Fermion mass hierarchy in simplified grand gauge-Higgs unification

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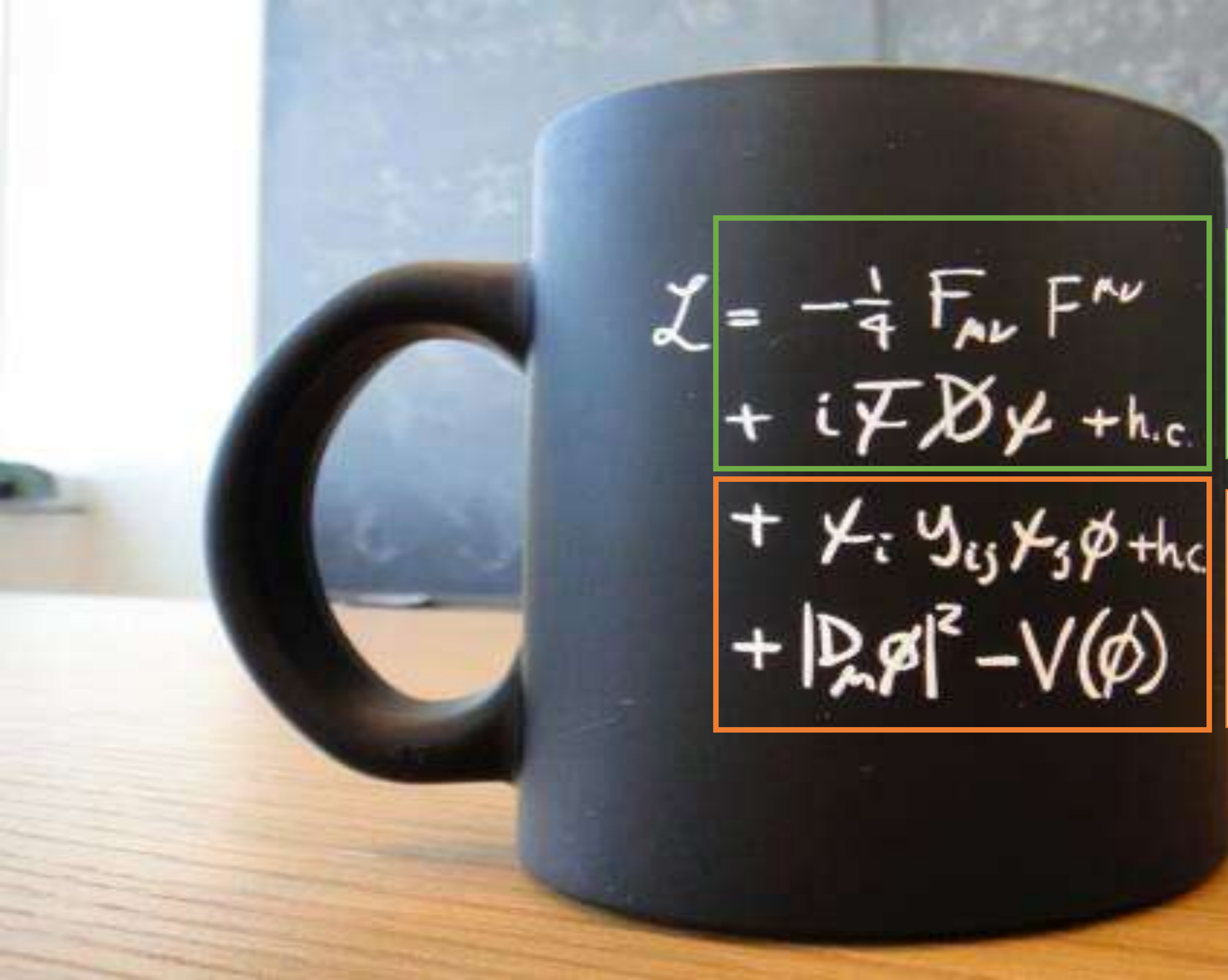
Based on:
N. Maru, **HT**, Y. Yatagai, arXiv:2205.05824 [hep-ph]

