Gauge-Higgs Grand Unification

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Ref. [1, Y.Hosotani and N.Yamatsu, arXiv:1504.03817]

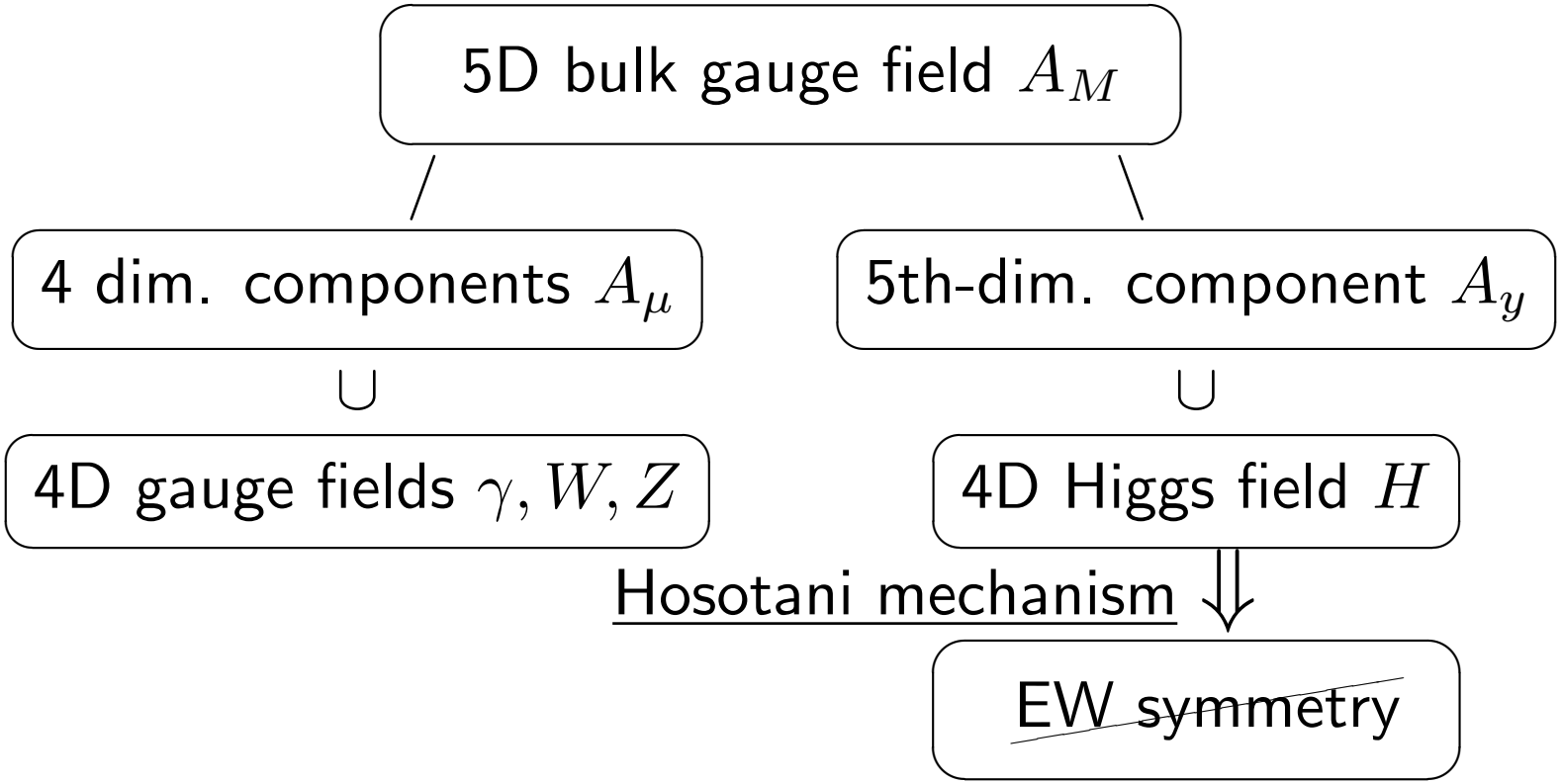
Purpose of this Talk

We propose SO(11) Gauge-Higgs Grand Unification.

