Little Higgs models

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目次

1. Overview

SLAC Summer Institute 2002, H. Georgi ---

The motivation for little Higgs models is that there is pretty strong circumstantial evidence from the success of the Standard Model at the level of radiative corrections that the Higgs boson exists with a mass small compared to 1TeV.

〜中略〜

We want "natural" cancellation of quadratic divergence --- not fine tuning!

1. Overview

Natural cancellation を起こす強力な武器は：

対称性

Little Higgs model の仮定その１：

理論が global 対称性 G を持つ

Little Higgs model の仮定その２：

その G は部分群 H に自発的に破れる

1. Overview

Little Higgs model の仮定その３：

G/H の NG boson に Higgs doublet

と identify できるものが存在する

Little Higgs model の仮定その４：

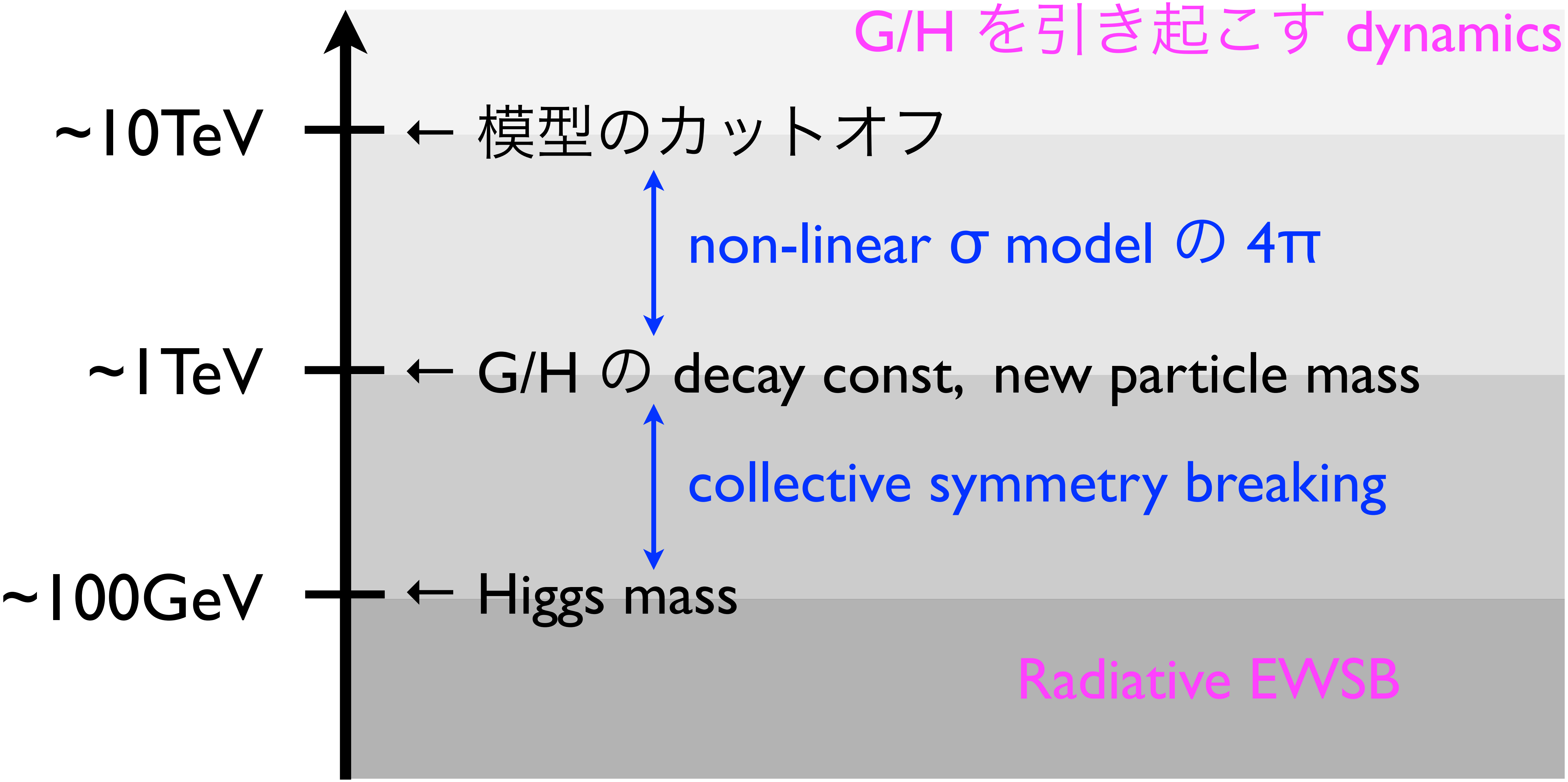
Higgs に small mass を与える

explicit breaking が存在する

（collective symmetry breaking）

1. Overview

Little Higgs model の エネルギースケールの構造



1. Overview

Little Higgs model とはなにかを

まとめて言うと・・・

・G/H gauged non-linear sigma model + fermion

・Higgs は pseudo NG boson

・Collective symmetry breaking が Higgs mass への radiative correction を制御

・EWSB は Coleman-Weinberg 的に

2. Collective symmetry breaking

Deconstruction から（と共に？）生まれた概念

↑

Arkani-Hamed 氏はそう言っていました。

N. Arkani-Hamed, A.G. Cohen and H. Georgi,
``(De)constructing dimensions,''
Phys. Rev. Lett. 86, 4757 (2001)
[arXiv:hep-th/0104005].

N. Arkani-Hamed, A.G. Cohen and H. Georgi,
``Electroweak symmetry breaking from dimensional deconstruction,''
Phys. Lett. B513, 232 (2001)
[arXiv:hep-ph/0105239].

