Gauge coupling unification in simplified grand gauge-Higgs unification

Haruki Takahashi (髙橋 晴輝)

Based on:
N. Maru, HT, Y. Yatagai, Phys. Rev. D **106**, 055033
(arXiv:2207.10253 [hep-ph])

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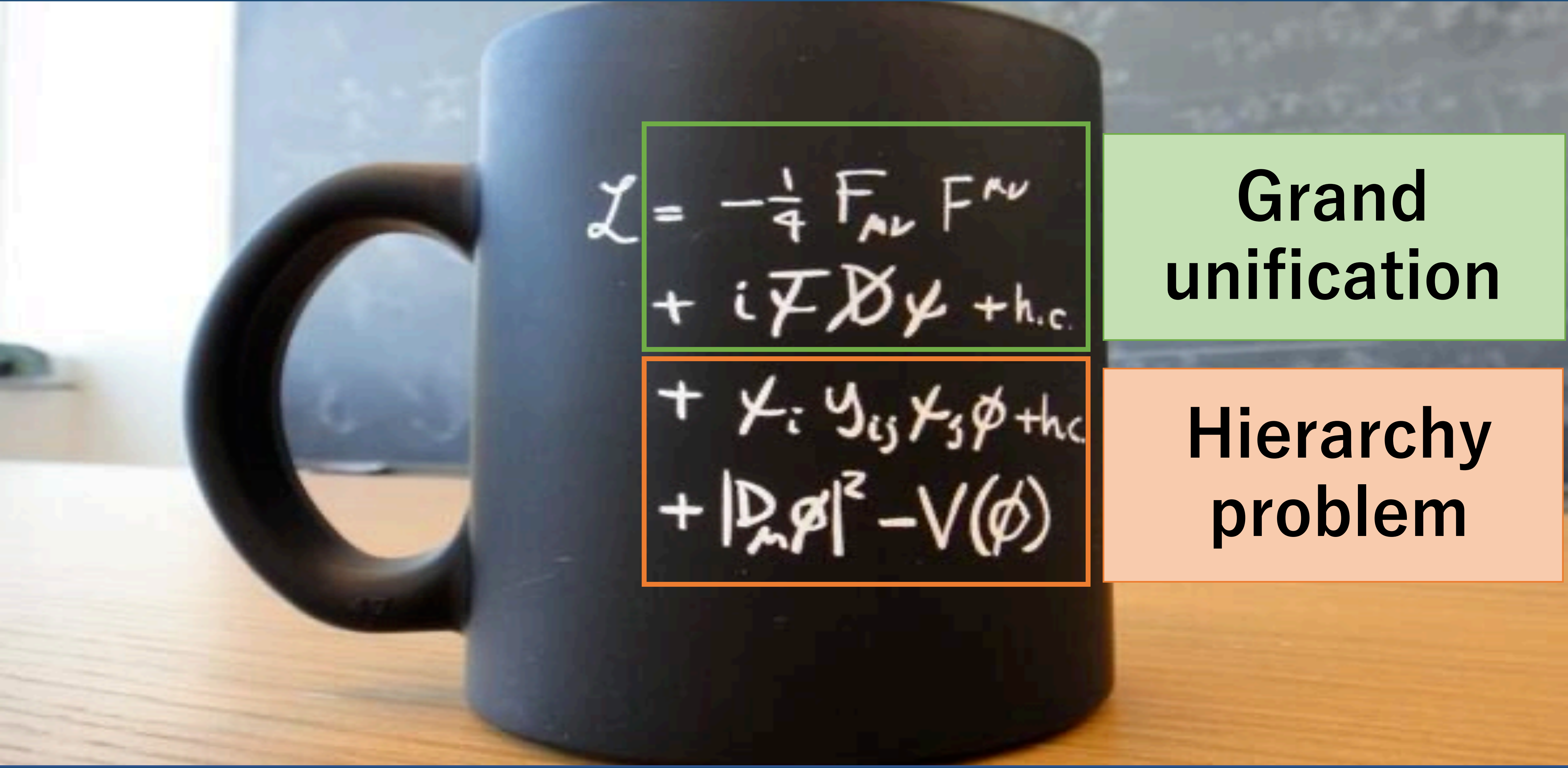
1-1 The Standard Model



1-2 Beyond the Standard Model

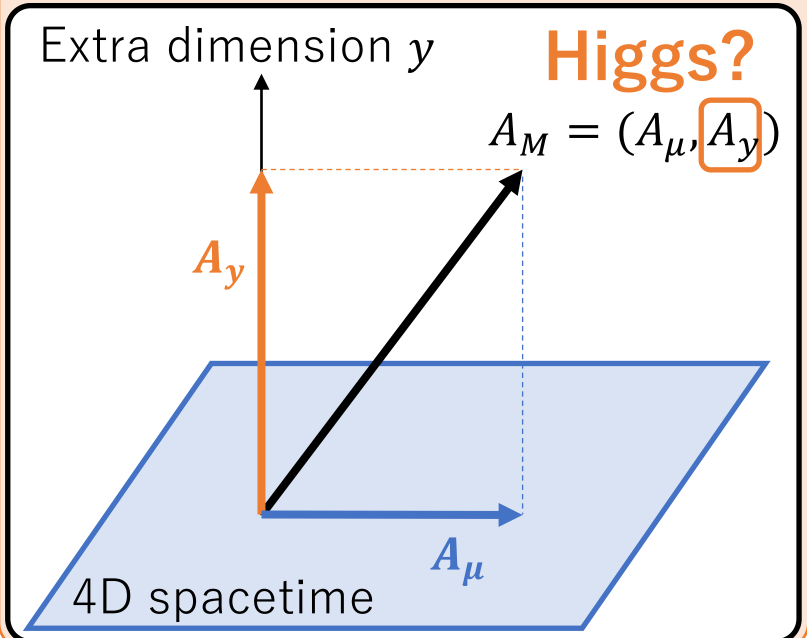
Grand Gauge Higgs Unification (GGHU)