Physics in LHC and Beyond, Matsue and online, May 14 2022

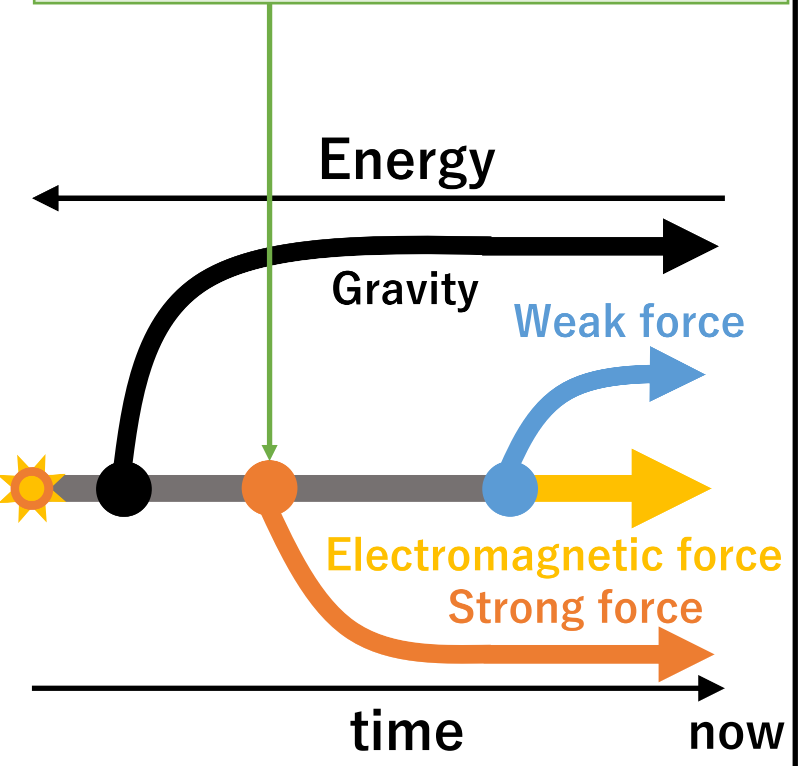


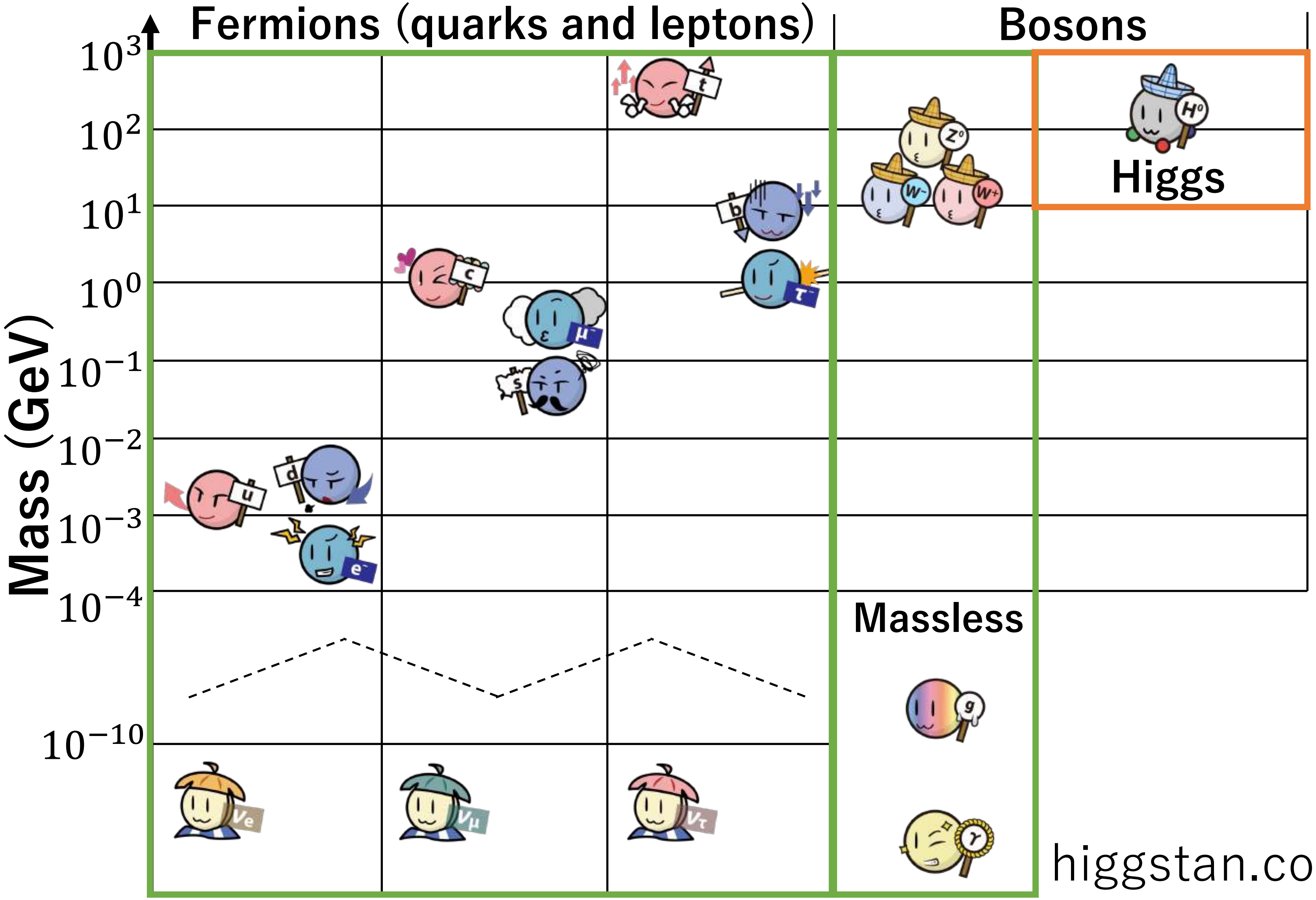
Grand unification

Hierarchy problem

Grand Unification

Grand unified theory





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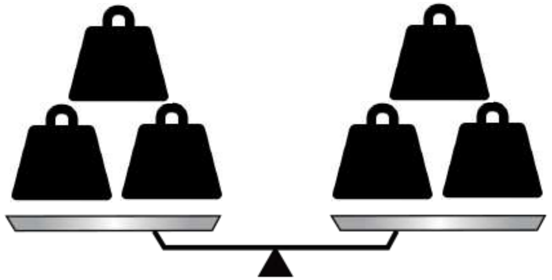
Hierarchy Problem