Collective symmetry breaking がない例：

$\pi^+ - \pi^0$ mass difference
in the Chiral Lagrangian + QED

$$G = SU(2)_L \times SU(2)_R$$

$H = SU(2)_V \longrightarrow \tau^3$ の部分をゲージ化することにより

$U(1)_{EM}$ に explicit にやぶれる

$$\mathcal{L} = \frac{f^2}{4} \mathrm{Tr}\left[(D_\mu U)^\dagger (D^\mu U) \right]$$

where $D_\mu U = \partial_\mu U - ie \frac{\tau^3}{2} B_\mu U + ieU \frac{\tau^3}{2} B_\mu$

$U = e^{i\tau^a \pi^a / f_\pi}$: pion, $\quad B_\mu$: photon

Collective symmetry breaking がない例：

２次発散の diagram が描けてしまう

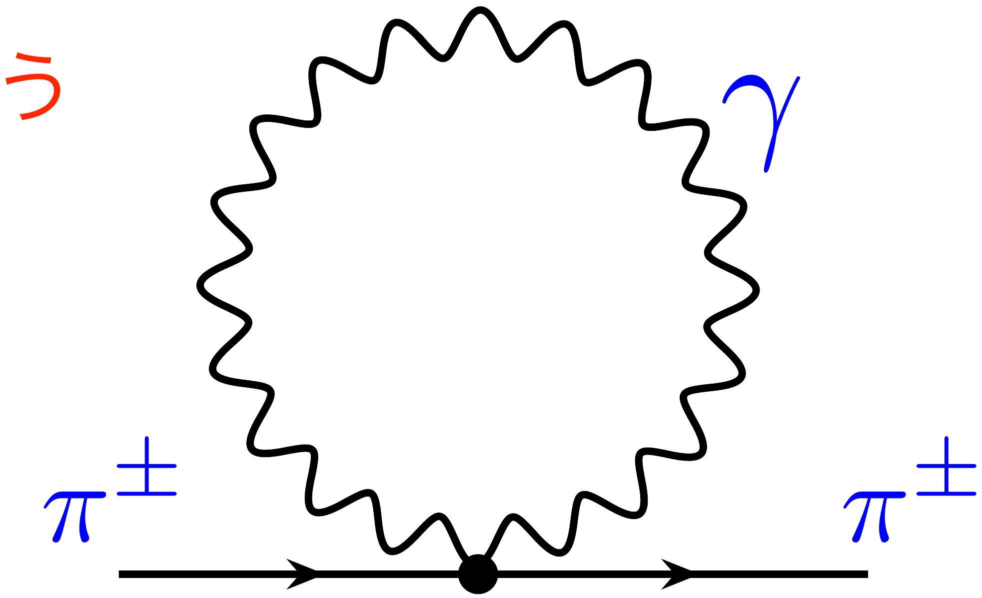
$\uparrow$

$\pi^+\pi^-\gamma\,\gamma$ vertex が存在

$\uparrow$

$$e^2 \mathrm{Tr}\left[\tau^3 U^\dagger \tau^3 U\right] B_\mu B^\mu$$

$\uparrow$



$$\sim\ e^2 \frac{\Lambda^2}{(4\pi)^2}\ \sim\ e^2 \frac{(4\pi f_\pi)^2}{(4\pi)^2}\ \sim\ e^2 f_\pi^2$$

$$\mathcal{L} = \frac{f^2}{4} \mathrm{Tr}\left[(D_\mu U)^\dagger (D^\mu U)\right]$$

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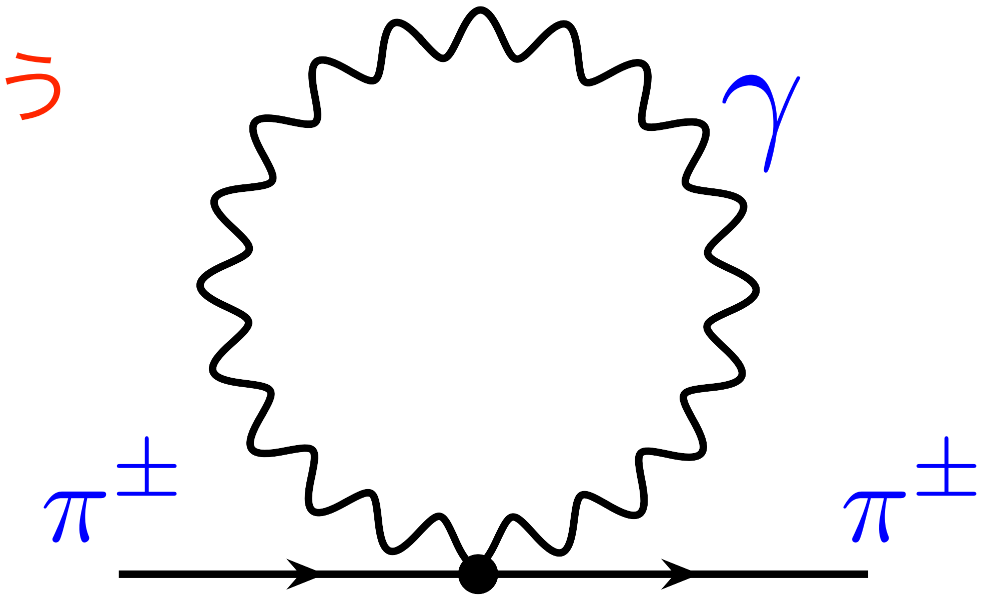
$$U = e^{i\tau^a\pi^a/f_\pi}\ :\ \text{pion},\qquad B_\mu\ :\ \text{photon}$$