GHU + GUT → GGHU   **5D SU(6) GGHU?**

[Y. Hosotani ’83; H. Hatanaka, T. Inami, C.S. Lim ’98]   [G. Burdman, Y. Nomura ’03; C.S. Lim, N. Maru ’07]

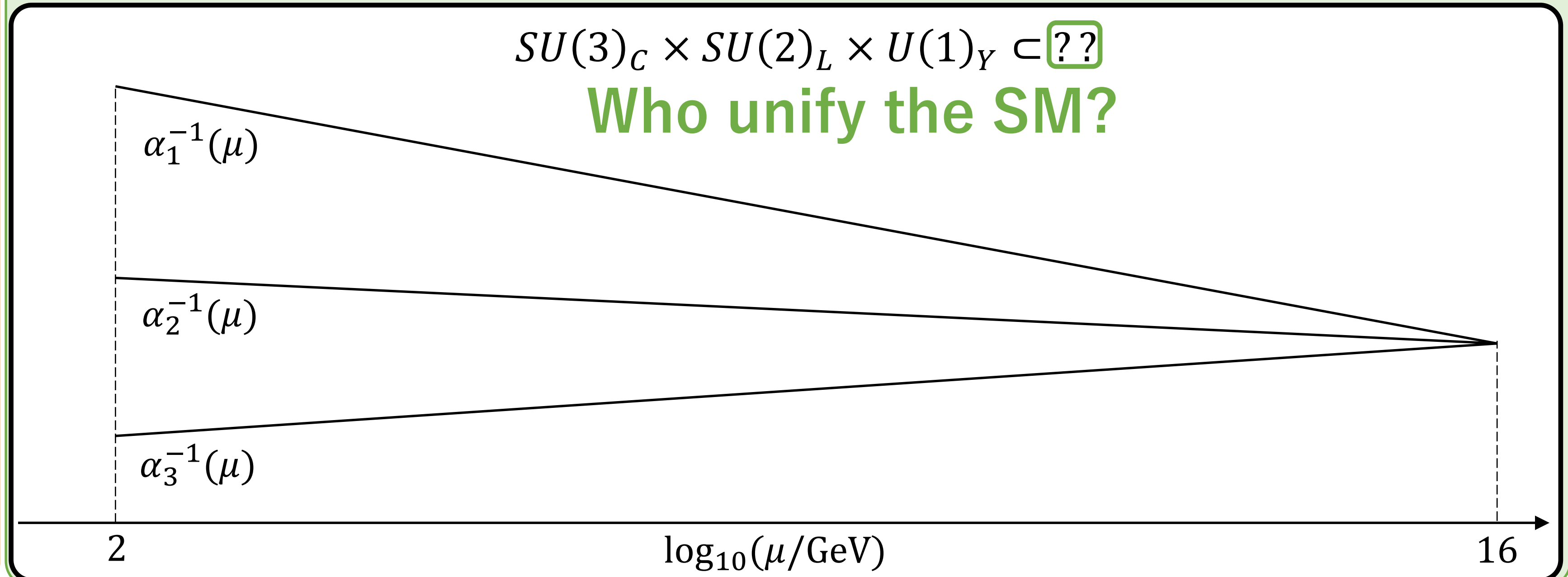
Gauge-Higgs Unification (GHU)

Hierarchy problem



Grand Unified Theory (GUT)

Grand unification



1-3 5D SU(6) Grand Gauge-Higgs Unification

Fermion mass hierarchy [N. Maru, Y. Yatagai '20]

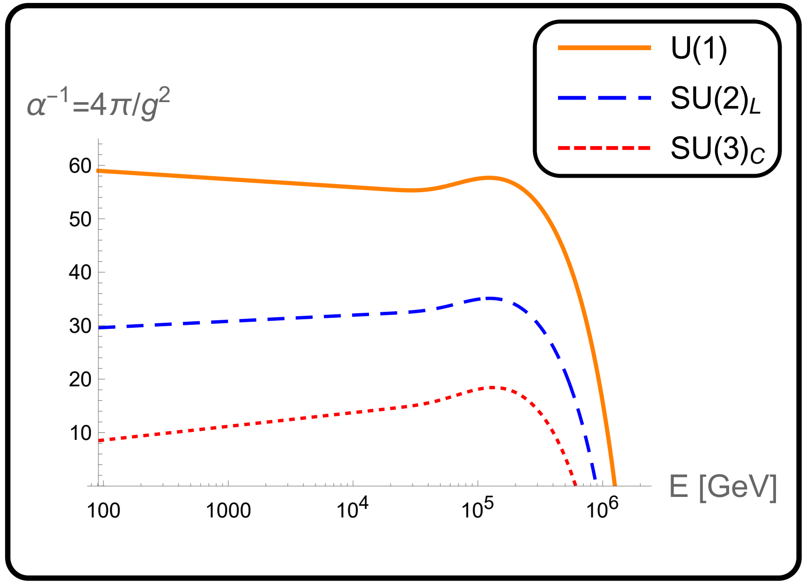
The SM fermion mass hierarchy including top quark mass was realized by introducing localized gauge kinetic terms without unnatural fine-tuning.