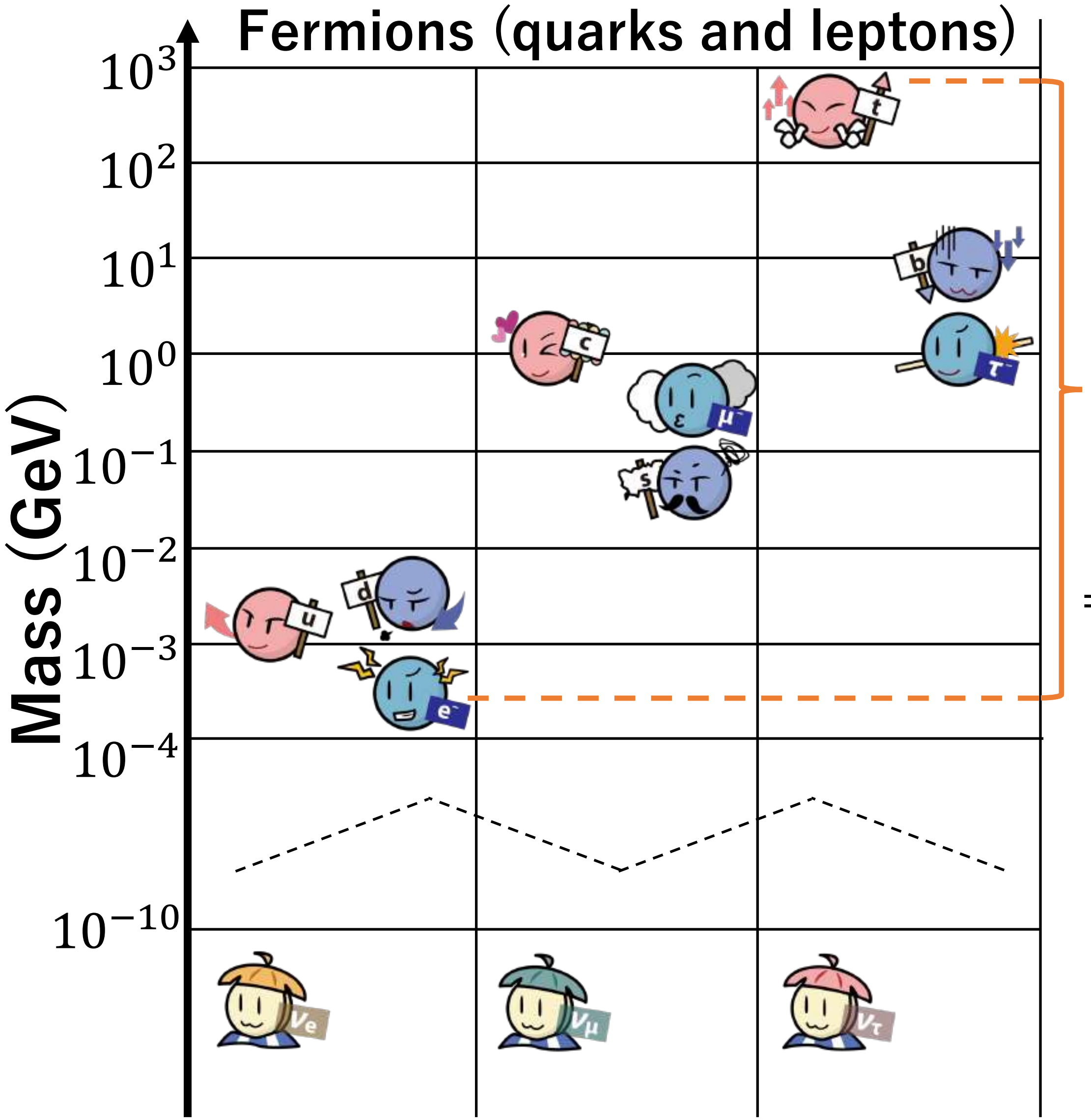
Unnatural fine tuning

$$m_H^2 = m_0^2 + \delta m^2$$

125 GeV 10^{18} GeV 10^{18} GeV

bare mass	quantum correction
m_0^2	$\delta m^2 \propto -\Lambda^2$





Mass hierarchy

$$\frac{y_t}{y_e} = \frac{m_t}{m_e} \approx \frac{173\ \text{GeV}}{0.51\ \text{MeV}} \approx \mathbf{3.4\times10^5}$$

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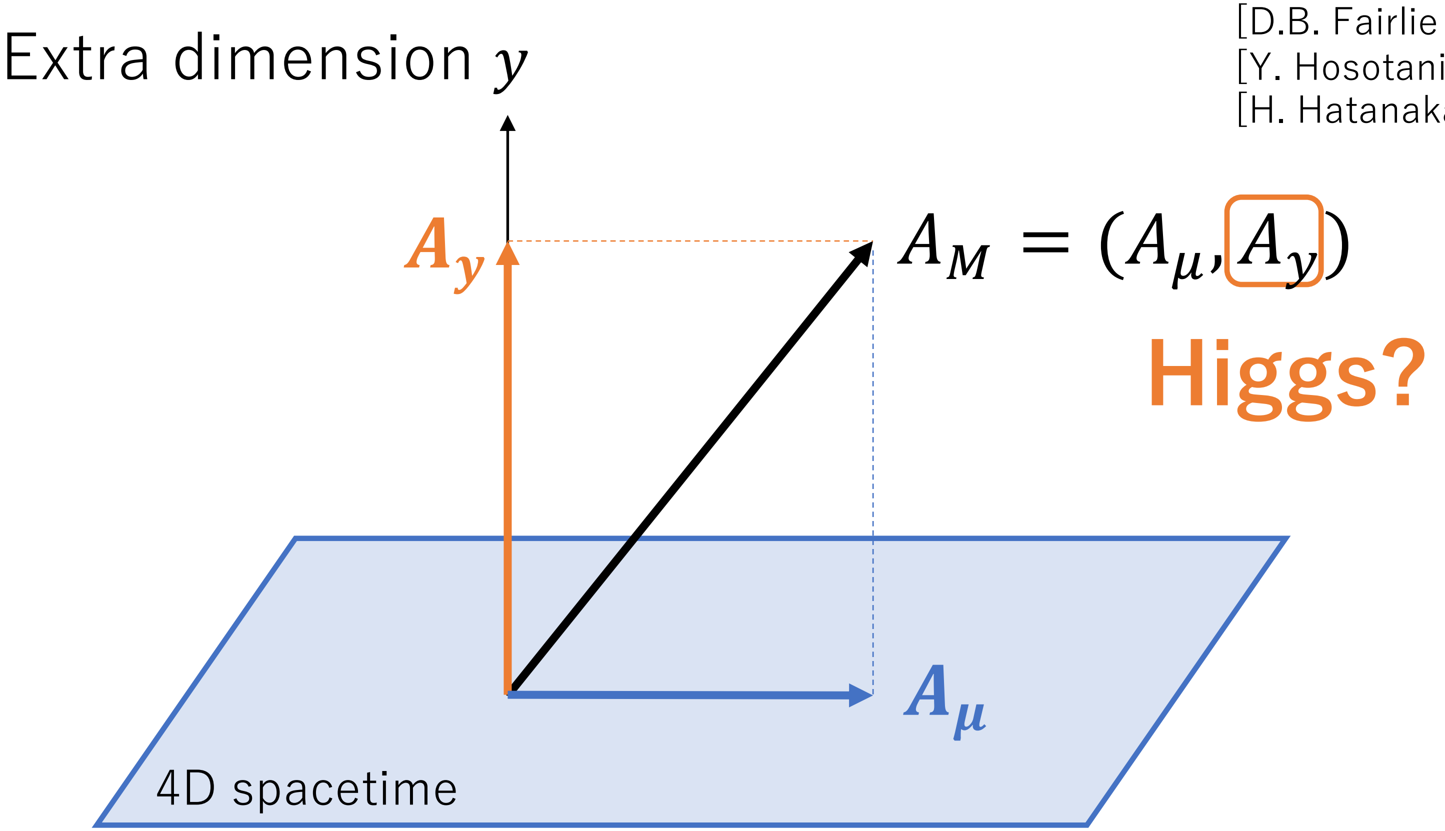
Beyond the Standard Model

Gauge-Higgs Unification (GHU)