Collective symmetry breaking がない例：

２次発散の diagram が描けてしまう

$$\pi^+\pi^-\gamma\ \gamma \text{ vertex が存在}$$

$$e^2 \mathrm{Tr}\left[\tau^3 U^\dagger \tau^3 U\right] B_\mu B^\mu$$



$$\sim\ e^2 \frac{\Lambda^2}{(4\pi)^2}\ \sim\ e^2 \frac{(4\pi f_\pi)^2}{(4\pi)^2}\ \sim\ e^2 f_\pi^2$$

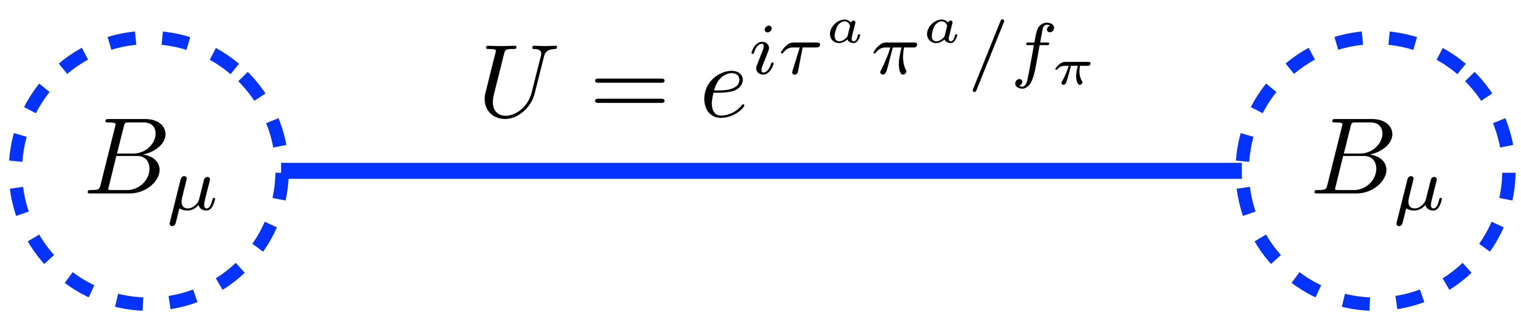
$$\mathcal{L} = \frac{f^2}{4}\mathrm{Tr}$$

Kaplan-Georgi model -- PLB 136, 183 (1984)
などはこのタイプ

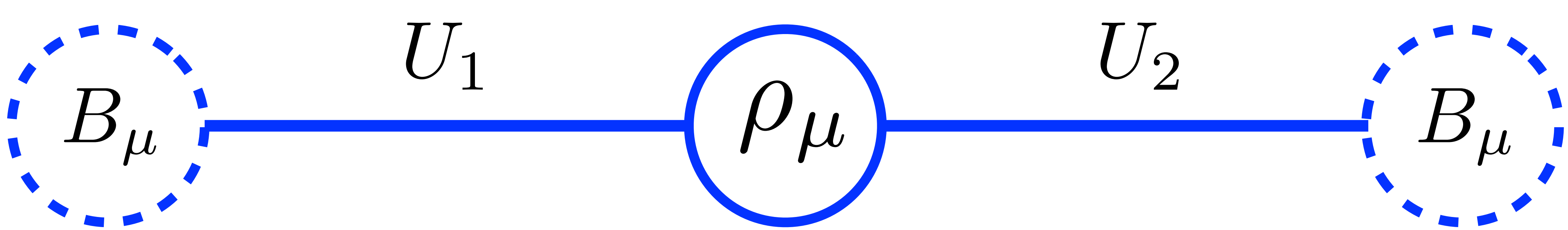
where $D_\mu U = \partial_\mu U - ie\frac{\tau^3}{2}B_\mu U + ieU\frac{\tau^3}{2}B_\mu$

$$U = e^{i\tau^a \pi^a / f_\pi}\ :\ \text{pion},\qquad B_\mu\ :\ \text{photon}$$

$\pi^+\pi^-\gamma\ \gamma$ vertex が存在する理由は、NG boson に
左右両方から直接 photon が couple するから

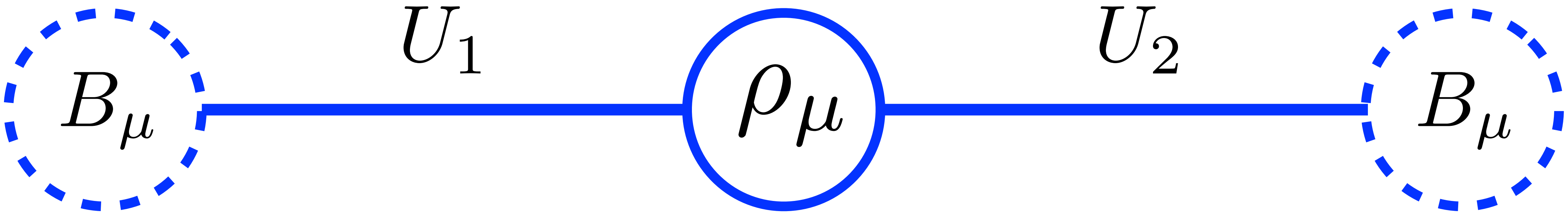


この状況を避けるため、新しい vector を導入して $SU(2)_L$ と $SU(2)_R$ の “距離” を遠くする



Hidden Local Symmetry (with a=1)

Bando, Kugo, Uehara, Yamawaki, Yanagida, PRL 54, 1215 (1985)



