# GUT inspired SO(5)×U(1)×SU(3) gauge-Higgs unification

Speaker: Shuichiro Funatsu (Central China Normal University)

Yutaka Hosotani (Osaka University), Hisaki Hatanaka (Osaka), Yuta Orikasa (Czech Technical University), Naoki Yamatsu (Hokkaido University)

arXiv:1902.01603

## gauge-Higgs unification

$$A_M = (A_\mu, A_y)$$

**4D gauge field** **Higgs field**

The Higgs boson is protected by the gauge symmetry
→ massless at the tree level
massive at the loop level

$$e^{i\theta_H} \equiv \exp\left(ig\int_C dy \langle A_y \rangle\right)$$

Higgs VEV appears as a Wilson-line phase

### gauge-Higgs Grand unification

$$SO(11) \xrightarrow[\text{B.C.}]{} SO(4)\times SO(6)_C \simeq SU(2)_L \times SU(2)_R \times SU(4)_C \xrightarrow[\text{brane int.}]{} SU(2)_L \times U(1)_Y \times SU(3)_C \xrightarrow[\text{Higgs VEV}]{} U(1)_{\rm EM} \times SU(3)_C$$

Defined on the 5D or 6D warped metric

Hosotani and Yamatsu, PTEP 111B01 (2015), 093B01 (2016), 091B01 (2017), 023B05 (2018)
Furui, Hosotani and Yamatsu, PTEP 093B01 (2016)

### gauge-Higgs EW unification

$$SO(5)\times U(1)_X \times SU(3)_C \xrightarrow[\text{B.C.}]{} SO(4)\times U(1)_X \times SU(3)_C \simeq SU(2)_L \times SU(2)_R \times U(1)_X \times SU(3)_C \xrightarrow[\text{brane int.}]{} SU(2)_L \times U(1)_Y \times SU(3)_C \xrightarrow[\text{Higgs VEV}]{} U(1)_{\rm EM} \times SU(3)_C$$

Defined on the 5D warped metric

Hosotani, Oda, Ohnuma and Sakamura, Phys. Rev. D78, 096002 (2008)
Yoon and Peskin, Phys. Rev. D96, 115030 (2017)
SF, Hatanaka, Hosotani and Orikasa, 6 papers

## Matter fields

### gauge-Higgs Grand unification

**In the bulk**

$$\Psi_{32} = \begin{pmatrix}\Psi_{16}\\ \Psi_{\bar{16}}\end{pmatrix}$$

$$\Psi_{16} = \begin{pmatrix}\nu & \nu_L\\ e & e_L\\ \hat{e} & \\ \hat{\nu} & \\ u_j & u_{jL}\\ d_j & d_{jL}\\ \hat{u}_j & \\ \hat{d}_j & \end{pmatrix} \qquad \Psi_{\bar{16}} = \begin{pmatrix}\nu' & \nu'_R\\ e' & e'_R\\ \hat{e}' & \\ \hat{\nu}' & \\ u'_j & u'_{jR}\\ d'_j & d'_{jR}\\ \hat{u}'_j & \\ \hat{d}'_j & \end{pmatrix}$$

$$\Psi_{11} = \begin{pmatrix}\hat{E} & N\\ \hat{N} & E\\ D_j & \hat{D}_j\\ & S\end{pmatrix}$$

$$\Psi'_{32} = \Psi_F$$

**On the UV brane**

$\Phi_{32}$ scalar

$\chi$ Majorana fermion

### gauge-Higgs EW unification (this work)

**In the bulk**

$$\Psi_{(1,4)} = \begin{pmatrix}\nu\\ e\\ \nu'\\ e'\end{pmatrix},\ \Psi_{(3,4)} = \begin{pmatrix}u_j\\ d_j\\ u'_j\\ d'_j\end{pmatrix}$$ bulk mass $c_L, c_Q$

$\Psi^{\pm}_{(3,1)} = D^{\pm}_j$ bulk mass $c_D$

pseudo-Dirac bulk mass $m_D$

$$\Psi^{\pm}_{(1,5)} = \begin{pmatrix}\hat{E}^{\pm} & N^{\pm}\\ \hat{N}^{\pm} & E^{\pm}\\ & S^{\pm}\end{pmatrix}$$ bulk mass $c_V, c_F$

$\Psi'_{(3,4)} = \Psi_F$ $\Psi^{\pm}_5, \Psi'_4$ do not include SM fields necessary to obtain small $\theta_H$

**On the UV brane**

$\Phi_{(1,4)}$ scalar

$\chi = \begin{pmatrix}\eta^c\\ \eta\end{pmatrix}$ Majorana fermion, Majorana mass $M$

$\langle\Phi_{(1,4)}\rangle\bar{\Psi}_{(3,4)}\Psi^{+}_{(3,1)}$ brane mass $\mu_1$, $d'$-$D^+$ mixing

$\langle\Phi_{(1,4)}\rangle\bar{\Psi}_{(1,4)}\chi$ brane mass $m_B$, $\nu'$-$\eta$ mixing

### gauge-Higgs EW unification (previous work)

**In the bulk**

$$\Psi^1_{(3,5)} = \begin{pmatrix}T & t\\ B & b\\ & t'\end{pmatrix},\ \Psi^2_{(3,5)} = \begin{pmatrix}U & X\\ D & Y\\ & b'\end{pmatrix}$$

left-handed top : $t, B, U$ left-handed bottom : $b, D, X$
right-handed top : $t'$ right-handed bottom : $b'$

(lepton sector and the brane interactions are abbreviated)

SO(5) branching rules

$\mathbf{4} = (\mathbf{2},\mathbf{1}) + (\mathbf{1},\mathbf{2})$
$\mathbf{5} = (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$
$\mathbf{10} = (\mathbf{3},\mathbf{1}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{3})$

$\begin{pmatrix}u\\ d\end{pmatrix} : (\mathbf{2},\mathbf{1})$ $\begin{pmatrix}u'\\ d'\end{pmatrix} : (\mathbf{1},\mathbf{2})$

$\begin{pmatrix}T & t\\ B & b\end{pmatrix}, \begin{pmatrix}U & X\\ D & Y\end{pmatrix} : (\mathbf{2},\mathbf{2})$ $t', b' : (\mathbf{1},\mathbf{1})$

this work: mainly SO(5)-**4** (spinor rep.)
previous work: mainly SO(5)-**5** (vector rep.)

