H_d - \mu \Phi \Phi_u \Phi_d - \mu \Omega (\Omega_+ \Omega_- - \zeta \eta)$$

$$+ \hat{\lambda} \left\{ H_d \Phi_u \zeta + H_u \Phi_d \eta - H_u \Phi_u \Omega_- - H_d \Phi_d \Omega_+ \right\}$$

$$\hat{\lambda}(\Lambda_H) \simeq 4\pi \text{ (Naive dimensional analysis)}$$

RG running of $\lambda$

$$\lambda = \lambda(\mu_{EW}) \text{ determines the cutoff scale}$$

Benchmark:

\[ \tan \beta = 15, \ m_{H^+} = 350 \text{GeV}, \mu = 200 \text{GeV}, \ M_{\tilde{t}} = M_{\tilde{d}} = 2000 \text{GeV} \]

\[ \bar{m}_{\Omega^+}^2 = \bar{m}_{\Phi_d}^2 = \bar{m}_{\zeta}^2 = (1500 \text{GeV})^2, \bar{m}_{\eta}^2 = (2000 \text{GeV})^2, \mu_{\Phi} = \mu_{\Omega} = 550 \text{GeV} \]

\[ m_0^2 \equiv \bar{m}_{\Phi_u}^2 = \bar{m}_{\Omega^-}^2 \text{ (Scanned)} \]

Lightest \( Z_2 \) odd masses

\( \varphi_c / T_c > 1 \) can be satisfied!!
1st order EWPT

\( \varphi_c/T_c > 1 \implies \lambda \gtrsim 1.5 \quad (\Lambda_H \lesssim 20 \text{TeV}) \)

S. Kanemura, E. Senaha, T.S. T. Yamada, JHEP1305, 066
Contribution to $h\gamma\gamma$

$\mu_\gamma = 0.78$.

$\frac{v_c}{T_c} = 1.0$

$\mu_\gamma \equiv \frac{\text{Br}(h \rightarrow \gamma\gamma)}{\text{Br}(h \rightarrow \gamma\gamma)_{\text{SM}}}$

$\sim 20\%$ deviation is possible in the region of $\frac{v_c}{T_c} > 1$

~20% deviation is possible in the region of $v_c/T_c > 1$
For radiative seesaw

We will introduce a Z neutrinos are introduced as SU(2) singlet fields

Then, Z neutrinos are introduced as SU(2) singlet fields

In the low energy effective theory,

\[ W_N = (y_N)_i N_i^c L_j \Phi_u + (h_N)_{ij} N_i^c E_j^c \Omega^- + \frac{M_i}{2} N_i^c N_i^c \]
Neutrino mass generation

S. Kanemura, N. Machida, T.S, T. Yamada,

Two different types of contributions are possible

1-loop driven by $y_N$

It corresponds to SUSY Ma model

3-loop driven by $h_N$

They correspond to SUSY AKS model
Fields in SUSY AKS

S. Kanemura, N. Machida, T. S., T. Yamada,

**e.g. Aoki-Kanemura-Seto model**

(2HD\(+\text{Z}_2\)-odd charged and neutral singlet + \text{Z}_2\)-odd RHN)

\[
\begin{array}{c}
\langle H \rangle \\
H^- \\
\langle H \rangle \\
\end{array}
\begin{array}{c}
\nu_L \\
\zeta \\
\nu_L \\
\end{array}
\begin{array}{c}
\langle H \rangle \\
\Omega^- \\
\langle H \rangle \\
\end{array}
\begin{array}{c}
\nu_R \\
\nu_R \\
\end{array}
\begin{array}{c}
e \\
\Omega^- \\
e \\
\end{array}
\]

Lighter one can be a DM

\rightarrow \text{neutrino mass}

Electroweak baryogenesis also can work

**In SUSY version,**

\[H_u, \ H_d \ (\text{MSSM-like Higgs)}\]

\[\Omega^+, \ \Omega^- \quad \phi_u, \ \phi_d\]

\[\zeta \quad \mathbb{N}^c \ (\text{RHN})\]

SU(2)_{\text{H}} \text{ model automatically provides all the fields in the Higgs sector!!}

Many new fields are required
Benchmark points

(A): 1-loop dominant point
(B): 3-loop dominant point

We are now making new BP which includes DM

LFV constraints: O.K.