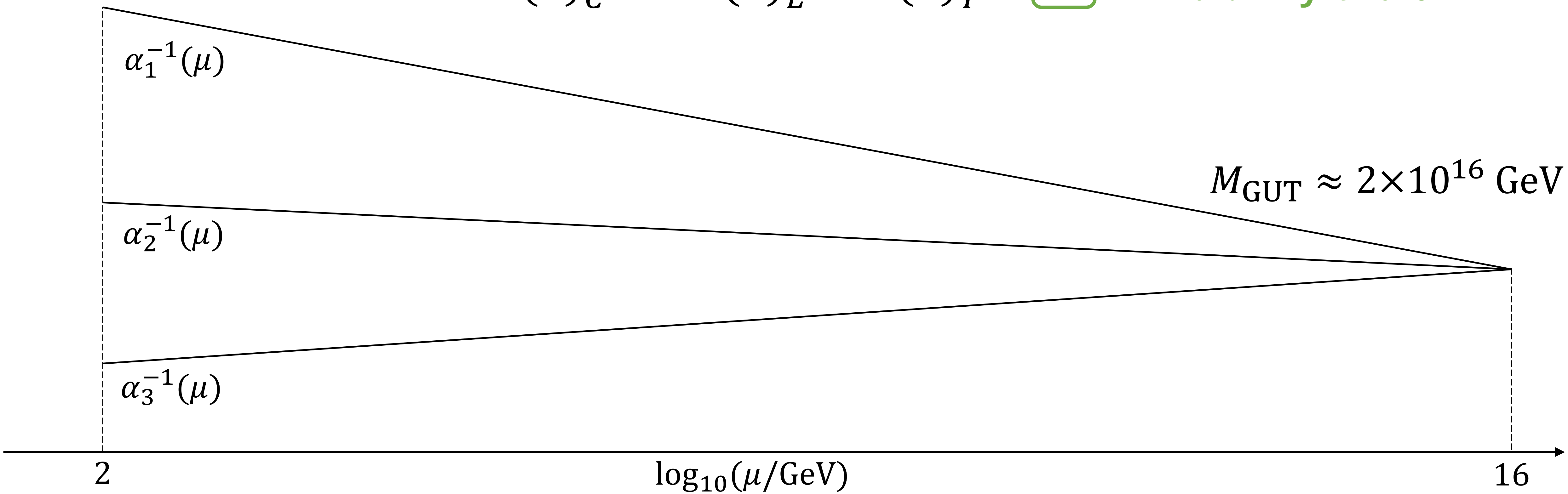
[D.B. Fairlie (1979)][N.S. Manton (1979)]
[Y. Hosotani (1983)]
[H. Hatanaka, T. Inami, C.S. Lim (1998)]



Beyond the Standard Model

Grand Unified Theory (GUT)

$SU(3)_C \times SU(2)_L \times U(1)_Y \subset$?? **Who unify the SM?**

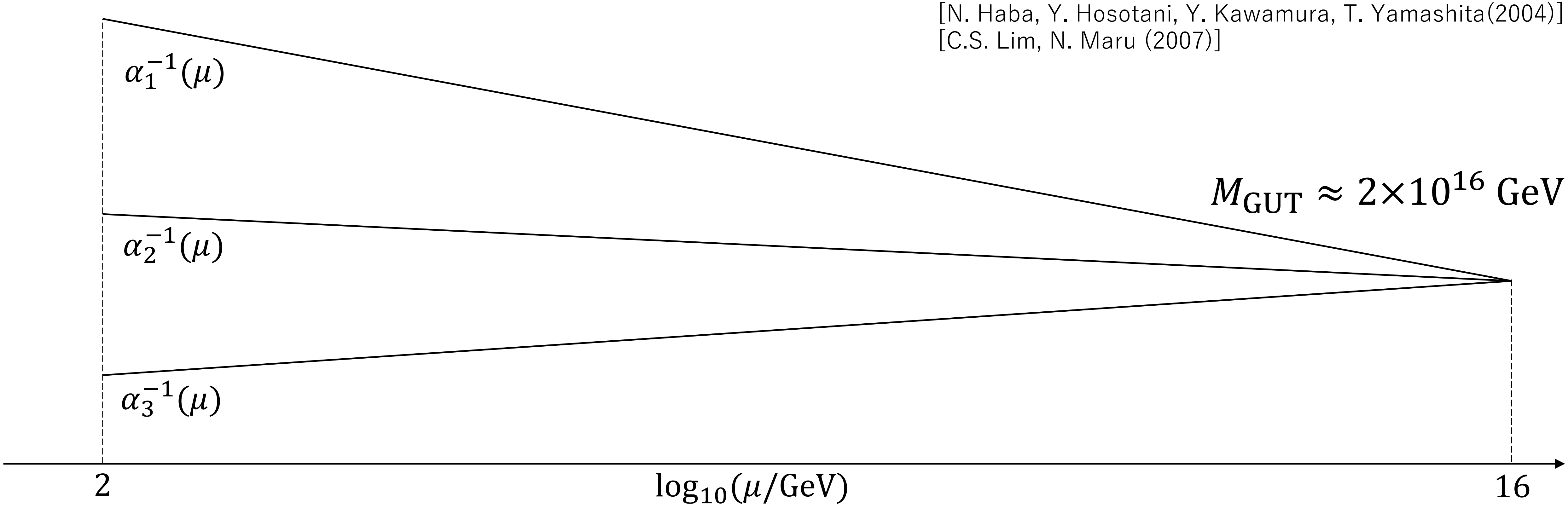


Beyond the Standard Model

Grand Gauge Higgs Unification (GGHU)

GHU + GUT → GGHU   **5D SU(6) GGHU?**

[G. Burdman, Y. Nomura (2003)]
[N. Haba, Y. Hosotani, Y. Kawamura, T. Yamashita(2004)]
[C.S. Lim, N. Maru (2007)]



5D SU(6) Grand Gauge-Higgs Unification

Fermion mass hierarchy

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

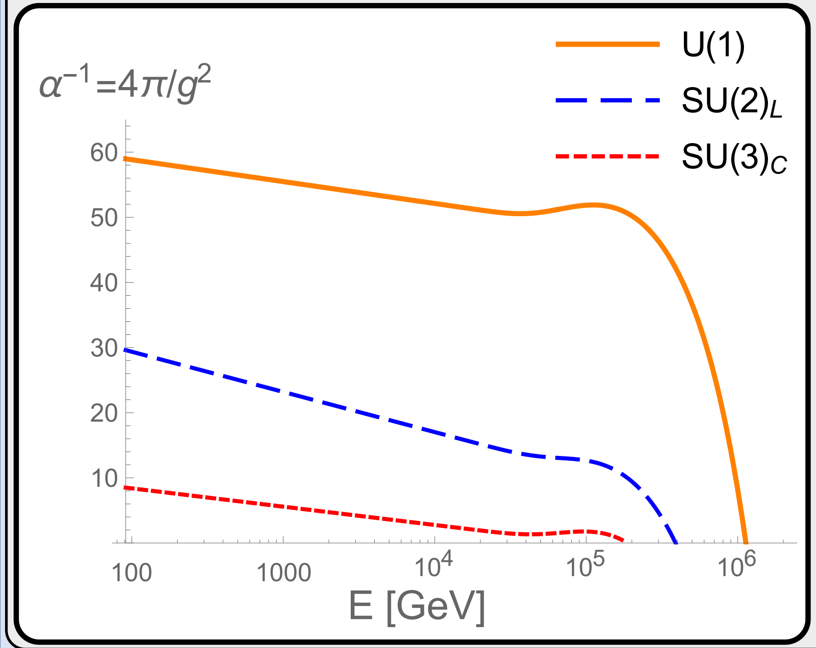
The SM fermion mass hierarchy including top quark can be realized by introducing localized gauge kinetic terms.