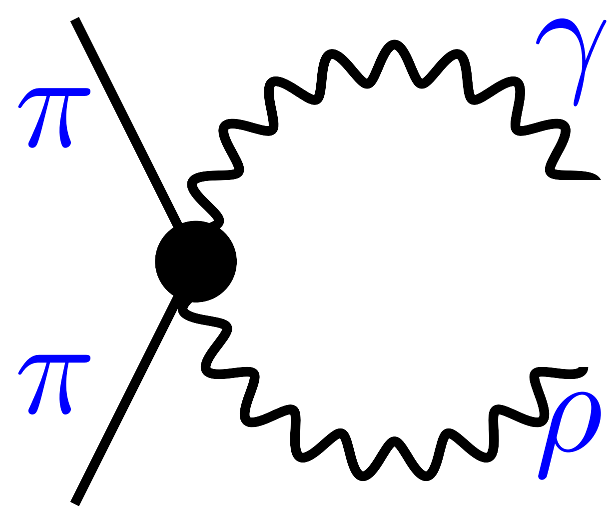
$$\mathcal{L} = \sum_{i=1}^{2} \frac{f_i^2}{4} \mathrm{Tr}\left[(D_\mu U_i)^\dagger (D^\mu U_i) \right]$$

$$D_\mu U_1 = \partial_\mu U_1 - ie\frac{\tau^3}{2} B_\mu U_1 + ig_\rho U_1 \frac{\tau^a}{2} \rho_\mu^a$$

$$D_\mu U_2 = \partial_\mu U_2 - ig_\rho \frac{\tau^a}{2} \rho_\mu^a U_2 + ieU_2 \frac{\tau^3}{2} B_\mu$$

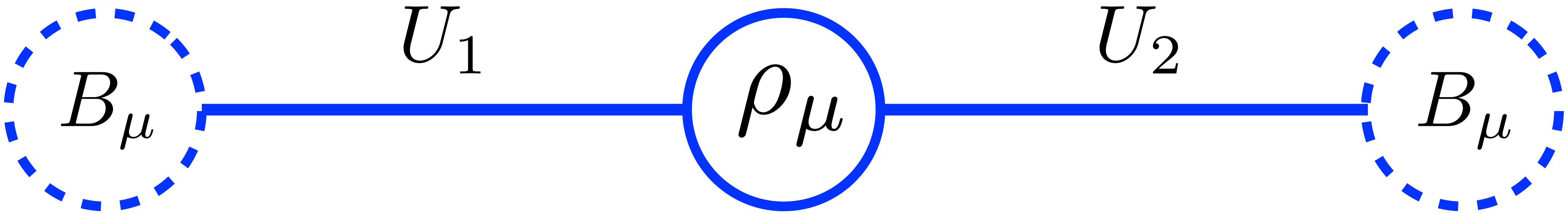
$\gamma\,\rho\,\pi\,\pi$ vertex はあるが

$\gamma\,\gamma\,\pi\,\pi$ vertex はない



２次発散を出す 1-loop diagram が描けない

Harada, Tanabashi, Yamawaki, PLB 568, 103 (2003)



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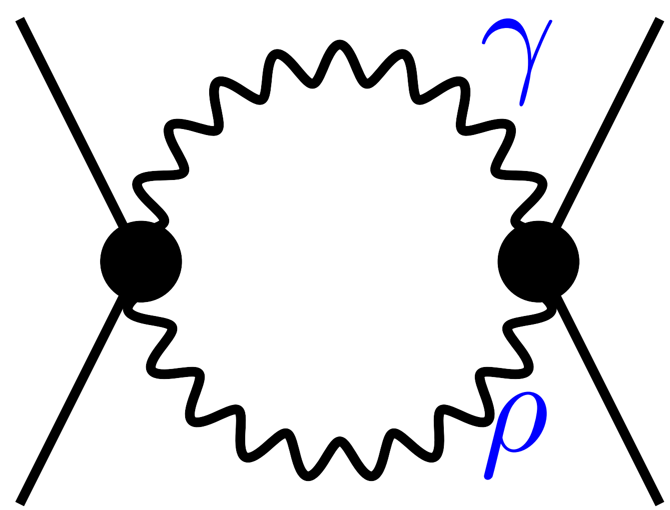
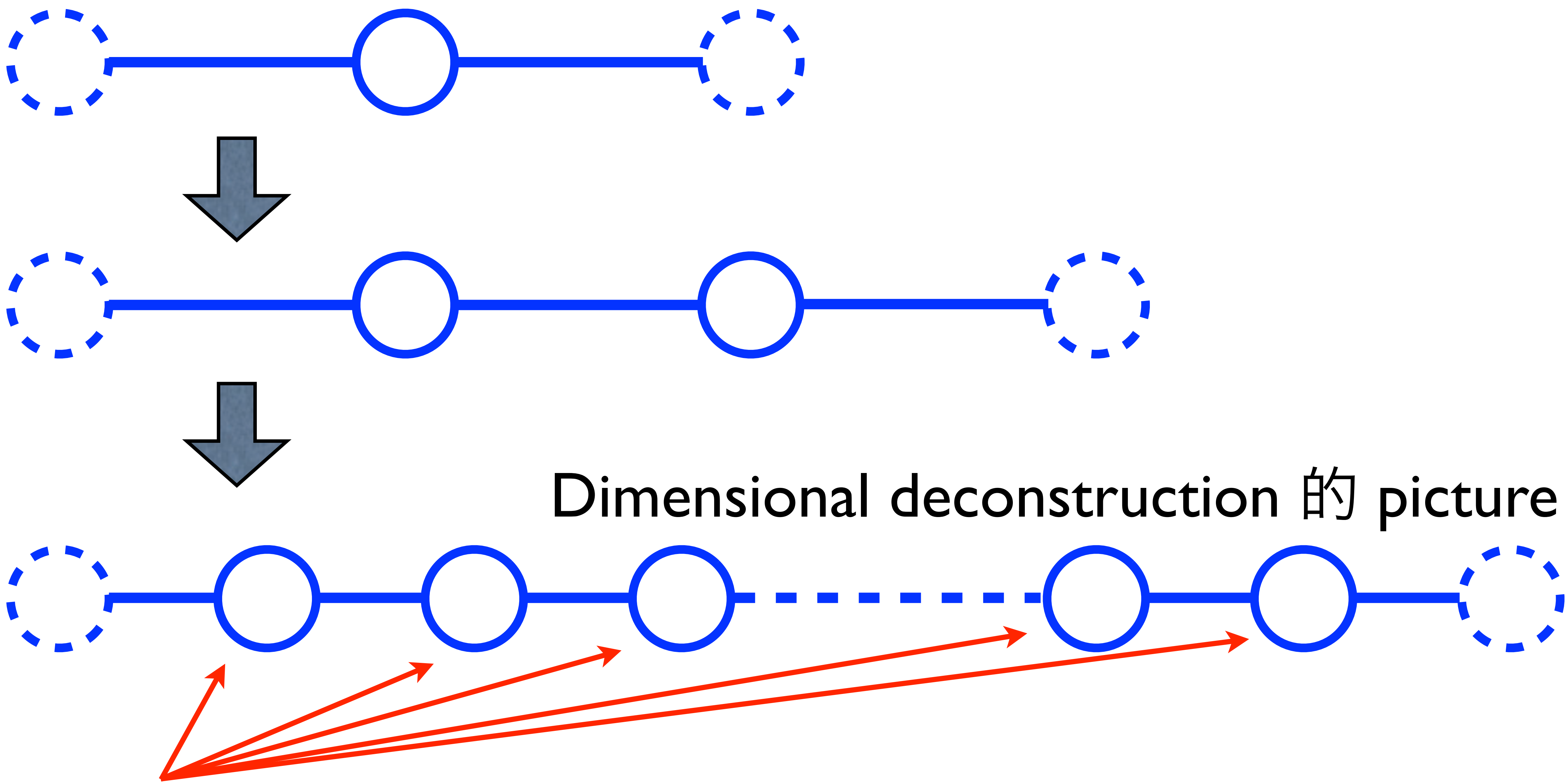