Content of this Talk:

- What is gauge-Higgs grand unification?
- $SO(11)$ symmetry breaking pattern
- $SO(11)$ matter content and its zero modes

Gauge-Higgs Unification



E.g., $SO(5) \times U(1)$ GHU [2–6, K.Agashe et al'05;Y.Hosotani et al.'08-'14]

Gauge-Higgs Grand Unification

= **Gauge-Higgs Unification**

- To unify gauge and Higgs bosons
- Gauge symmetry for Higgs field
- ...

+ **Grand Unification**

- To unify SM gauge bosons
- To unify SM fermions
- Charge quantization
- Anomaly cancellation
- ...

Gauge-Higgs Grand Unification

$=$ **Gauge-Higgs Unification** $+$ **Grand Unification**

E.g., $SU(5)$, $SU(6)$, $SO(11)$ GHGU (in $M^4 \times S^1/Z_2$ or RS)

[7, G.Burdman and Y.Nomura, NPB656 (2003)]
[8, N.Haba, Y.Hosotani, Y.Kawamura, T.Yamashita, PRD70 (2004)]
[9, C.S.Lim and N.Maru, PLB653 (2007)]
[10, K.Kojima, K.Takenaga, and T.Yamashita, PRD84 (2011)]
[11, M.Frigerio, J.Serre, and A.Varagnolo, JHEP1106 (2011)]
[1, Y.Hosotani and N.Yamatsu, arXiv:1504.03817]

$SO(11)$ gauge-Higgs GUT in RS [1, Y.Hosotani,N.Yamatsu,'15]

Symmetry breaking pattern:

$SO(11)$

$SO(11)$ gauge-Higgs GUT in RS [1, Y.Hosotani,N.Yamatsu,'15]

Symmetry breaking pattern:

$$SO(11) \underset{BC}{\to} \begin{cases} SO(10) & \text{on Planck brane} \\ SO(4) \times SO(7) & \text{on TeV brane} \end{cases}$$

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$$\underset{\theta_H}{\to} SU(3)_C \times U(1)_{em} \quad \text{(Hosotani mechanism [12, Y.Hosotani,PLB'83])}$$

Matter content of $SO(11)$ gauge-Higgs GUT in RS

Bulk field	A_M	$\Psi^{(a)}_{\mathbf{32}}$	$\Psi^{(b)}_{\mathbf{11}}$
$SO(11)$	$\mathbf{55}$	$\mathbf{32}$	$\mathbf{11}$
5D RS_1	$\mathbf{5}$	$\mathbf{4}$	$\mathbf{4}$
Orbifold BC		$(-,-)$	$(-,-)$

Brane field	$\phi_{\mathbf{16}}$
$SO(10)$	$\mathbf{16}$
$SL(2,\mathbb{C})$	(0,0)
5th dim.	Planck

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Orbifold boundary conditions(BC):

$$\begin{pmatrix} A_\mu \\ A_y \end{pmatrix}(x, y_j - y) = P_{j\mathbf{11}} \begin{pmatrix} A_\mu \\ -A_y \end{pmatrix}(x, y_j + y) P^{-1}_{j\mathbf{11}},$$

$$P_{0\mathbf{11}} = \mathrm{diag}(I_{10}, -I_1), \quad P_{1\mathbf{11}} = \mathrm{diag}(I_4, -I_7).$$

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5th dim.	Planck

Orbifold boundary conditions(BC):

$$\Psi_{\mathbf{32}}(x, y_j - y) = \pm P_{j\mathbf{32}}\Gamma^5\Psi_{\mathbf{32}}(x, y_j + y),$$
$$\Psi_{\mathbf{11}}(x, y_j - y) = \pm P_{j\mathbf{11}}\Gamma^5\Psi_{\mathbf{11}}(x, y_j + y),$$
$$P_{0\mathbf{32}} = \Gamma^{(5)}_{11}, \quad P_{1\mathbf{32}} = \Gamma^{(5)}_{1234}.$$

Zero modes of $SO(11)$ gauge boson

Orbifold BCs on the Planck brane: $SO(11) \underset{BC_0}{\to} SO(10)$

$$A_\mu \sim \left(\begin{array}{c|c|c} (++)_{4\times4} & (+-)_{4\times6} & (--)_{4\times1} \\ \hline (+-)_{6\times4} & (++)_{6\times6} & (-+)_{6\times1} \\ \hline (--)_{1\times4} & (-+)_{1\times6} & (++)_{1\times1} \end{array}\right)_{11\times11},$$

$$A_y \sim \left(\begin{array}{c|c|c} (--)_{4\times4} & (-+)_{4\times6} & (++)_{4\times1} \\ \hline (-+)_{6\times4} & (--)_{6\times6} & (+-)_{6\times1} \\ \hline (++)_{1\times4} & (+-)_{1\times6} & (--)_{1\times1} \end{array}\right)_{11\times11}.$$