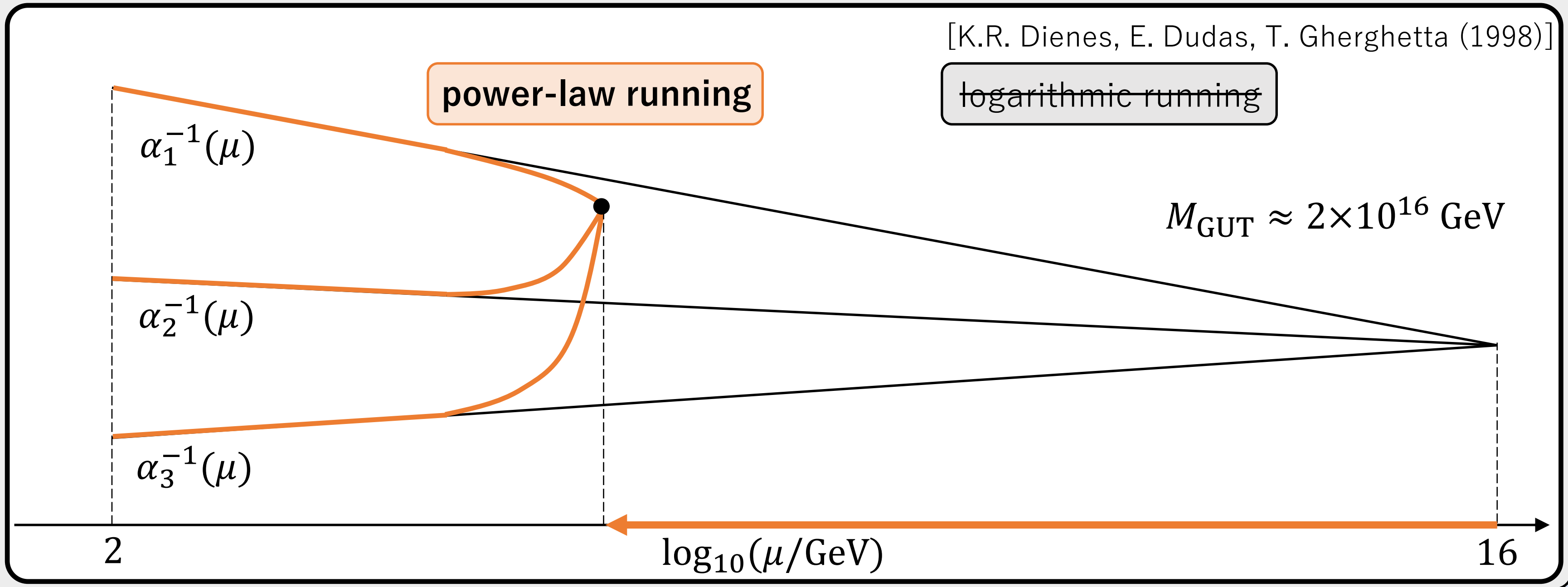
Gauge coupling unification

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

Simplification

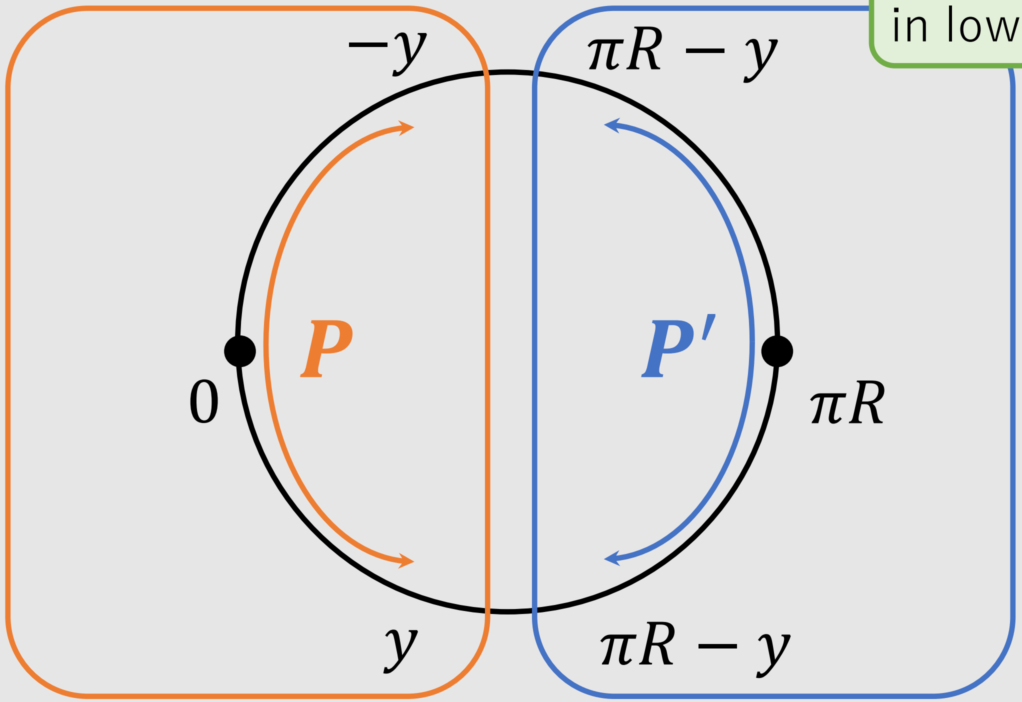
We **reduced the number of them.**





Orbifold Breaking

Orbifold S^1/Z_2



(+,+) only survive in low energy EFT

Assign Z_2 Parity

$$P = \mathrm{diag}(+,+,+,+,+,-)$$

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

Orbifold Breaking

$$A_\mu = \begin{pmatrix} (+,+) & (+,+) & (+,-) & (+,-) & (+,-) & (-,-) \\ (+,+) & (+,+) & (+,-) & (+,-) & (+,-) & (-,-) \\ (+,-) & (+,-) & (+,+) & (+,+) & (+,+) & (-,+) \\ (+,-) & (+,-) & (+,+) & (+,+) & (+,+) & (-,+) \\ (+,-) & (+,-) & (+,+) & (+,+) & (+,+) & (-,+) \\ (-,-) & (-,-) & (-,+) & (-,+) & (-,+) & (+,+) \end{pmatrix}$$