We have not taken care of DM in these points yet

S. Kanemura, N. Machida, T.S, T.Yamada,
Comments on direct detection

Our model is characterized by the $Z_2$ odd sector

$Z_2$-odd particle search is important

colorless

Case (A): light inert doublet

\[ e^+ e^- \rightarrow H' A' \rightarrow Z H' H' \]
\[ e^+ e^- \rightarrow H^{'+} H^{-'} \rightarrow W^+ W^- H' H' \]

Mass determination can be done with a few GeV accuracy

M. Aoki, S. Kanemura and H. Yokoya, PLB725, 302.

Case (B): Singlet-like charged particle $\Omega^+$

\[ e^+ e^- \rightarrow \Omega_1^+ \Omega_1^- \]
\[ e^- e^- \rightarrow \Omega_1^- \Omega_1^- \]

Strong evidence of the model

Aoki & Kanemura & Seto, PRD80, 033007; Aoki & Kanemura, PLB689, 28.
Light inert doublet @ ILC

M. Aoki, S. Kanemura and H. Yokoya, PLB725,302.

\[ e^+ e^- \rightarrow H' A' \rightarrow Z H' H' \]

\[ m_{H'} = 65 \text{GeV} \]
\[ m_{A'} = 73 \text{GeV} \]
\[ m_{H^\pm} = 120 \text{GeV} \]

(Similar to Case (A))
Light inert doublet @ ILC

M. Aoki, S. Kanemura and H. Yokoya, PLB725,302.

\[ e^+ e^- \rightarrow H^+ H^- \rightarrow W^+ W^- H' H' \]

The masses can be precisely determined.
Singlet-like scalar @ ILC

$$e^+ e^- \rightarrow S^+ S^- \rightarrow \tau^+ \tau^- + \text{missing}$$

$$m_S = 400 \text{GeV}$$

A signal can be seen at the ILC@1TeV

Aoki&Kanemura, PLB689,28.
Singlet-like scalar @e

The signal is quite clear evidence of the Majorana nature and the scenario

Aoki&Kanemura, PLB689,28.
Summary

- It is quite interesting, NP in the Higgs sector provides solutions for baryogenesis, neutrino mass, DM.
  - Electroweak baryogenesis, radiative generation of neutrino mass,…
  - It can be tested at collider experiments
  - Many models have been considered but they have been developed purely phenomenologically
  - We have succeeded to provide a candidate of fundamental theory of such models
  - SUSY SU(2)$_H$ with $N_f=3 + Z_2$-odd RHN is attractive simple candidate
    - It also provides new DM candidate
  - It’s very different from GUT beyond the grand desert
  - Rich fields may wait for us just above the TeV scale
Back up
Introducing several new fields (SU(2)\(_H\) singlets) as

\[
W_f = M_f (\varphi_u \bar{\varphi}_u + \varphi_d \bar{\varphi}_d) + \bar{\varphi}_d T T_4 + \varphi_u T T_3 + h_{ij}^{ui} Q_i u_j \varphi_u + h_{ij}^{ij} Q_i d_j \varphi_d + h_{ij}^{ij} L_i e_j \varphi_d
\]

\[
T = \begin{pmatrix} T_1 \\ T_2 \end{pmatrix}
\]

Q, L, u, d, e: Matter fields in the SM

\(\varphi_u, d\) and \(\bar{\varphi}_u, d\) are integrated out

\[
W = \frac{4\pi}{M_f} \left\{ h_{ij}^{ui} Q_i u_j (T T_3) + h_{id}^{ij} Q_i d_j (T T_4) + h_{ie}^{ij} L_i e_j (T T_4) \right\}
\]