## quark & lepton masses

$u, u'$ → **up quark**
$|c_Q|$ → $m_u$

$e, e'$ → **charged lepton**
$|c_L|$ → $m_e$

$d, d', D^{\pm}$ → **down quark**
$c_Q, c_D, m_D, \mu$ → $m_d$

$\nu, \nu', \eta$ → **neutrino**
$c_L, m_B, M$ → $m_\nu$

brane masses are necessary to obtain
mass difference between u-quark and d-quark and the small deviation of the *W*-coupling

| Leptons | $c_L$ | $M$ | $\frac{g^W_L}{g_w/\sqrt{2}} - 1$ | $\frac{g^W_R}{g_w/\sqrt{2}}$ |
|---|---|---|---|---|
| $(\nu_e, e)$ | 1.086 | 1 TeV | $-2.64\times10^{-3}$ | $O(10^{-11})$ |
| | −1.086 | 1 TeV | $-5.24\times10^{-3}$ | $O(10^{-23})$ |
| $(\nu_\mu, \mu)$ | 0.839 | 1 TeV | $-2.64\times10^{-3}$ | $O(10^{-14})$ |
| | −0.839 | 1 TeV | $-5.25\times10^{-3}$ | $O(10^{-21})$ |
| $(\nu_\tau, \tau)$ | 0.703 | 1 TeV | $-2.64\times10^{-3}$ | $O(10^{-15})$ |
| | −0.703 | 1 TeV | $-5.25\times10^{-3}$ | $O(10^{-19})$ |

$\tilde{m}_D \equiv m_D/k$

| Quarks | $c_Q$ | $\mu_1$ | $\tilde{m}_D$ | $\frac{g^W_L}{g_w/\sqrt{2}} - 1$ | $\frac{g^W_R}{g_w/\sqrt{2}}$ |
|---|---|---|---|---|---|
| $(u, d)$ | −1.044 | 0.1 | 1.0 | $-5.24\times10^{-3}$ | $O(10^{-14})$ |
| $(c, s)$ | −0.7546 | 0.1 | 1.0 | $-5.25\times10^{-3}$ | $O(10^{-9})$ |
| $(t, b)$ | 0.2287 | 0.1 | 0.1 | $-3.43\times10^{-3}$ | $O(10^{-4})$ |
| | −0.2287 | 0.1 | 1.0 | $-4.41\times10^{-3}$ | $O(10^{-5})$ |

| Quarks | $c_Q$ | $\mu_1$ | $c_D$ | $\tilde{m}_D$ | $m_{d^{(1)}}$ (TeV) | $m_{u^{(1)}}$ (TeV) |
|---|---|---|---|---|---|---|
| $(u, d)$ | −1.044 | 0.01 | 0.6194 | 1.0 | 4.59 | 8.23 |
| | | 0.1 | 0.4612 | 1.0 | 4.80 | |
| $(c, s)$ | −0.7546 | 0.1 | 0.6808 | 1.0 | 5.40 | 7.16 |
| | | 10. | 0.0949 | 1.0 | 5.22 | |
| $(t, b)$ | +0.2287 | 0.1 | 0.5838 | 0.1 | 2.84 | 7.20 |
| | | 10. | 0.3791 | 0.1 | 2.84 | |
| | −0.2287 | 0.1 | 1.044 | 1.0 | 5.06 | |
| | | 10. | 0.8352 | 1.0 | 5.06 | |

| Leptons | $c_L$ | $M$ (GeV) | $m_B$ (GeV) | $m_{\nu_s}$ | $m_{\nu^{(1)}}$ (TeV) | $m_{e^{(1)}}$ (TeV) |
|---|---|---|---|---|---|---|
| $(\nu_e, e)$ | 1.086 | $1.\times10^3$ | $6.6\times10^{19}$ | 6.8 MeV | 8.38 | 8.38 |
| | | 1. | $2.1\times10^{18}$ | 6.8 MeV | 8.38 | 8.38 |
| | −1.086 | $1.\times10^3$ | $1.5\times10^4$ | – | 8.38 | 8.38 |
| | | 1. | $4.7\times10^2$ | – | 0.51 | 8.38 |
| $(\nu_\mu, \mu)$ | 0.839 | $1.\times10^3$ | $5.0\times10^{19}$ | 1.4 GeV | 7.47 | 7.47 |
| | −0.839 | $1.\times10^3$ | $1.2\times10^7$ | – | 7.47 | 7.47 |
| $(\nu_\tau, \tau)$ | 0.703 | $1.\times10^3$ | $3.9\times10^{19}$ | 24. GeV | 6.96 | 6.96 |
| | −0.703 | $1.\times10^3$ | $8.8\times10^8$ | – | 6.96 | 6.96 |

## Future work

- Calculation of the effective potential
- $m_d > m_u$ is not realised yet
- Flavor physics
- Neutrino physics
- Dark matter constraints
- KK bottom search