Fermion mass hierarchy in grand Gauge-Higgs unification

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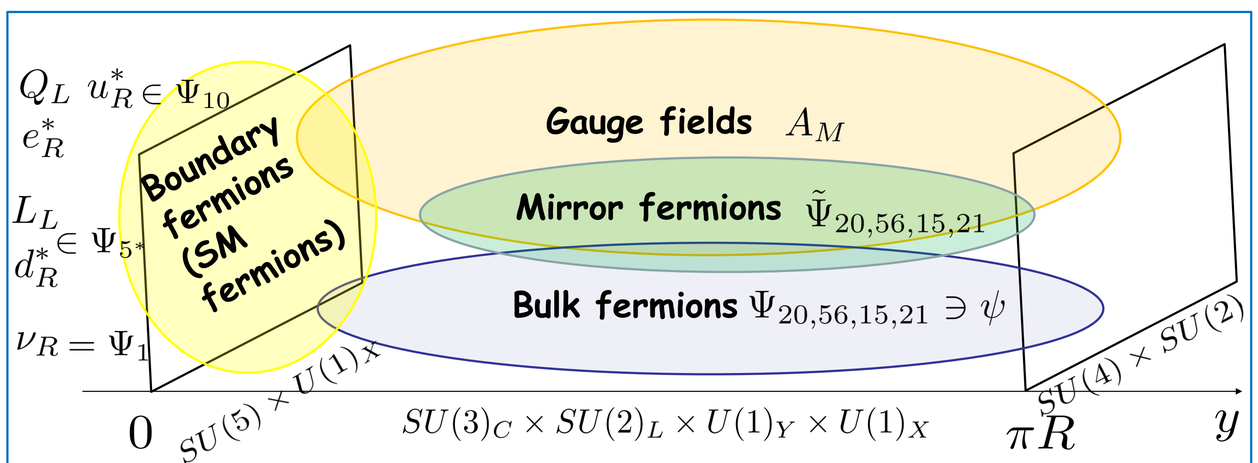
Motivation

- SU(6) Gauge-Higgs unification **(GHU) is minimal model** contained Standard Model (SM) gauge fields and Higgs field.
- In SU(6) GHU, embedding the SM fermions into bulk , **Yukawa couplings are not allowed.**
  [C.S.Lim,N.Maru,PLB**653** (2007) 320]
- **In SU(3)×U(1) GHU, by identifying boundary fermions with SM fermions and introducing bulk and mirror fermions, Yukawa couplings are obtained.**
  [C.A.Scrucca,M.Serone,L.Silvestrini,NPB**669** (2003) 128]
- **We solve Yukawa coupling problem by using this method in SU(6) GHU.**

Results

- **Yukawa couplings suppressed by bulk masses are obtained.**
- Except for top quark, we can achieve realistic masses **without unnatural fine-tuning of parameters.**
- Introducing a extra bulk and mirror fermion, **electro weak symmetry breaking are achieved.**

Set up



$$\mathcal{L} = -\frac{1}{4}\mathrm{tr}(F^{MN}F_{MN}) + \sum_{a\in 20,56,15,21}\left[\overline{\Psi}_a i\Gamma^M D_M \Psi_a + \overline{\tilde{\Psi}}_a i\Gamma^M D_M \tilde{\Psi}_a + \left(\frac{\lambda^a}{\pi R}\overline{\Psi}_a\tilde{\Psi}_a + \mathrm{h.c.}\right)\right]$$
$$+ \delta(y)\Big[\overline{\Psi}_{10} i\Gamma^\mu D_\mu \Psi_{10} + \overline{\Psi}_{5^*} i\Gamma^\mu D_\mu \Psi_{5^*} + \overline{\Psi}_1 i\Gamma^\mu D_\mu \Psi_1$$
$$+ \sqrt{\frac{2}{\pi R}}\left(\overline{Q^*}_L\psi_{20} + \overline{Q}_L\psi_{56^*} + \overline{u^*}_R\psi_{20} + \overline{d}_R\psi_{56^*} + \overline{L}^*_L(\psi_{15^*}+\psi_{21^*}) + \overline{e^*}_R\psi_{15^*} + \overline{\nu^*}_R\psi_{21^*}\right)\Big]$$

5D spacetime with extra space on an orbifold S^1/Z_2

parity operators
$P = \mathrm{diag}(+,+,+,+,+,-)$, at $y=0$
$P' = \mathrm{diag}(+,+,-,-,-,-)$, at $y=\pi R$

→ fields decompose 4 type modes
$(P,P') = (+,+), (+,-), (-,+), (-,-)$ zero-mode is massless!