Log 発散はある

Harada, Tanabashi, Yamawaki, PLB 568, 103 (2003)

挿入する vector を増やしていけば（Deconstruction）
発散はもっとマイルドに



どれか一つでも switch off すると left-right の correlation がきれる

collective symmetry breaking ⟺ theory space locality

- 実際には log 発散まで禁止する必要はない
- Collective symmetry breaking のエッセンスを理解してしまったいまとなっては、linear-moose タイプの G/H 構造にこだわる必要もない

Little Higgs model と dimensional deconstruction の概念の分離

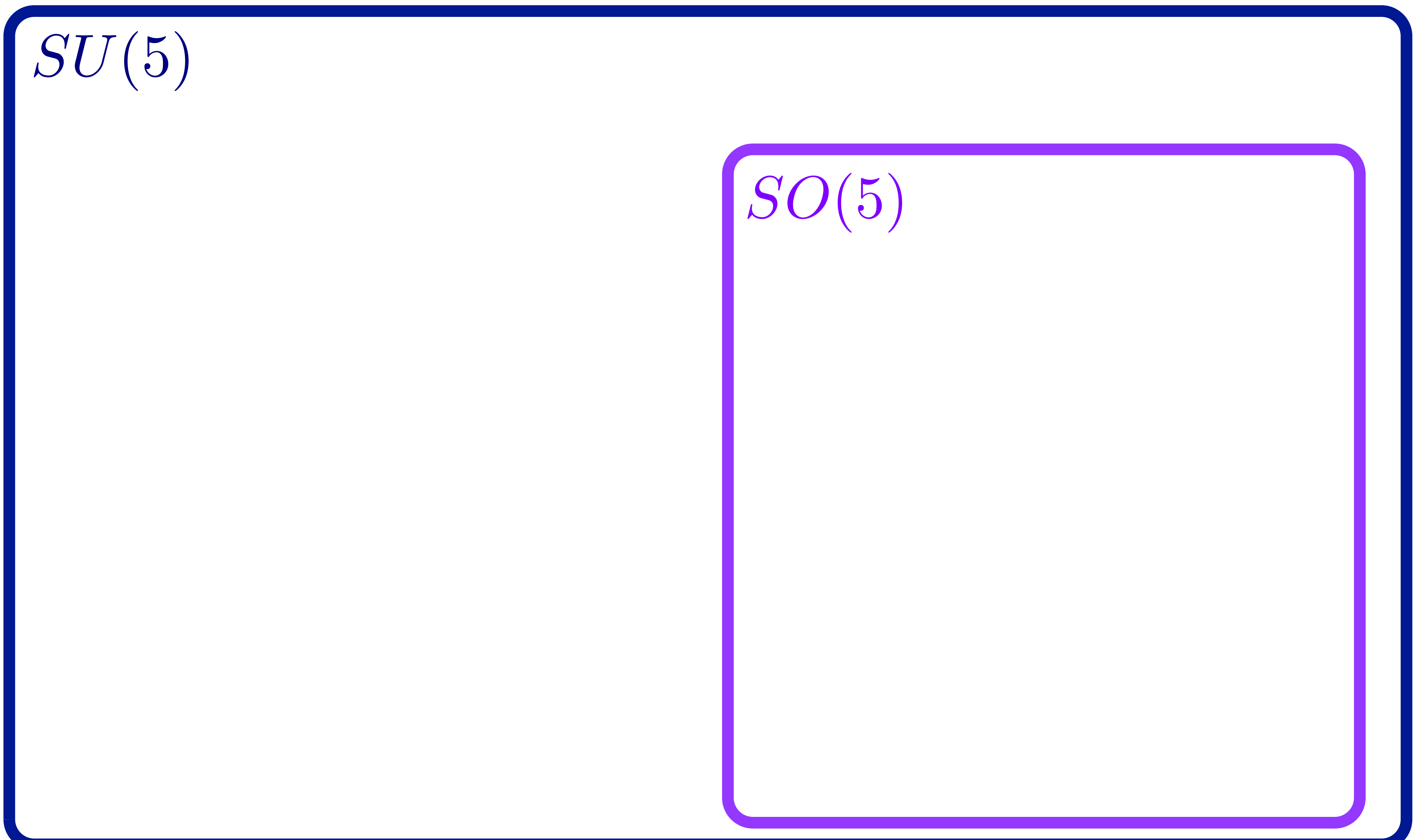
より economical な模型

3. Littlest Higgs model

Arkani-Hamed, Cohen, Katz, Nelson, JHEP 0207, 034 (2002)

