grand gauge-Higgs unification & its Higgs sector

2015/2/12 @Toyama HPNP2015

Toshifumi Yamashita (Aichi Medical Univ.)

based on:
• PRD84, 051701 (2011) (arXiv:1103.1234)
  w/ K.Kojima (Kyushu U.), K.Takenaga (Kumamoto Health Sci. U.)
• PRD89, 075013 (2014) (arXiv:1312.7575)
  w/ M.Kakizaki, S.Kanemura, H.Taniguchi (U. of Toyama)
GUT-breaking via Hosotani mechanism

= "grand gauge-Higgs unification"

- natural Doublet-Triplet (DT) splitting
- general prediction: light adjoints

We may get a hint of the GUT-breaking @LHC&LC.

Cf) Lim&Maru(2007)

SUSY version (SGGHU)


grand gauge-Higgs unification

- Hosotani mechanism
  - symmetry breaking by a continuous Wilson loop
  - The order parameter, \( W \equiv \mathcal{P} \exp(i \int_C A_5 dy) \), is valued on the group (instead of the algebra).
  - \( \langle W \rangle = \text{diag}(1, 1, 1, -1, -1) \equiv P_W \)
  - \( \sim \text{diag}(0, 0, 0, v, v) \)

Y. Hosotani (1983)

Maru-san’s talk

gauge-Higgs unification

T.Y. (2011)
grand gauge-Higgs unification

• difficulty

  • orbifold action projects out adjoint scalars due to the opposite orbifold BCs.

  • this difficulty is shared w/ heterotic string
    - very well studied, classified w/ Kac-Moody level
    - "diagonal embedding" method

We apply this in our pheno. models.

Cf) Lim & Maru (2007)
grand gauge-Higgs unification

- diagonal embedding (in field theory)

ex) $S^1 / \mathbb{Z}_2$ \((G \times G \rightarrow G_D)\)

\[
A^{(1)}_\mu (x^\mu, y_i - y) = A^{(2)}_\mu (x^\mu, y_i + y)
\]

\[\Rightarrow A^{(-)}_5 = (A^{(1)}_5 - A^{(2)}_5)/\sqrt{2}\] has a zero-mode.

- “deconstruction”

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chiral fermions

(similar to $S^1$ model)
grand gauge-Higgs unification

- diagonal embedding (in field theory)

This provides a way to “introduce” chiral fermions in $S^1$ models!!

• “deconstruction”

- Similar to $S^1$ model

\[ y_0 = 0 \]

\[ y_\pi = \pi R \]
grand gauge-Higgs unification

matter content

- **bulk fields**
  - similar to $S^1$ model: vector-like
  - couple to W.L.: $SU(5)$ incomplete multiplets

- **boundary fields**
  - essentially 4D fields: chiral
  - not couple to W.L.: $SU(5)$ full multiplets

in contrast to the orbifold GUTs
low energy effective theory

- low energy prediction
  - $A_5$ (= adjoint Higgs) is massless at tree level, & acquires a mass of $O(m_{SB})$ via loop.
  - Its superpartners can have masses of $O(m_{SB})$.

Light adjoint chiral superfields, $\Sigma_1 : (1, 1)_0$, $\Sigma_2 : (1, 3)_0$, $\Sigma_3 : (8, 1)_0$ are predicted.

- $\mathbb{Z}_2$-symm. : $\Sigma_i \rightarrow -\Sigma_i$ (may be broken)
**low energy effective theory**

**gauge coupling unification**

- The adjoint matters: $$\delta_{adj} b = (0, 2, 3)$$
  recovered with $$\delta_{add} b = (3 + n, 1 + n, n)$$

ex1) additional matters for $$\delta_{add} b = (4, 2, 1):$$

$$2 \times (L, \bar{L}), (U^c, \bar{U}^c), (E, \bar{E}^c)$$

- MSSM
- MSSM + adj
- MSSM + adj + add

$$\alpha_G \sim 0.3$$

$$\log_{10} \mu (\text{GeV})$$
low energy effective theory

- phenomenology of adjoints
  - $SU(3)$ is not asymptotically free, & remains strong @ high energy
  - squarks & octet become rather heavy.
- colorless fields may be produced @ LHC/LC.
- these may affect the higgs sector indirectly.
  - e.g. NMSSM-like contribution $\rightarrow$ heavier higgs
  - Higgs couplings are corrected at a few % level.