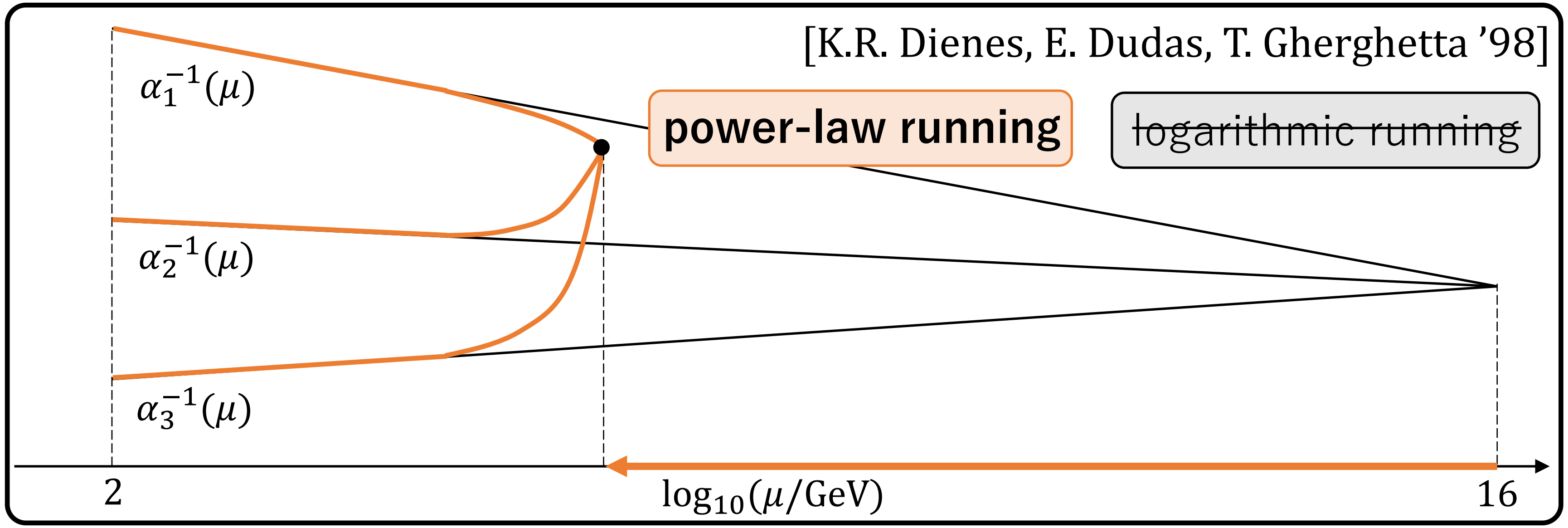
Gauge coupling unification

Many bulk fermions → ~~perturbative gauge coupling unification~~

Perturbative gauge coupling unification [N. Maru, HT, Y. Yatagai '22]

We have reduced the number of them and reproduced fermion mass hierarchy & mixing so that **perturbative gauge coupling unification is indeed realized** in our model.





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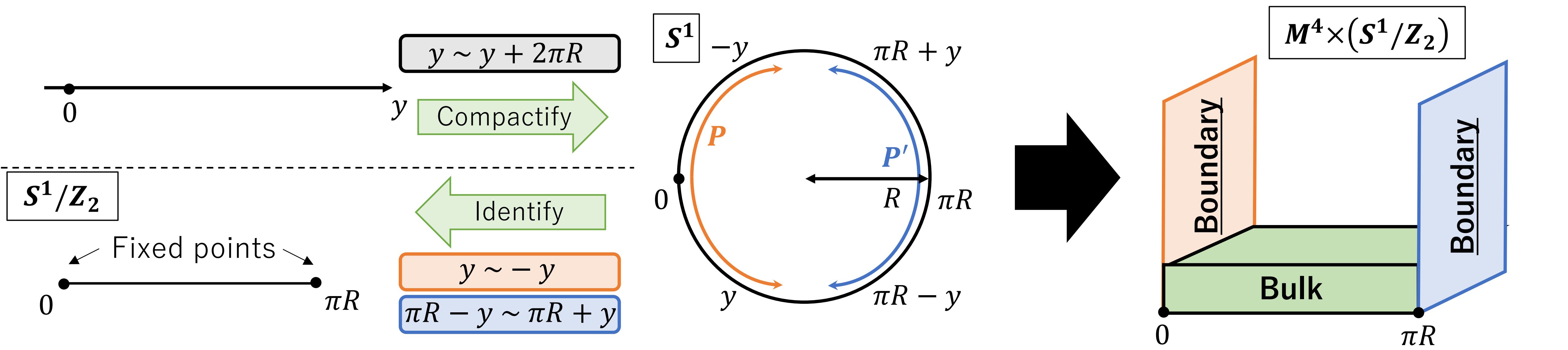
2-1 Orbifold breaking



[G. Burdman, Y. Nomura ’03; C.S. Lim, N. Maru ’07; N. Maru, Y. Yatagai ’20; N. Maru, HT, Y. Yatagai ’22]

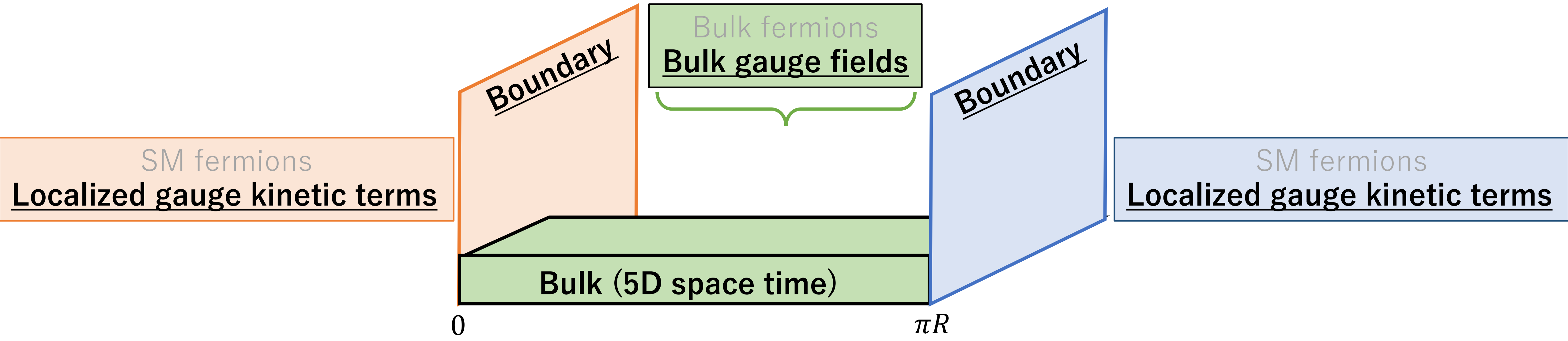
Boundary at $y = 0$	Bulk	Boundary at $y = \pi R$
$SU(5) \times U(1)_X$ ←	$SU(6)$	→ $SU(2) \times SU(4) \times U(1)'$
$P = \mathrm{diag}(+,+,+,+,+,-)$		$P' = \mathrm{diag}(+,+,-,-,-,-)$
$A_\mu(-y) = P A_\mu(y) P^\dagger$ $A_y(-y) = -P A_y(y) P^\dagger$	**Orbifold breaking**	$A_\mu(-y) = P' A_\mu(y) P'^\dagger$ $A_y(-y) = -P' A_y(y) P^\dagger$