Zero modes of $SO(11)$ gauge boson

Orbifold BCs on the TeV brane: $SO(11) \underset{BC_1}{\to} SO(4) \times SO(7)$

$$A_\mu \sim \left(\begin{array}{c|c|c} (++)_{4\times4} & (+-)_{4\times6} & (--)_{4\times1} \\ \hline (+-)_{6\times4} & (++)_{6\times6} & (-+)_{6\times1} \\ \hline (--)_{1\times4} & (-+)_{1\times6} & (++)_{1\times1} \end{array}\right)_{11\times11},$$

$$A_y \sim \left(\begin{array}{c|c|c} (--)_{4\times4} & (-+)_{4\times6} & (++)_{4\times1} \\ \hline (-+)_{6\times4} & (--)_{6\times6} & (+-)_{6\times1} \\ \hline (++)_{1\times4} & (+-)_{1\times6} & (--)_{1\times1} \end{array}\right)_{11\times11}.$$

Zero modes of $SO(11)$ gauge boson

BCs: $SO(11) \underset{BC_0, BC_1}{\to} SO(4) \times SO(6) \simeq SU(2)_L \times SU(2)_R \times SU(4)_C$

$$A_\mu \sim \left(\begin{array}{c|c|c} (++)_{4\times4} & (+-)_{4\times6} & (--)_{4\times1} \\ \hline (+-)_{6\times4} & (++)_{6\times6} & (-+)_{6\times1} \\ \hline (--)_{1\times4} & (-+)_{1\times6} & (++)_{1\times1} \end{array}\right)_{11\times11},$$

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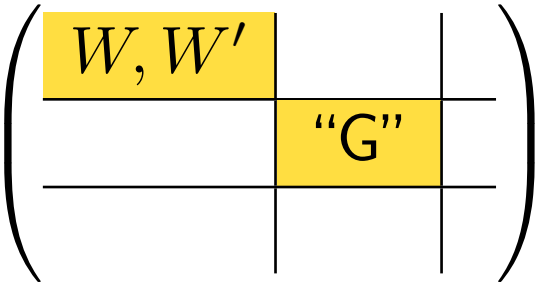
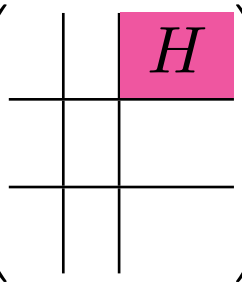
Zero modes of $SO(11)$ gauge boson

Orbifold BCs without brane interaction:

$$A_\mu \sim$$ 

$$, \quad A_y \sim$$ 

$$.$$

Symmetry breaking pattern:

$$SO(11) \underset{BC}{\to} G_{PS} = SU(2)_L \times SU(2)_R \times SU(4)_C.$$

Zero modes of $SO(11)$ gauge boson

Orbifold BCs with brane interaction:

$$A_\mu \sim \left(\begin{array}{|c|c|c|} \hline W & & \\ \hline & G & \\ \hline & & \\ \hline \end{array} \right), \quad A_y \sim \left(\begin{array}{|c|c|c|} \hline & H & \\ \hline & & \\ \hline & & \\ \hline \end{array} \right).$$

Symmetry breaking pattern:

$$SO(11) \underset{SSB,BC}{\longrightarrow} G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y.$$

Zero modes of $SO(11)$ spinor fermion

Orbifold BCs without brane interaction:

$$\Psi^{(a)}_{\mathbf{32}} \sim \left(\begin{array}{c} q_L, \ell_L \\ \hline u_R, d_R, e_R, \nu_R \end{array} \right) .$$

Symmetry breaking pattern:

$$SO(11) \underset{BC}{\to} G_{PS} = SU(2)_L \times SU(2)_R \times SU(4)_C .$$

Zero modes of $SO(11)$ spinor fermion

Orbifold BCs with brane interaction:

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Symmetry breaking pattern:

$$SO(11) \underset{SSB,BC}{\to} G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y.$$