Higgs sector extended

\[ H_u, H_d + S \left( = \Sigma_1 : (1, 1)_0 \right) \& \Delta \left( = \Sigma_2 : (1, 3)_0 \right) \]

2 more [CP even, CP odd, charged] modes.

- superpotential

\[
W = \mu H_u \cdot H_d + \mu_{\Delta} \text{tr}(\Delta^2) + \frac{\mu S}{2} S^2 + \xi_S S \\
+ \lambda_{\Delta} H_u \cdot \Delta H_d + \lambda_S S H_u \cdot H_d
\]

✓ no self couplings for \( S \& \Delta \)
✓ \( \lambda_{\Delta} \& \lambda_S \) are related to the gauge couplings control the effects

highly predictive
Higgs sector

- RG running
  - fix a model → gauge coupling unification
  - set $\lambda_\Delta = 2\sqrt{5/3}\lambda_S (= \lambda'_S) = g_{1,2,3}$ @ GUT scale

  \[ \lambda_\Delta = 1.1, \quad \lambda_S = 0.25 \]

  @ weak scale

[Graph showing RG running of gauge couplings]
phenomenology of adjoints

- $SU(3)$ is no longer asymptotically free, & remains strong @ high energy
  - squarks & octet become rather heavy.

- $\alpha_G \sim 0.3 \implies$ large $M_{1/2}$.
- $y_t$ mediates the large $\tilde{m}_t$ to the Higgs sector.
  - ✓ fine tuning for EWSB (little hierarchy)
  - ✓ large $m_A$, $m_S$, $m_\Delta$
- further tunings w/ inputs @ GUT scale
  - benchmark points with rich pheno.
Higgs sector

- three Benchmark Points
  (A) the SM-like Higgs boson is light (less-tuned)
  (B) the MSSM-like Higgs bosons are light
  (C) the adjoints affect the SM-like Higgs couplings

<table>
<thead>
<tr>
<th>Case</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$M_3$</th>
<th>$\mu_\Delta$</th>
<th>$\mu_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)(B)(C)</td>
<td>194 GeV</td>
<td>388 GeV</td>
<td>1360 GeV</td>
<td>-252 GeV</td>
<td>-85.8 GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>$\mu$</th>
<th>$B\mu$</th>
<th>$\tilde{m}_{u_3}$</th>
<th>$\tilde{m}_{q_3}$</th>
<th>$y_t A_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>205 GeV</td>
<td>41400 GeV</td>
<td>13290 GeV</td>
<td>4830 GeV</td>
<td>4030 GeV</td>
</tr>
<tr>
<td>(B)</td>
<td>177 GeV</td>
<td>40800 GeV</td>
<td>1730 GeV</td>
<td>4480 GeV</td>
<td>6050 GeV</td>
</tr>
<tr>
<td>(C)</td>
<td>174 GeV</td>
<td>42000 GeV</td>
<td>4220 GeV</td>
<td>5550 GeV</td>
<td>2910 GeV</td>
</tr>
</tbody>
</table>

$\tan \beta = 3$

<table>
<thead>
<tr>
<th>Case</th>
<th>$m_\Delta$</th>
<th>$m_S$</th>
<th>$\lambda_\Delta A_\Delta$</th>
<th>$\lambda'_SA_S$</th>
<th>$B_\Delta\mu_\Delta$</th>
<th>$B_S\mu_S$</th>
<th>$m_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>607 GeV</td>
<td>805 GeV</td>
<td>662 GeV</td>
<td>683 GeV</td>
<td>92000 GeV</td>
<td>-78700 GeV</td>
<td>123 GeV</td>
</tr>
<tr>
<td>(B)</td>
<td>784 GeV</td>
<td>612 GeV</td>
<td>1340 GeV</td>
<td>1110 GeV</td>
<td>30700 GeV</td>
<td>-110000 GeV</td>
<td>123 GeV</td>
</tr>
<tr>
<td>(C)</td>
<td>521 GeV</td>
<td>216 GeV</td>
<td>284 GeV</td>
<td>446 GeV</td>
<td>207000 GeV</td>
<td>-33600 GeV</td>
<td>122 GeV</td>
</tr>
</tbody>
</table>
Higgs sector