2-2 Gauge sector with localized gauge kinetic terms

Boundary at $y = 0$	Bulk	Boundary at $y = \pi R$
$-2\pi R c_1 \delta(y) \frac{1}{4} \mathcal{F}^{b\,\mu\nu} \mathcal{F}^{b}_{\mu\nu}$	$-\frac{1}{4} \mathcal{F}^{a\,MN} \mathcal{F}^{a}_{MN}$	$-2\pi R c_2 \delta(y - \pi R) \frac{1}{4} \mathcal{F}^{c\,\mu\nu} \mathcal{F}^{c}_{\mu\nu}$
$b : SU(5) \times U(1)_X \to SU(5)$	$a : SU(6)$	$c : SU(2) \times SU(4) \times U(1)' \to SU(3)_c \times SU(2)_L \times U(1)_Y$

c_i: dimensionless free parameters
a, b, c: gauge indices
$M, N = 0, 1, 2, 3, 5 / \mu, \nu = 0, 1, 2, 3$

Localized gauge kinetic terms help us reproduce fermion mass hierarchy including top quark.



2-3 Lagrangian for the bulk and mirror fermions

Bulk

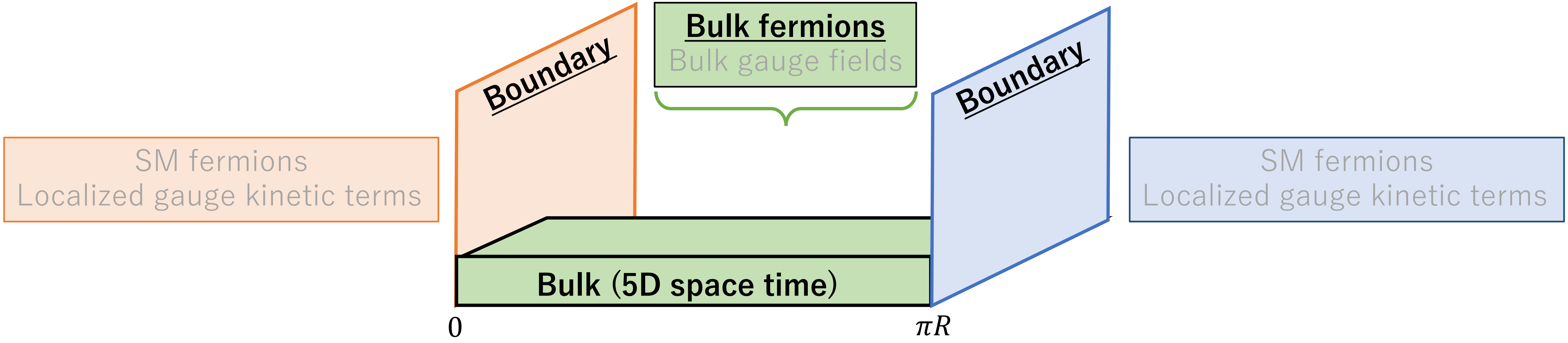
$$\mathcal{L}_{\text{bulk+mirror}} = \underbrace{\bar{\Psi} i \Gamma^M D_M \Psi}_{\text{Bulk fermion } \Psi} + \underbrace{\bar{\tilde{\Psi}} i \Gamma^M D_M \tilde{\Psi}}_{\text{Mirror fermion } \tilde{\Psi}} + \left(M \bar{\Psi} \tilde{\Psi} + \text{h.c.} \right)$$

$\Gamma^M = (\Gamma^\mu, \Gamma^y) = (\gamma^\mu, i\gamma^5)$
M: bulk mass

Bulk fermion Ψ Mirror fermion $\tilde{\Psi}$ with opposite Z_2 parities each other

Mass term to avoid exotic massless fermions

Bulk fermions couple to the SM fermions on the boundary so that the fermion mass hierarchy can be reproduced.