$$SU(6) \to SU(2)_L \times SU(3)_C \times U(1)_Y \times U(1)_X$$

$$A_y = \begin{pmatrix} (-,-) & (-,-) & (-,+) & (-,+) & (-,+) & (+,+) \\ (-,-) & (-,-) & (-,+) & (-,+) & (-,+) & (+,+) \\ (-,+) & (-,+) & (-,-) & (-,-) & (-,-) & (+,-) \\ (-,+) & (-,+) & (-,-) & (-,-) & (-,-) & (+,-) \\ (-,+) & (-,+) & (-,-) & (-,-) & (-,-) & (+,-) \\ (+,+) & (+,+) & (+,-) & (+,-) & (+,-) & (-,-) \end{pmatrix}$$

SM Higgs field is identified with **this part**

Gauge sector with localized gauge kinetic terms

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4}\mathcal{F}^{a\,MN}\mathcal{F}^{a}_{MN} - 2\pi R c_1 \delta(y)\frac{1}{4}\mathcal{F}^{b\,\mu\nu}\mathcal{F}^{b}_{\mu\nu} - 2\pi R c_2 \delta(y-\pi R)\frac{1}{4}\mathcal{F}^{c\,\mu\nu}\mathcal{F}^{c}_{\mu\nu}$$

$a : SU(6)$

c_i : dimensionless free parameters

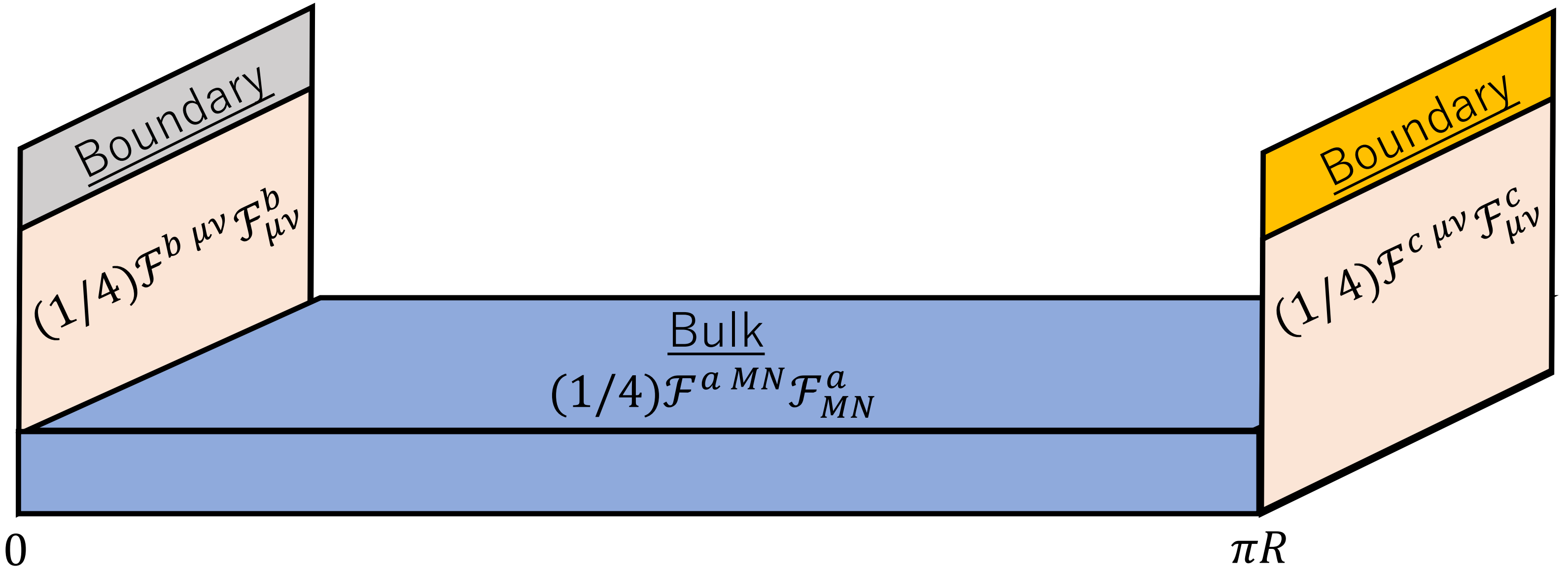
$c = c_1 + c_2$

Boundary at $y = 0$

$b : SU(5) \times U(1)_X \to SU(5)$

Boundary at $y = \pi R$

$c : SU(2) \times SU(4) \times U(1)' \to SU(3)_c \times SU(2)_L \times U(1)_Y$



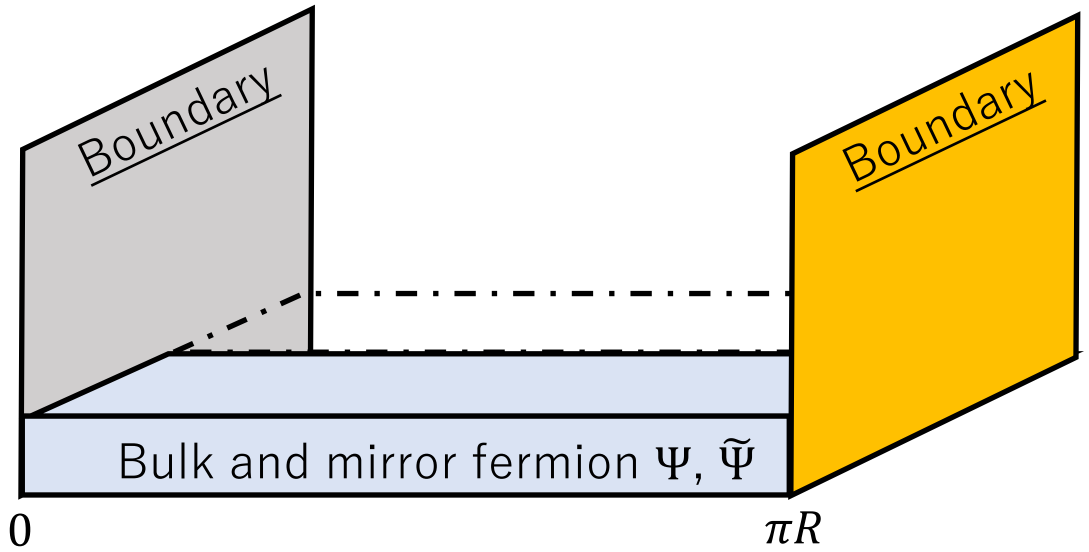
Lagrangian for the bulk and mirror fermions