\[ \kappa_X = \frac{g_{hXX}}{g_{hXX}^{SM}} \]

deviations of the SM-like Higgs couplings

The deviations are same as the NMSSM
Higgs sector

- MSSM-like charged Higgs boson mass

\[ m_{H^\pm}^2 = m_{H^\pm}^2 |_{\text{MSSM}} (1 + \delta_{H^\pm})^2 \]

\[ \simeq m_A^2 + m_W^2 + \frac{1}{8} \lambda_\Delta v^2 - \frac{1}{2} \lambda_S v^2 \]

Direct search?

- Case (C)

<table>
<thead>
<tr>
<th>CP-even</th>
<th>CP-odd</th>
<th>Charged</th>
</tr>
</thead>
<tbody>
<tr>
<td>122 GeV</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>139 GeV</td>
<td>171 GeV</td>
<td>204 GeV</td>
</tr>
<tr>
<td>370 GeV</td>
<td>304 GeV</td>
<td>496 GeV</td>
</tr>
<tr>
<td>745 GeV</td>
<td>497 GeV</td>
<td>745 GeV</td>
</tr>
</tbody>
</table>

\[ e^+ e^- \rightarrow \Delta^+ \Delta^- \rightarrow t\bar{b}t\bar{b} \]
SUSY grand GHU
- natural doublet-triplet splitting
  - theoretically well motivated
- generally predicts light adjoint chiral matters
  - the Higgs sector is extended, $S$ & $\Delta$

Phenomenological study
- heavier Higgs mass
- distinguishable charged Higgs mass
- a few % deviations from the SM/MSSM
  - can be a reasonable target of the ILC

T.Y. (2011)
back up
grand gauge-Higgs unification

- basis transformation

  (broken) gauge transformation w/ $\alpha^{(-)} = g \langle A_5^{(-)} \rangle (y - y_0)$

  $\langle A_5 \rangle \rightarrow 0$  $\rightarrow$  $\langle W \rangle \rightarrow 1$

- BCs around $y = y_\pi$ are modified:

  ex) $\Psi(y_\pi - y) = \eta_\pi^\Psi \gamma_5 \Psi(y_\pi + y)$

  $P_W = \text{diag} (1,1,1,-1,-1)$
grand gauge-Higgs unification

- basis transformation
  (broken) gauge transformation w/ \( \alpha^{(-)} \),
  \[ \langle A_5 \rangle \rightarrow 0 \quad \Rightarrow \quad \langle W \rangle \rightarrow 1 \]

- BCs around \( y = y_\pi \) are modified:
  \[ \psi(y_\pi - y) = \eta_\pi \gamma_5 P_W \psi(y_\pi + y) \]
  \( P_W = \text{diag.}(1, 1, 1, -1, -1) \)
  \[ \Rightarrow \quad \text{symmetry breaking by BCs, as in the orbifold breaking} \]

- DT splitting \( \text{T.Y. (2011)} \)
  “anti-periodic” 5 chiral \( \Rightarrow \) massless doublet
### Higgs sector

- **three Benchmark Points**
  - (A) the SM-like Higgs boson is light (less-tuned)
  - (B) the MSSM-like Higgs bosons are light
  - (C) the adjoints affect the SM-like Higgs couplings