Summary for Zero modes in $SO(11)$ gauge-Higgs GUT

Bulk field	A_M			
Zero modes	G_μ	W_μ	A_μ	ϕ
G_{SM}	$(\mathbf{8},\mathbf{1})_0$	$(\mathbf{1},\mathbf{3})_0$	$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{1},\mathbf{2})_{-1/2}$
$SL(2,\mathbb{C})$	(1/2,1/2)	(1/2,1/2)	(1/2,1/2)	(0,0)

Bulk field	$\Psi^{(a)}_{\mathbf{32}}$				
Zero modes	$q^{(a)}_L$	$u^{(a)}_R$	$d^{(a)}_R$	$\ell^{(a)}_L$	$e^{(a)}_R$
G_{SM}	$(\mathbf{3},\mathbf{2})_{+1/6}$	$(\mathbf{3},\mathbf{1})_{+2/3}$	$(\mathbf{3},\mathbf{1})_{-1/3}$	$(\mathbf{1},\mathbf{2})_{-1/2}$	$(\mathbf{1},\mathbf{1})_{-1}$
$SL(2,\mathbb{C})$	(1/2,0)	(0,1/2)	(0,1/2)	(1/2,0)	(0,1/2)

Summary

We proposed $SO(11)$ gauge-Higgs grand unification in RS.

- $SO(11)$ symmetry is broken to $SU(3)_C \times SU(2)_L \times U(1)_Y$ by orbifold boundary conditions and the VEV of a brane scalar field.
- The zero modes of the $SO(11)$ bulk gauge field are the G_{SM} gauge fields and the SM Higgs field. The zero modes of an $SO(11)$ spinor fermion field are one generation of the SM fermions.

Other topics:

- Proton decay and EW symmetry breaking via Hosotani mechanism are discussed in Ref. [1, Y.Hosotani,N.Yamatsu,'15].

References

[1] Y. Hosotani and N. Yamatsu, "Gauge-Higgs Grand Unification," arXiv:1504.03817 [hep-ph].

[2] K. Agashe, R. Contino, and A. Pomarol, "The Minimal composite Higgs model," *Nucl. Phys.* **B719** (2005) 165–187, arXiv:hep-ph/0412089 [hep-ph].

[3] Y. Hosotani, K. Oda, T. Ohnuma, and Y. Sakamura, "Dynamical Electroweak Symmetry Breaking in $SO(5) \times U(1)$ Gauge-Higgs Unification with Top and Bottom Quarks," *Phys.Rev.* **D78** (2008) 096002, arXiv:0806.0480 [hep-ph].

[4] Y. Hosotani, S. Noda, and N. Uekusa, "The Electroweak gauge couplings in SO(5) x U(1) gauge-Higgs unification," *Prog. Theor. Phys.* **123** (2010) 757–790, arXiv:0912.1173 [hep-ph].

[5] S. Funatsu, H. Hatanaka, Y. Hosotani, Y. Orikasa, and T. Shimotani, "LHC Signals of the $SO(5) \times U(1)$ Gauge-Higgs Unification," arXiv:1404.2748 [hep-ph].

[6] S. Funatsu, H. Hatanaka, Y. Hosotani, Y. Orikasa, and T. Shimotani, "Dark Matter in the $SO(5) \times U(1)$ Gauge-Higgs Unification," arXiv:1407.3574 [hep-ph].

[7] G. Burdman and Y. Nomura, "Unification of Higgs and gauge fields in five-dimensions," *Nucl. Phys.* **B656** (2003) 3–22, arXiv:hep-ph/0210257 [hep-ph].

[8] N. Haba, Y. Hosotani, Y. Kawamura, and T. Yamashita, "Dynamical symmetry breaking in gauge Higgs unification on orbifold," *Phys. Rev.* **D70** (2004) 015010, arXiv:hep-ph/0401183 [hep-ph].

[9] C. Lim and N. Maru, "Towards a realistic grand gauge-Higgs unification," *Phys.Lett.* **B653** (2007) 320–324, arXiv:0706.1397 [hep-ph].

[10] K. Kojima, K. Takenaga, and T. Yamashita, "Grand Gauge-Higgs Unification," *Phys. Rev.* **D84** (2011) 051701, arXiv:1103.1234 [hep-ph].

[11] M. Frigerio, J. Serra, and A. Varagnolo, "Composite GUTs: models and expectations at the LHC," *JHEP* **06** (2011) 029, arXiv:1103.2997 [hep-ph].

[12] Y. Hosotani, "Dynamical Mass Generation by Compact Extra Dimensions," *Phys.Lett.* **B126** (1983) 309.