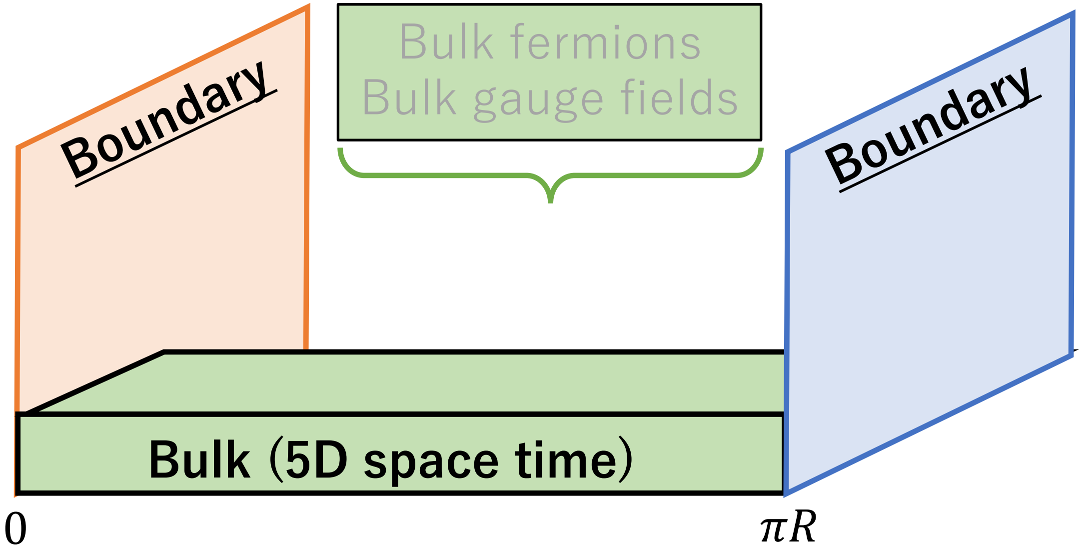


2-4 Lagrangian for the SM fermions in this model

Boundary at $y = 0$ ($j = 1, 2$)	Bulk	Boundary at $y = \pi R$ ($j = 3$)
$\bar{\chi}_{10}^{j} i \Gamma^{\mu} D_{\mu} \chi_{10}^{j}$		$\overline{q_L^3} i \Gamma^{\mu} D_{\mu} q_L^3 + \overline{u_R^3} i \Gamma^{\mu} D_{\mu} u_R^3$
$\bar{\chi}_{5^*}^{j} i \Gamma^{\mu} D_{\mu} \chi_{5^*}^{j}$		$\overline{d_R^3} i \Gamma^{\mu} D_{\mu} d_R^3 + \overline{l_L^3} i \Gamma^{\mu} D_{\mu} l_L^3$
$\bar{\chi}_{1}^{j} i \Gamma^{\mu} D_{\mu} \chi_{1}^{j}$		$\overline{e_R^3} i \Gamma^{\mu} D_{\mu} e_R^3 + \overline{\nu_R^3} i \Gamma^{\mu} D_{\mu} \nu_R^3$

j : "Generation" of the SM fermions

SM fermions
Localized gauge kinetic terms

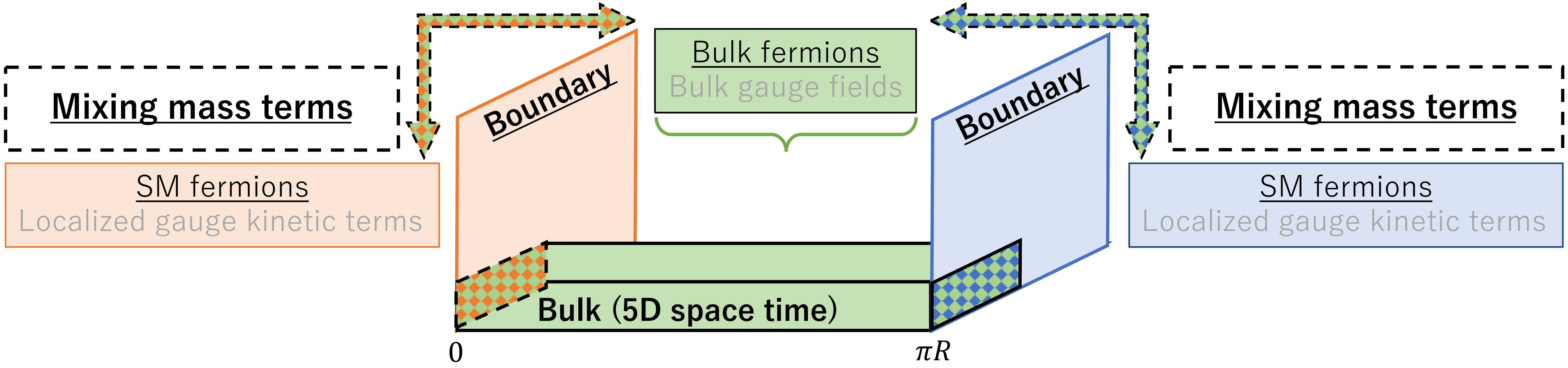


SM fermions
Localized gauge kinetic terms

2-5 Mixing mass terms in this model

Boundary at $y = 0$ $(j = 1, 2)$	Bulk	Boundary at $y = \pi R$ $(j = 3)$
$\epsilon_{20}^{j}\left(\bar{\chi}_{10}^{j}\Psi_{10\subset 20} + \bar{\chi}_{10}^{j,c}\Psi_{10^{*}\subset 20}\right)$	Ψ_{20}	$\epsilon_{20e}\left(\overline{e_R}^{3}E_{20} + \overline{u_R}^{3}U_{20}\right) + \epsilon_{20q}\overline{q_L}^{3}Q_{20}$
……	Ψ_{15}	……
……	$\Psi_{15'}$	
……	Ψ_{6}	……
……	$\Psi_{6'}$	……

The number of the bulk fermions has been reduced from nine to five in this model.



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Gauge coupling unification
in simplified grand gauge-Higgs unification

3-2a Bulk fields and their β function

$(+,+),(-,-)$: periodic fields
$(+,-),(-,+)$: anti-periodic fields

Higher-dimensional RGE

$$\alpha_i^{-1}(\Lambda) = \alpha_i^{-1}(\mu) - \frac{b_i - \tilde{b}_i^{(+)}}{4\pi} \ln\frac{\Lambda}{\mu} - \frac{\tilde{b}_i^{(+)} + \tilde{b}_i^{(-)}}{\pi} R(\Lambda - \mu)$$

$\pm$ in $\tilde{b}_i^{(\pm)}$ means its contribution comes from the **periodic fields $\tilde{b}_i^{(+)}$** or **anti-periodic fields $\tilde{b}_i^{(-)}$**.