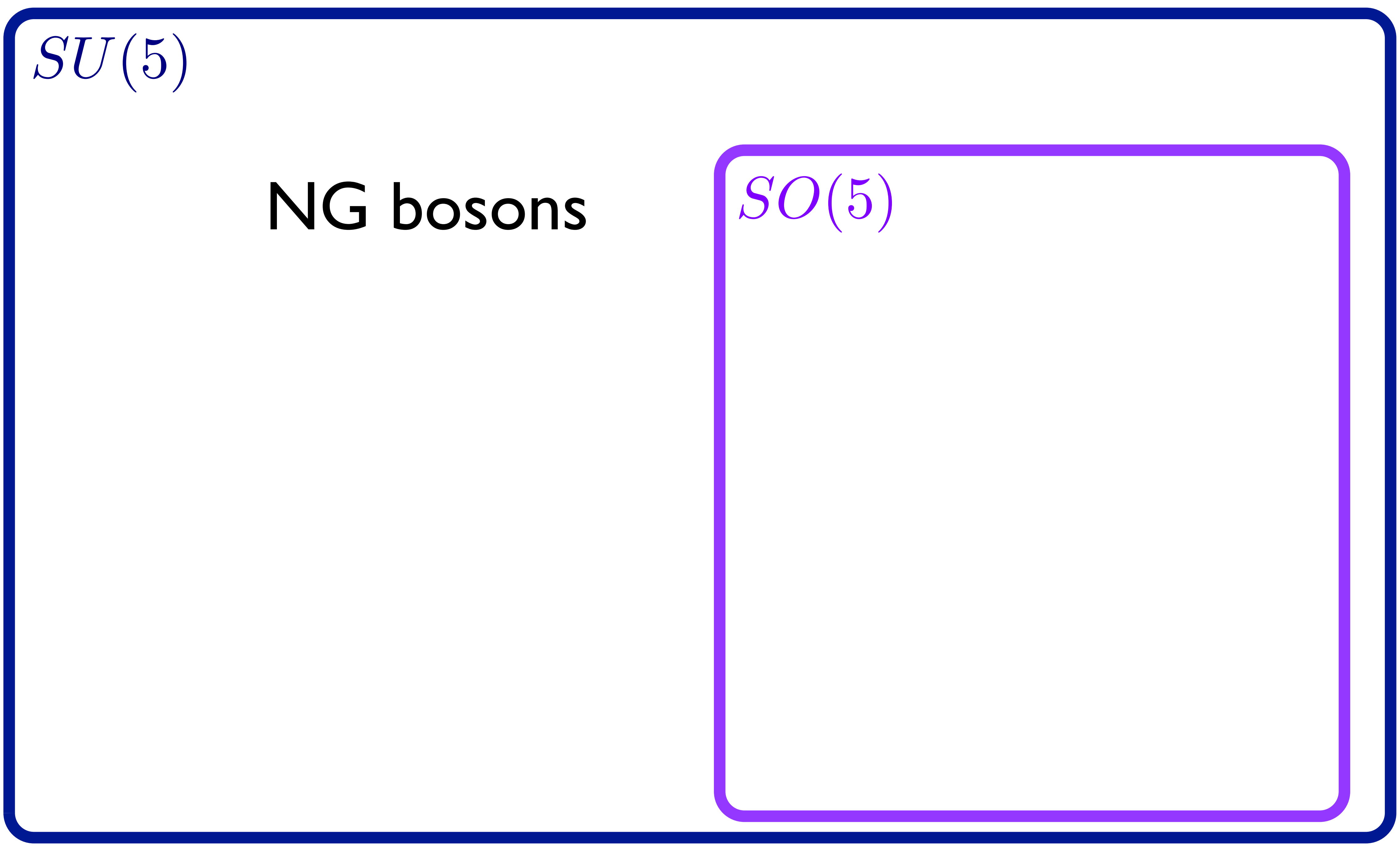
Littlest Higgs model

$$G/H = SU(5)/SO(5)$$



Littlest Higgs model

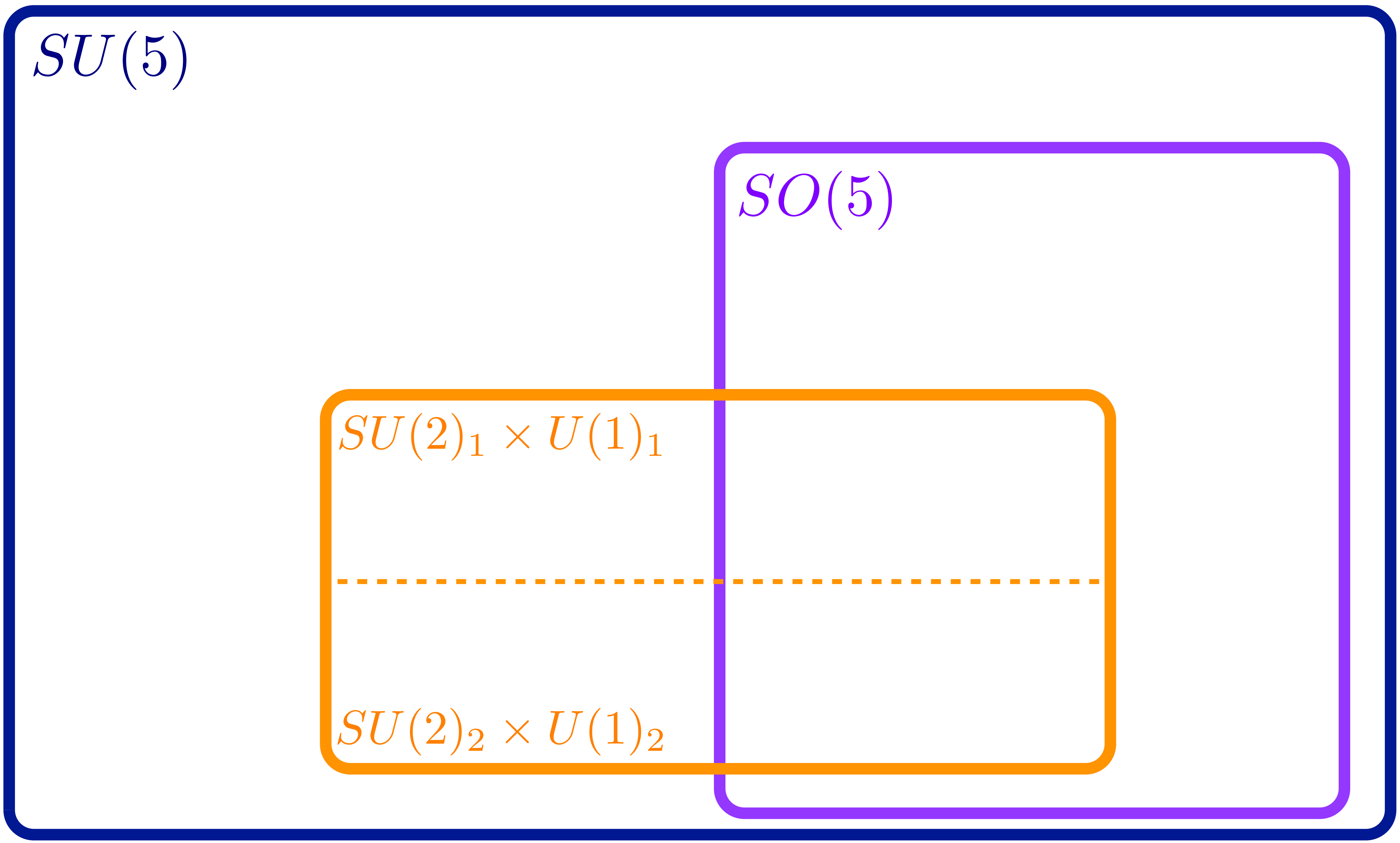
$$G/H = SU(5)/SO(5)$$