Gauge field

$P^\dagger A_\mu P = \mu = 0,1,2,3$

	$U(1)_Y$	$SU(2)_L$		$SU(3)_C$			$U(1)_X$
	$(+,+)$	$(+,+)$	$(+,-)$	$(+,-)$	$(+,-)$	$(-,-)$	
	$(+,+)$	$(+,+)$	$(+,-)$	$(+,-)$	$(+,-)$	$(-,-)$	
	$(+,-)$	$(+,-)$	$(+,+)$	$(+,+)$	$(+,+)$	$(-,+)$	
	$(+,-)$	$(+,-)$	$(+,+)$	$(+,+)$	$(+,+)$	$(-,+)$	
	$(+,-)$	$(+,-)$	$(+,+)$	$(+,+)$	$(+,+)$	$(-,+)$	
	$(-,-)$	$(-,-)$	$(-,+)$	$(-,+)$	$(-,+)$	$(+,+)$	Higgs!

$-P^\dagger A_y P =$

$(-,-)$	$(-,-)$	$(-,+)$	$(-,+)$	$(-,+)$	$(+,+)$	
$(-,-)$	$(-,-)$	$(-,+)$	$(-,+)$	$(-,+)$	$(+,+)$	
$(-,+)$	$(-,+)$	$(-,-)$	$(-,-)$	$(-,-)$	$(+,-)$	
$(-,+)$	$(-,+)$	$(-,-)$	$(-,-)$	$(-,-)$	$(+,-)$	
$(-,+)$	$(-,+)$	$(-,-)$	$(-,-)$	$(-,-)$	$(+,-)$	
$(+,+)$	$(+,+)$	$(+,-)$	$(+,-)$	$(+,-)$	$(-,-)$	Higgs!

Bulk fermions

bulk fermions		representation coupling to SM fermions	
$20^{(-,-)}$	$\ni$	$(3,2)^{(-,-)}_{1/6,-3} + (3,1)^{(+,+)}_{2/3,1}$	$\to \psi_{20}$
$56^{*(-,+)}$	$\ni$	$(3^*,2)^{(+,+)}_{-1/6,3} + (3^*,1)^{(-,-)}_{1/3,9}$	$\to \psi_{56}$
$15^{*(+,+)}$	$\ni$	$(1,1)^{(+,+)}_{-1,-2} + (1,2)^{(-,-)}_{-1/2,4}$	$\to \psi_{15}$
$21^{*(+,+)}$	$\ni$	$(1,2)^{(-,-)}_{-1/2,4} + (1,1)^{(+,+)}_{0,10}$	$\to \psi_{21}$

$\psi(-y) \overset{P,P'}{\to} \pm\gamma^5\psi(y)$
$\psi(\pi R - y) \to \pm\gamma^5\psi(\pi R + y)$

→ $\psi^{(+,+)} \to$ right handed is massless
$\psi^{(-,-)} \to$ left handed is massless

Mirror fermions → fermions with parity opposite to bulk felmion

mass term $\frac{\lambda}{\pi R}\overline{\Psi}\Psi$ is not allowed for parity invariance.
but $\frac{\lambda}{\pi R}\overline{\Psi}\tilde{\Psi}$ is allowed!