Gauge field and its β function

gauge field $SU(6) \to SU(3)_C \times SU(2)_L \times U(1)_Y$
$35^{(+,+)} = (8,1)_0^{(+,+)} \oplus (1,3)_0^{(+,+)} \oplus (1,1)_0^{(+,+)} \oplus (1,1)_0^{(+,+)}$ $\oplus (3,2)_{5/6}^{(+,-)} \oplus (3^*,2)_{-5/6}^{(+,-)} \oplus (3,1)_{-1/3}^{(-,+)} \oplus (3^*,1)_{1/3}^{(-,+)} \oplus (1,2)_{-1/2}^{(-,-)} \oplus (1,2)_{-1/2}^{(-,-)}$

β function (b_3, b_2, b_1)
$(3,0,0)+(0,2,0)+(0,0,0)+(0,0,0)$ $+(1,\frac{3}{2},\frac{5}{2})+(1,\frac{3}{2},\frac{5}{2})+(\frac{1}{2},\frac{3}{2},\frac{1}{5})+(\frac{1}{2},\frac{3}{2},\frac{1}{5})+(0,\frac{1}{2},\frac{3}{10})+(0,\frac{1}{2},\frac{3}{10})$

$SU(3), SU(2)$ representation in the SM — $(r_1, r_2)_a^{(P,P')}$

P, P': Z_2 Parity

a: charges for $U(1)_Y$

3-2b Bulk fields and their β function

$(+,+),(-,-)$: periodic fields
$(+,-),(-,+)$: anti-periodic fields

Higher-dimensional RGE

$$\alpha_i^{-1}(\Lambda) = \alpha_i^{-1}(\mu) - \frac{b_i - \tilde{b}_i^{(+)}}{4\pi}\ln\frac{\Lambda}{\mu} - \frac{\tilde{b}_i^{(+)} + \tilde{b}_i^{(-)}}{\pi}R(\Lambda-\mu)$$

$\pm$ in $\tilde{b}_i^{(\pm)}$ means its contribution comes from the **periodic fields $\tilde{b}_i^{(+)}$** or **anti-periodic fields $\tilde{b}_i^{(-)}$**.

Bulk fermion (20 rep.) and its β function

bulk fermion $SU(5) \to SU(3)_C \times SU(2)_L \times U(1)_Y$	β function $(\tilde{b}_3, \tilde{b}_2, \tilde{b}_1)$
$10 = Q_{20}(3,2)^{(+,+)}_{1/6} \oplus U^*_{20}(3^*,1)^{(+,-)}_{-2/3} \oplus E^*_{20}(1,1)^{(+,-)}_{1}$	$(1,\ \frac{3}{2},\ \frac{1}{10}),\ (\frac{1}{2},\ 0,\ \frac{4}{5}),\ (0,\ 0,\ \frac{3}{5})$
$10^* = Q^*_{20}(3^*,2)^{(-,-)}_{-1/6} \oplus U_{20}(3,1)^{(-,+)}_{2/3} \oplus E_{20}(1,1)^{(-,+)}_{-1}$	$(1,\ \frac{3}{2},\ \frac{1}{10}),\ (\frac{1}{2},\ 0,\ \frac{4}{5}),\ (0,\ 0,\ \frac{3}{5})$

$SU(3), SU(2)$ representation in the SM

$(r_1, r_2)^{(P,P')}_{a}$

P, P': Z_2 Parity

a: charges for $U(1)_Y$

3-3a Perturbative gauge coupling unification

(+, +), (−, −): periodic fields
(+, −), (−, +): anti-periodic fields

Higher-dimensional RGE

$$\alpha_i^{-1}(\Lambda) = \alpha_i^{-1}(\mu) - \frac{b_i - \tilde{\boldsymbol{b}}_i^{(+)}}{4\pi}\ln\frac{\Lambda}{\mu} - \frac{\tilde{\boldsymbol{b}}_i^{(+)} + \tilde{\boldsymbol{b}}_i^{(-)}}{\pi} R(\Lambda - \mu)$$

$\pm$ in $\tilde{b}_i^{(\pm)}$ means its contribution comes from the **periodic fields** $\tilde{\boldsymbol{b}}_i^{(+)}$ or **anti-periodic fields** $\tilde{\boldsymbol{b}}_i^{(-)}$.

Asymptotic freedom of gauge couplings can be confirmed by the fact that the beta function $\tilde{\boldsymbol{b}}_i^{(+)} + \tilde{\boldsymbol{b}}_i^{(-)}$ is **negative**.

Using the tables shown in the previous slides

$$\tilde{\boldsymbol{b}}_i^{(+)} + \tilde{\boldsymbol{b}}_i^{(-)} = -\frac{2}{3} < \mathbf{0}.$$

<u>The perturbative gauge coupling unification is indeed realized</u>.

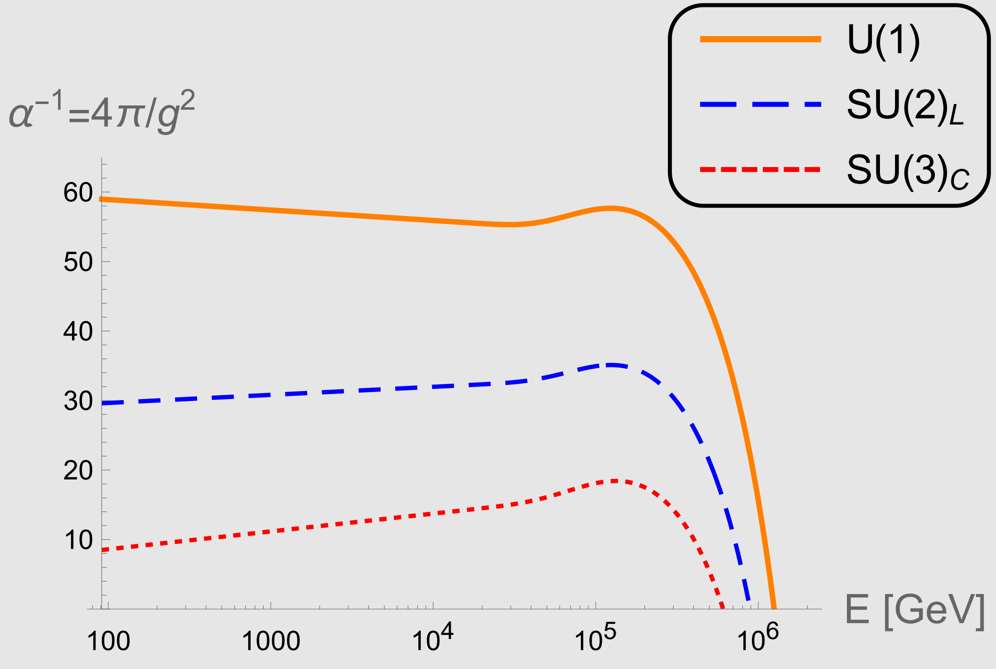
3-3b Perturbative gauge coupling unification