Littlest Higgs model

$$G/H = SU(5)/SO(5)$$

$(SU(2)\times U(1))^2$をゲージ化



Littlest Higgs model

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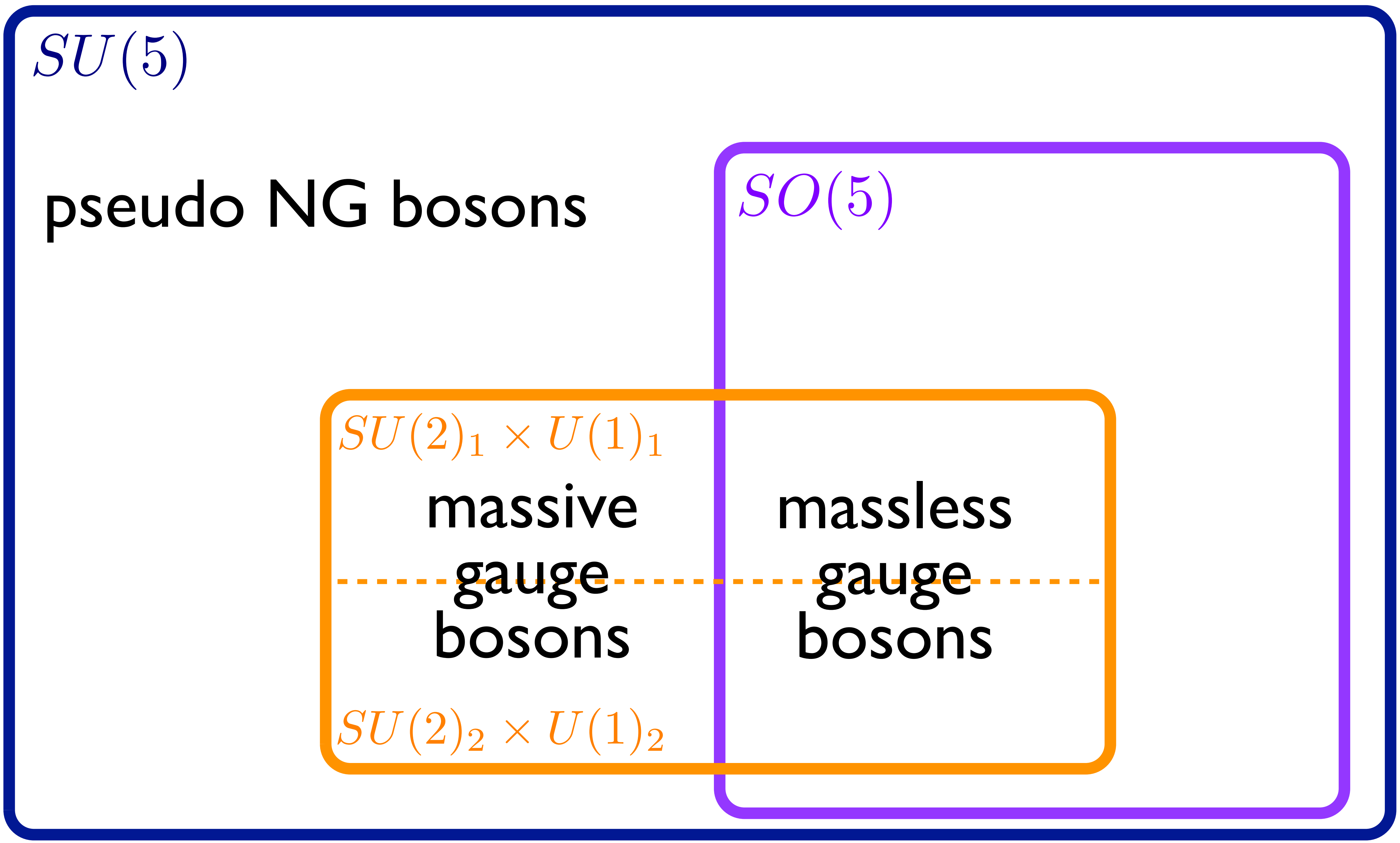