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<tr>
<th>Case</th>
<th>( \tan \beta )</th>
<th>( M_{1/2} )</th>
<th>( \mu \Sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)(B)(C)</td>
<td>3</td>
<td>3600 GeV</td>
<td>-300 GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>( A_0 )</th>
<th>( \tilde{m}_0^2 )</th>
<th>( \tilde{m}_{H_u}^2 )</th>
<th>( \tilde{m}_{H_d}^2 )</th>
<th>( \tilde{m}_5^2 )</th>
<th>( \tilde{m}_{10}^2 )</th>
<th>( \tilde{m}_{\Sigma}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>5500 GeV</td>
<td>(1000 GeV)^2</td>
<td>(10375 GeV)^2</td>
<td>(8570 GeV)^2</td>
<td>-(6300 GeV)^2</td>
<td>-(2000 GeV)^2</td>
<td>-(570 GeV)^2</td>
</tr>
<tr>
<td>(B)</td>
<td>1000 GeV</td>
<td>(1800 GeV)^2</td>
<td>(12604 GeV)^2</td>
<td>(10381.5 GeV)^2</td>
<td>-(7700 GeV)^2</td>
<td>-(1960 GeV)^2</td>
<td>-(670 GeV)^2</td>
</tr>
<tr>
<td>(C)</td>
<td>8000 GeV</td>
<td>(3000 GeV)^2</td>
<td>(10605.1 GeV)^2</td>
<td>(8751.4 GeV)^2</td>
<td>-(6418 GeV)^2</td>
<td>-(1638.5 GeV)^2</td>
<td>-(400 GeV)^2</td>
</tr>
</tbody>
</table>
extra dimension

Compact Dimension

\[ \phi(x) = \phi(x + k2\pi R) \]
\[ (k = 0, 1, 2, ...) \]
\[ p = k/R \]

our 4D
extra dimension

**Orbifold**

**ex)** $S^1 / \mathbb{Z}_2$

$y = \pi R$

$T = P' P$

$L(x^\mu, y) = L(x^\mu, y + 2\pi R) : T$

$L(x^\mu, -y) : P$

$L(x^\mu, \pi R - y) = L(x^\mu, \pi R + y) : P'$

**Fields may not be invariant!**

**ex)**

$A_\mu(x^\mu, -y) = PA_\mu(x^\mu, y)P^\dagger$

$A_5(x^\mu, -y) = \Box PA_5(x^\mu, y)P^\dagger$

$\Psi(x^\mu, -y) = \eta \Psi P\gamma_5 \Psi(x^\mu, y)$

$P : \text{symm. transformation}$

$\eta^2 = 1$
Kaluza-Klein decomposition

\[ \Phi^{(P, P')} (x, y) = \left\{ \begin{array}{l}
\sum_{n=0}^{\infty} \Phi^{(+,+)}_n (x) \cos \left( \frac{ny}{R} \right) \\
\sum_{n=1}^{\infty} \Phi^{(+,-)}_n (x) \cos \left( \frac{(n + 1/2)y}{R} \right) \\
\sum_{n=1}^{\infty} \Phi^{(-,+)}_n (x) \sin \left( \frac{(n + 1/2)y}{R} \right) \\
\sum_{n=1}^{\infty} \Phi^{(-,-)}_n (x) \sin \left( \frac{ny}{R} \right)
\end{array} \right. \]
extra dimension

Kaluza-Klein mass

$\Phi^{(+,+)}$, $\Phi^{(-,-)}$, $\Phi^{(+,-)}$, $\Phi^{(-,+)}$

Fermion: $(\Psi^{(+,+)}_L, \Psi^{(-,-)}_R, \Psi^{(+,-)}_L, \Psi^{(-,+)}_R)$
Hosotani mechanism

- overview

5D theory

compactification

4D theory

with KK modes

gauge field

\[ A_M = (A_\mu, A_5) \]

gauge field

scalar field

Higgs

5D gauge invariance protect the Higgs mass!!

D.B. Fairlie (1979)
N.S. Manton (1979)

Y. Hosotani (1983-)
Orbifolding & Hosotani breaking

Orbifold breaking  Y. Kawamura

ex) $SU(3) \rightarrow SU(2) \times U(1)$

$P = P' = \text{diag.}(+, -, -)$

$(P, P') A_\mu = \begin{pmatrix}
(+, +) & (\cdot, \cdot) & (\cdot, \cdot) \\
(\cdot, \cdot) & (+, +) & (+, +) \\
(\cdot, \cdot) & (+, +) & (+, +)
\end{pmatrix}$

$(P, P') A_5 = \begin{pmatrix}
(+, +) & (\cdot, \cdot) & (\cdot, \cdot) \\
(\cdot, \cdot) & (+, +) & (+, +) \\
(\cdot, \cdot) & (+, +) & (+, +)
\end{pmatrix}$

Doublet Higgs!