Below \(\Lambda_H\)

\( (T T_3) \rightarrow \frac{\Lambda_H}{4\pi} H_u \quad (T T_4) \rightarrow \frac{\Lambda_H}{4\pi} H_d \)

\[
W = h_{ij}^{ui} Q_i u_j H_u + h_{id}^{ij} Q_i d_j H_d + h_{ij}^{ie} L_i e_j H_d
\]

for \(M_f \sim \Lambda_H\)
In the high temperature approximation, 

\[ V(\varphi, T) \approx D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots \]

\[ \frac{\varphi_c}{T_c} = \frac{2E}{\lambda T_c} \]

1st order PT is possible due to the cubic term

\[ E = \frac{1}{12\pi v^3} (6m_W^2 + 3m_Z^2) \]

\[ \lambda_T = \frac{m_h^2}{2v^2} + \text{log corrections} \]

\[ \frac{\varphi_c}{T_c} \propto \frac{1}{m_h^2} \]

Light Higgs is required!!

In SM, Higgs should be lighter than 50GeV

NEW CP phases are also necessary for successful baryogenesis

excluded by LEP data

Extension of the SM at TeV scale is necessary

New bosonic loop contribution

Higher dim. term in the potential

...
EWBG in the MSSM

Lighter stop loop can contribute

large top Yukawa coupling

\[ E \approx \frac{1}{12\pi v^3} (6m_W^3 + 3m_Z^3) + \frac{m_t^3}{2\pi v^3} \left( 1 - \frac{|A_t + \mu \cot \beta|^2}{M_{\tilde{q}}^2} \right)^{3/2} \]

where the maximal contribution case is considered;

\[ m_{\tilde{t}_1}^2 (\varphi, \beta) = M_{\tilde{T}_R}^2 + \frac{y_t^2 s_\beta^2}{2} \left( 1 - \frac{|A_t + \mu \cot \beta|^2}{M_{\tilde{q}}^2} \right) \varphi^2 \]

For larger \( M_{\tilde{T}_R} \), the effect is smaller

Light stop is necessary \( \rightarrow \) No new coloured particles at LHC...

Even with such a maximal case, it’s not easy to get \( \varphi_c/T_c > 1 \)

MSSM should be also modified at TeV scale for EWBG
What kind of modification?

\[ \frac{\varphi_c}{T_c} \propto \frac{1}{m_h^2} \quad \Rightarrow \quad \text{Small } m_h \text{ is preferable} \quad \Rightarrow \quad \text{support } m_h = 126 \text{GeV@LHC} \]

A Good point of MSSM: \( h^4 \) coupling is from gauge coupling \( \rightarrow \) Light Higgs

Large bosonic loop contribution

A strong Higgs coupling with additional bosons (h-\( \Phi' - \Phi'' \))

Mass of \( \phi' \) is dominated by vev \( m_{\phi'}^2 = M^2 + \lambda^2 v^2 \)

A natural realization of “strong but light” in SUSY model:

MSSM Higgs \( Z_2 \) odd new fields

\[ W = \lambda \Phi_{u,d} \Phi'_{1,2} \Phi''_{1,2} \]

\[ \Delta V = |\lambda|^2 h^2 \phi^*_{1,2} \phi'_{1,2} \]

It provides strong coupling but \( m_h \) is kept small!
Tests of the scenario

Enhancement of $\varphi_{c/T_c}$

Extra bosonic loop
positive contribution

collection of $h hh$ coupling

Ino loop
negative contribution

Linear Collider

Inert scalar mass: $m_{\Phi'}^2 = M'^2 + \lambda^2 v^2$

Inert ino mass: $m_{\tilde{\Phi}} = \mu' + \lambda v$

The loop contributions are significant when $\lambda v$ dominates the masses.

$Z_2$ odd scalars as light as $\sim \lambda v$

Large $\mu'$ and small $M'^2$ provides large deviation in $h hh$ and large $\varphi_{c/T_c}$