(Ψ : bulk fermion, $\tilde{\Psi}$: mirror felmion, λ : bulk mass)

Mass spectrum of SM fermions

By integrating out bulk and mirror fermions , SM fermion masses are generated.

$$\left[1 + \sum \frac{P_L + P_R}{\lambda}\mathrm{Re}f(\lambda, q\alpha)\right]\bar{a}\gamma^\mu\partial_\mu a + \frac{i}{\pi R}\mathrm{Im}f(\lambda,q\alpha)\bar{a}a$$

$\left[1+\sum \frac{P_L+P_R}{\lambda}\mathrm{Re}f(\lambda,q\alpha)\right] = Z_L^a, Z_R^a$: kinetic term
$\frac{i}{\pi R}\mathrm{Im}f(\lambda,q\alpha) = m^a$: mass term

a:SM fermion
α:Higgs VEV
q:integer defined each representation

$$f(\lambda, q\alpha) = \sum_{n=-\infty}^{\infty}\frac{1}{\lambda + i\pi(n+q\alpha)} = \coth(\lambda + i\pi q\alpha)$$

canonically normalized

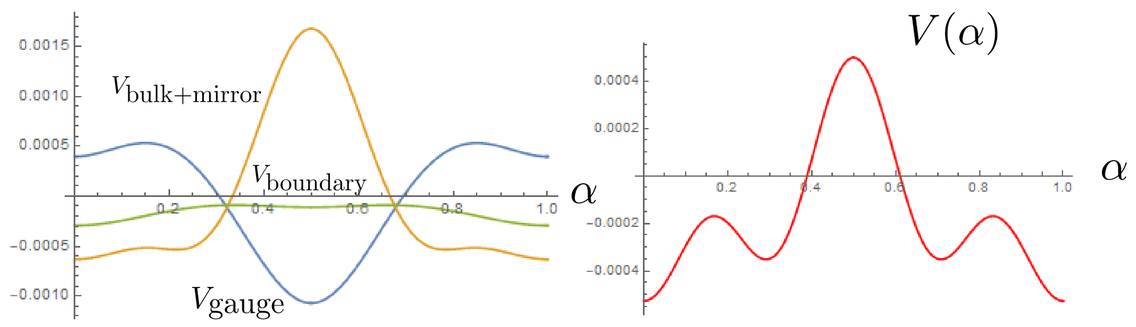
$$m^a_{\mathrm{phys}} = \frac{m^a}{\sqrt{Z_L^a Z_R^a}} \sim m_W e^{-\lambda}$$

parameter \ generation	1	2	3
$\lambda^{(20)}$	5.9	2.55	0.1
$\lambda^{(56)}$	5.65	4.1	1.1
$\lambda^{(15)}$	6.58	3.87	2.4
$\lambda^{(21)}$	13	10	10

without unnatural fine-tuning of parameter

Effective potential and Higgs mass

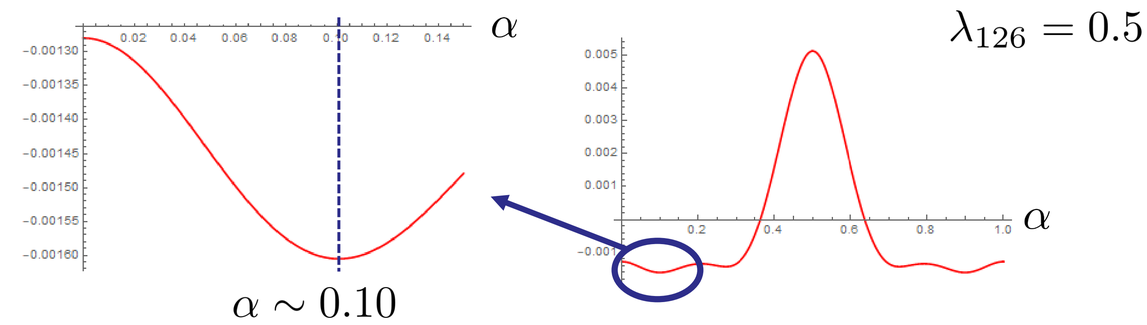
$$V(\alpha) = V_{\mathrm{gauge}} + V_{\mathrm{bulk+mirror}} + V_{\mathrm{boundary}}$$



→ Not breaking…

We add **126**(4th symmetry tensor) as extra bulk fermion

$$V(\alpha) = V_{\mathrm{gauge}} + V_{\mathrm{bulk+mirror}} + V_{\mathrm{boundary}} + V_{\mathrm{extra}}(\lambda_{126})$$



$SU(2)_L \times U(1)_Y \to U(1)_{em}$!!

$\to M_H \sim 147 g_4 \mathrm{GeV}$, $1/R \sim 0.8\mathrm{TeV}$