Higher-dimensional RGE

$$\alpha_i^{-1}(\Lambda) = \alpha_i^{-1}(\mu) - \frac{b_i - \tilde{b}_i^{(+)}}{4\pi} \ln\frac{\Lambda}{\mu} - \frac{\tilde{b}_i^{(+)} + \tilde{b}_i^{(-)}}{\pi} R(\Lambda - \mu)$$

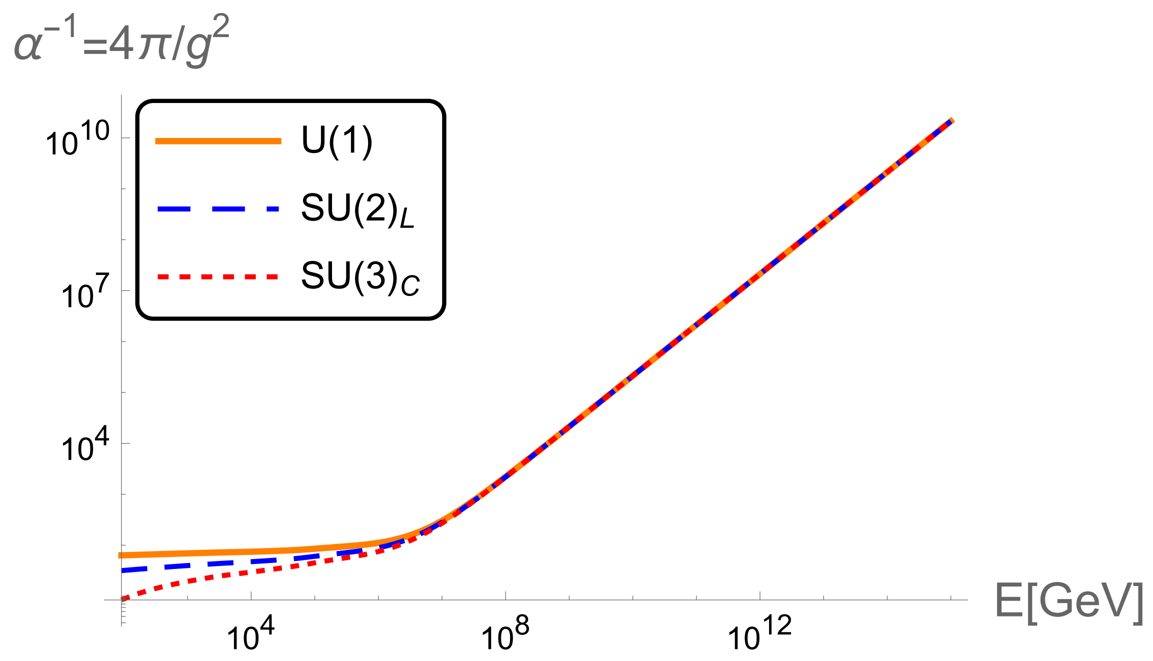
In the previous model

[N. Maru, Y. Yatagai (2020)]