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

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

$M = \frac{\lambda}{\pi R}$
dimensionless parameters

Mass term in the bulk
to avoid exotic massless fermions

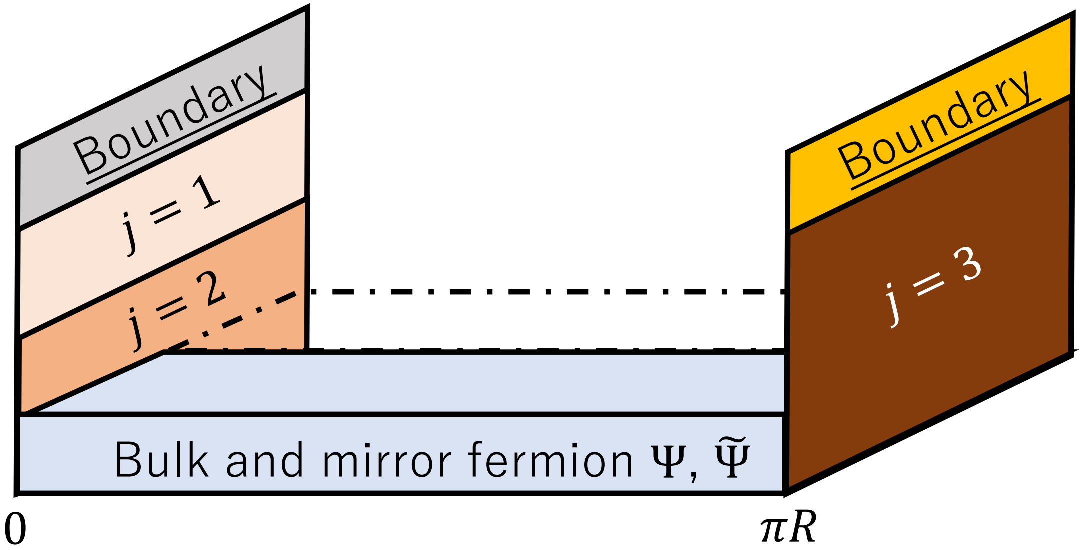


Lagrangian for the SM fermions

$$\mathcal{L}_{\mathrm{SM}}^{j=1,2} = \delta(y)\left[\bar{\chi}_{10}^{j} i\Gamma^{\mu} D_{\mu} \chi_{10}^{j} + \bar{\chi}_{5^*}^{j} i\Gamma^{\mu} D_{\mu} \chi_{5^*}^{j} + \bar{\chi}_{1}^{j} i\Gamma^{\mu} D_{\mu} \chi_{1}^{j}\right]$$

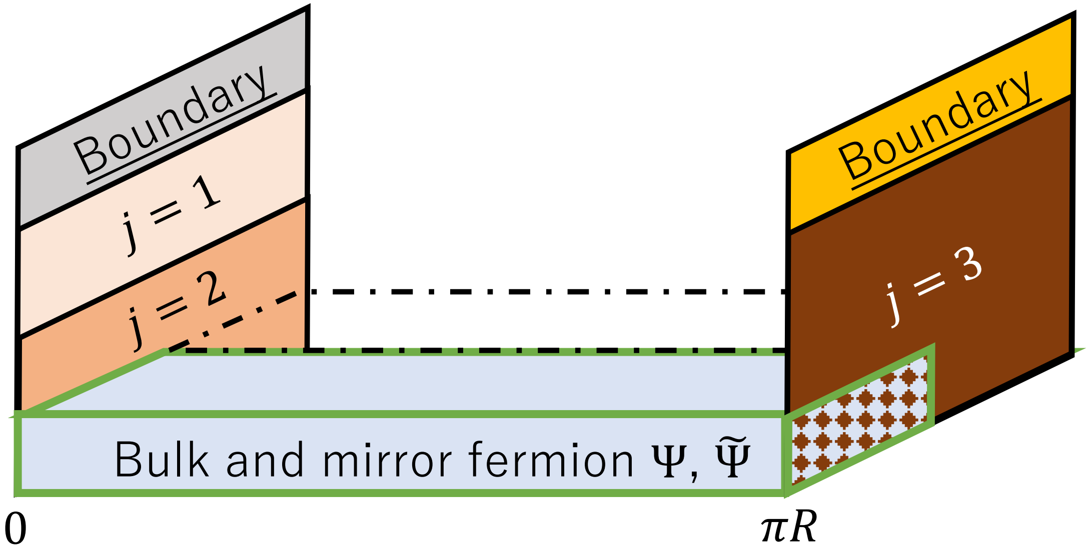
$$\mathcal{L}_{\mathrm{SM}}^{j=3} = \delta(y-\pi R)\left[\overline{q_L^3} i\Gamma^{\mu} D_{\mu} q_L^3 + \overline{u_R^3} i\Gamma^{\mu} D_{\mu} u_R^3 + \overline{d_R^3} i\Gamma^{\mu} D_{\mu} d_R^3 + \overline{l_L^3} i\Gamma^{\mu} D_{\mu} l_L^3 + \overline{e_R^3} i\Gamma^{\mu} D_{\mu} e_R^3 + \overline{\nu_R^3} i\Gamma^{\mu} D_{\mu} \nu_R^3\right]$$

j : "Generation" of the SM fermions



Mixing mass terms between the bulk fermions and the SM fermions

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



Mixing mass terms between the bulk fermions and the SM fermions

$$\mathcal{L}_{\rm SM} = \delta(y)\left[\bar{\psi}_{{\rm SM}\,L} i\Gamma^\mu D_\mu \psi_{{\rm SM}\,L} + \cdots\right]$$

$$\mathcal{L}_{\rm SM+bulk} = \delta(y)\{\epsilon\bar{\psi}_{\rm SM}\Psi + \cdots\}$$

$$\mathcal{L}_{\rm SM} = \delta(y)\left[\bar{\psi}_{{\rm SM}\,R} i\Gamma^\mu D_\mu \psi_{{\rm SM}\,R} + \cdots\right]$$