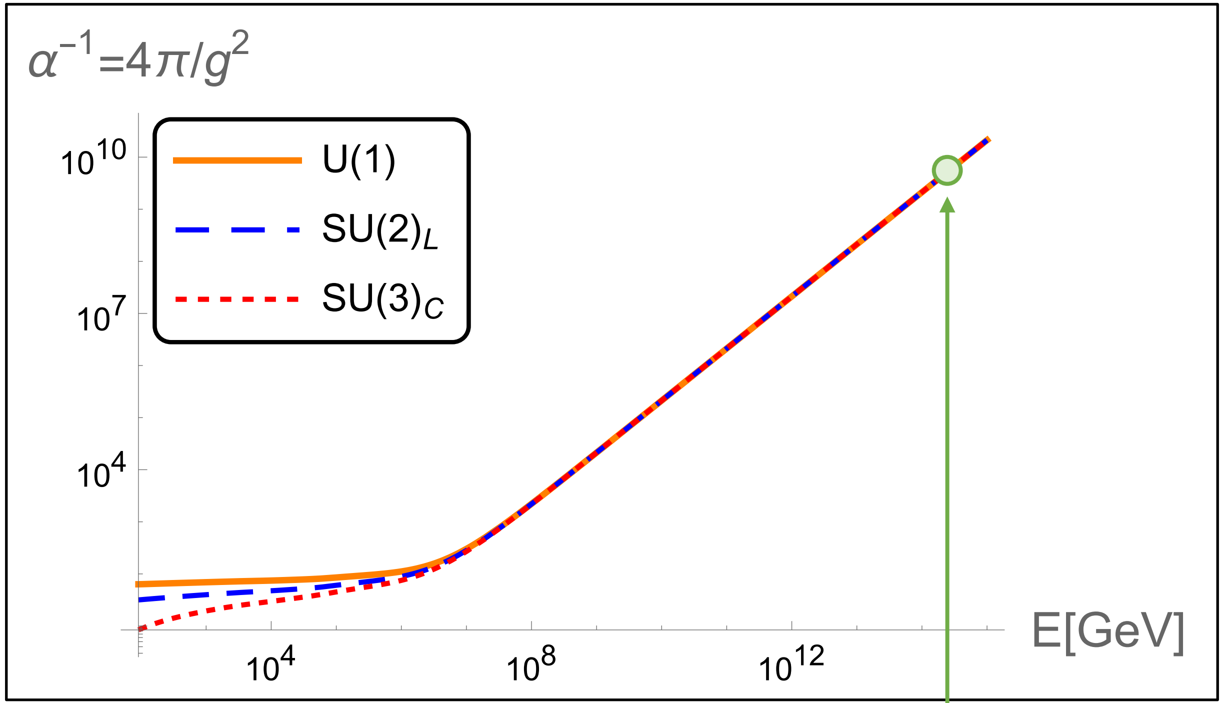


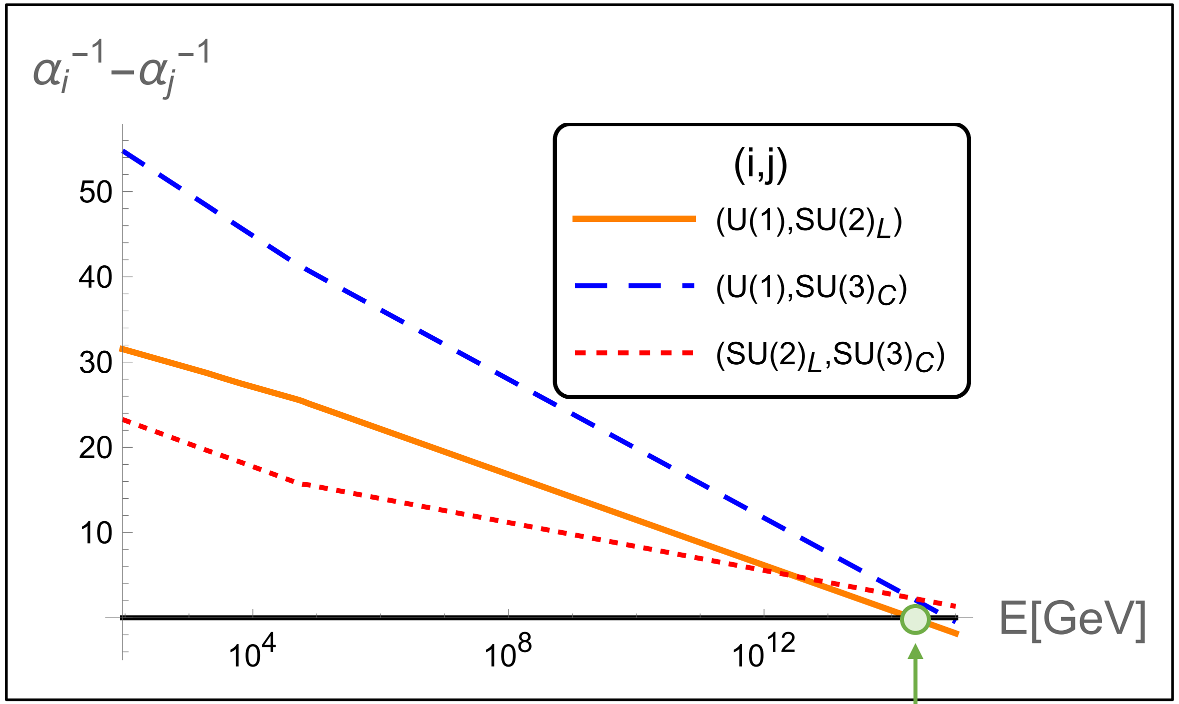
In this model

[N. Maru, HT, Y. Yatagai (2022)]



3-4a GUT scale





α_G^{-1} : unification coupling

M_G : unification scale

3-4b GUT scale

$$\alpha_i^{-1}(\Lambda) = \alpha_i^{-1}(\mu) - \frac{b_i - \tilde{b}_i^{(+)}}{4\pi}\ln\frac{\Lambda}{\mu} - \frac{\tilde{b}_i^{(+)} + \tilde{b}_i^{(-)}}{\pi}R(\Lambda - \mu)$$

$$-)\quad \alpha_j^{-1}(\Lambda) = \alpha_j^{-1}(\mu) - \frac{b_j - \tilde{b}_j^{(+)}}{4\pi}\ln\frac{\Lambda}{\mu} - \frac{\tilde{b}_j^{(+)} + \tilde{b}_j^{(-)}}{\pi}R(\Lambda - \mu)$$

$$\alpha_i^{-1} - \alpha_j^{-1} = \alpha_i^{-1}(\mu) - \alpha_j^{-1}(\mu) - \frac{(b_i - b_j) - (\tilde{b}_i^{(+)} - \tilde{b}_j^{(+)})}{4\pi}\ln\frac{\Lambda}{\mu}$$

$\tilde{b}_i^{(+)} + \tilde{b}_i^{(-)} (i = 1, 2, 3)$ are common. The running of $\alpha_i^{-1} - \alpha_j^{-1}$ are dominated by the logarithmic terms.

3-4c GUT scale

c	R^{-1}	M_G	α_G^{-1}	$\lvert(\alpha_G^{-1} - \alpha_3^{-1})/\alpha_G^{-1}\rvert$
80	10 TeV	2.1×10^{14} GeV	4.4×10^{9}	5.26×10^{-10}
80	15 TeV	2.2×10^{14} GeV	3.2×10^{10}	6.12×10^{-10}
90	10 TeV	2.1×10^{14} GeV	4.3×10^{9}	5.25×10^{-10}
90	15 TeV	2.3×10^{14} GeV	3.2×10^{9}	6.1×10^{-10}

GUT scale

The GUT scale in our model was found to be 10^{14} GeV, which is a few smaller than the 4D one 10^{15-16} GeV.

Accuracy of the grand unification

The difference $\lvert(\alpha_G^{-1} - \alpha_3^{-1})/\alpha_G^{-1}\rvert$ at M_G is around 5×10^{-10}.
Three gauge couplings are unified with an accuracy of 10^{-10}.

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4 Summary

5D SU(6) grand gauge-Higgs unification has been discussed.

N. Maru, HT, Y. Yatagai, arXiv:2205.05824 [hep-ph]

- The number of the bulk fermions is reduced in order to achieve **perturbative gauge coupling unification** which could not be realized in the previous model.
- Fermion mass hierarchy and its mixing are reproduced.

N. Maru, HT, Y. Yatagai, arXiv:2207.10253 [hep-ph]

- **Perturbative gauge coupling unification is indeed realized in our model**.

→This can be a good starting point for constructing a realistic model of GGHU.

Future work

Proton decay

Investigate the main mode of the proton decay in our model and give predictions of its life time for experiments.