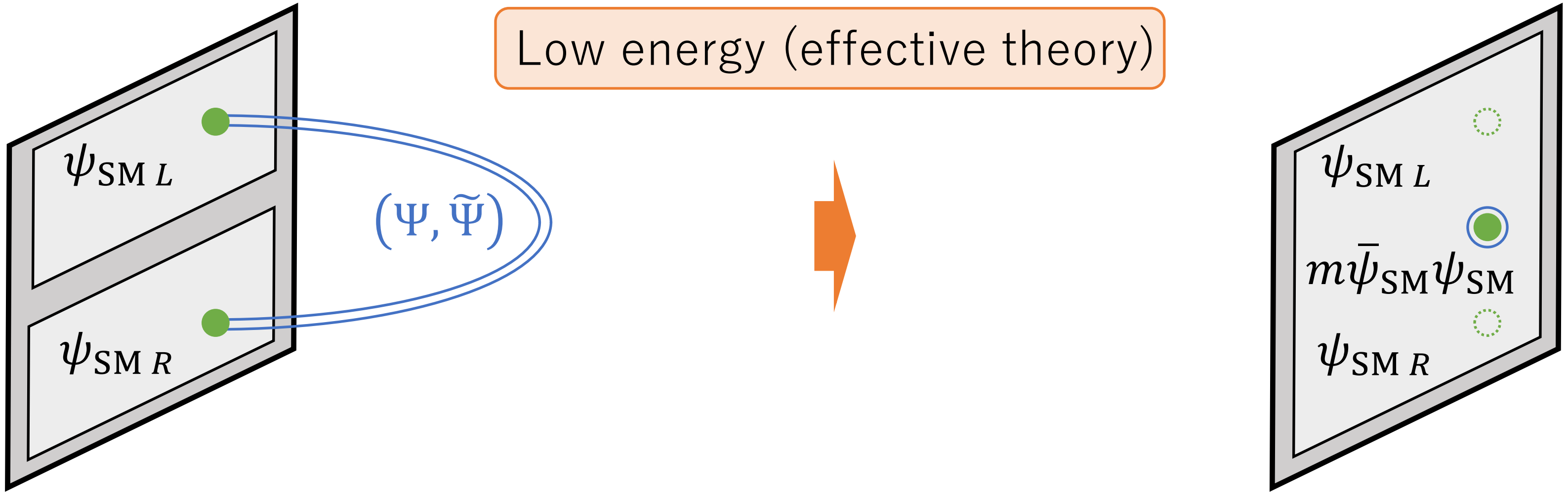
$$\mathcal{L}_{\rm bulk+mirror} = \bar{\Psi} i\Gamma^M D_M \Psi + \bar{\tilde{\Psi}} i\Gamma^M D_M \tilde{\Psi} + \left(M\bar{\Psi}\tilde{\Psi} + {\rm h.c.}\right)$$

$$\mathcal{L}_{\rm SM} = \delta(y)\left[\bar{\psi}_{{\rm SM}\,L} i\Gamma^\mu D_\mu \psi_{{\rm SM}\,L} + \cdots\right]$$

$$m\bar{\psi}_{\rm SM}\psi_{\rm SM}$$

$$\mathcal{L}_{\rm SM} = \delta(y)\left[\bar{\psi}_{{\rm SM}\,R} i\Gamma^\mu D_\mu \psi_{{\rm SM}\,R} + \cdots\right]$$

Mixing mass terms between the SM fermions and the bulk fermions produce the SM fermion masses.



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c	m_u	m_c	m_t
70	1.724 MeV	1.291 GeV	181.918 GeV
75	2.413 MeV	1.271 GeV	177.497 GeV
80	2.223 MeV	1.290 GeV	178.684 GeV
Data	$2.16^{+0.49}_{-0.26}$ MeV	1.27 ± 0.02 GeV	172 ± 0.30 GeV

c	m_d	m_s	m_b
70	5.119 MeV	94.0 MeV	4.928 GeV
75	4.727 MeV	85.2 MeV	5.090 GeV
80	4.856 MeV	84.5 MeV	5.150 GeV
Data	$4.67^{+0.48}_{-0.17}$ MeV	93^{+11}_{-5} MeV	$4.18^{+0.13}_{-0.02}$ GeV

c	$\sin\theta_{12}$	$\sin\theta_{13}$	$\sin\theta_{23}$	δ
70	0.157976	0.003336	0.041942	0.9834
75	0.165093	0.003767	0.048009	1.3759
80	0.168864	0.003985	0.044065	1.3053
Data	0.22650 ± 0.00048	$0.00361^{+0.00011}_{-0.00009}$	$0.04053^{+0.00083}_{-0.00061}$	$1.196^{+0.045}_{-0.043}$

https://pdg.lbl.gov

c	m_e	m_μ	m_τ
70	0.5093 MeV	106.358 MeV	1912.20 MeV
75	0.5125 MeV	103.804 MeV	1856.99 MeV
80	0.5100 MeV	105.381 MeV	1899.96 MeV
Data	0.5109989461(31) MeV	105.6583745(24) MeV	1776.86(12) MeV

c	Δm_{21}^2	Δm_{32}^2 (Normal)
70	7.7514×10^{-5} eV^2	2.4777×10^{-3} eV^2
75	7.6760×10^{-5} eV^2	2.4367×10^{-3} eV^2
80	7.7279×10^{-5} eV^2	2.4670×10^{-3} eV^2
Data	$(7.53\pm0.18)\times10^{-5}$ eV^2	$(2.453\pm0.033)\times10^{-3}$ eV^2

c	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$ (Normal)	δ
70	0.4421	2.234×10^{-2}	0.5200	1.729π rad
75	0.4567	2.127×10^{-2}	0.5197	1.626π rad
80	0.3855	2.225×10^{-2}	0.4108	1.916π rad
Data	0.307 ± 0.013	$(2.20\pm0.07)\times10^{-2}$	0.546 ± 0.021	$1.36^{+0.20}_{-0.16}\,\pi$ rad

Summary

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

・**The number of the bulk fermions is reduced.**

→**Simplified model** is expected to realize perturbative gauge coupling unification.

・**Fermion mass hierarchy and its mixing** are reproduced.

Future work

- Reanalyzing electroweak symmetry breaking and Higgs mass
- Gauge coupling unification
- Proton decay