Littlest Higgs model

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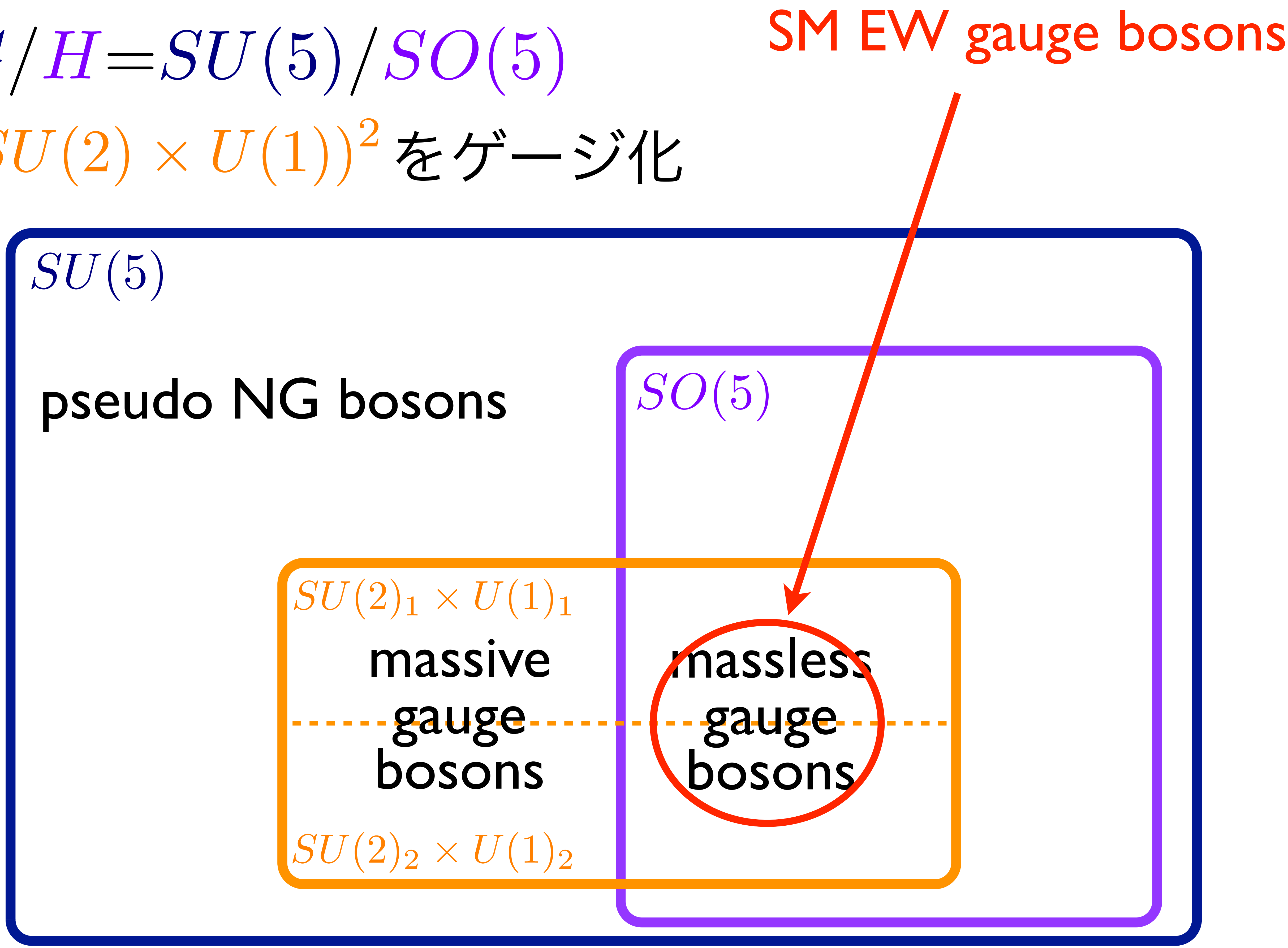

Littlest Higgs model

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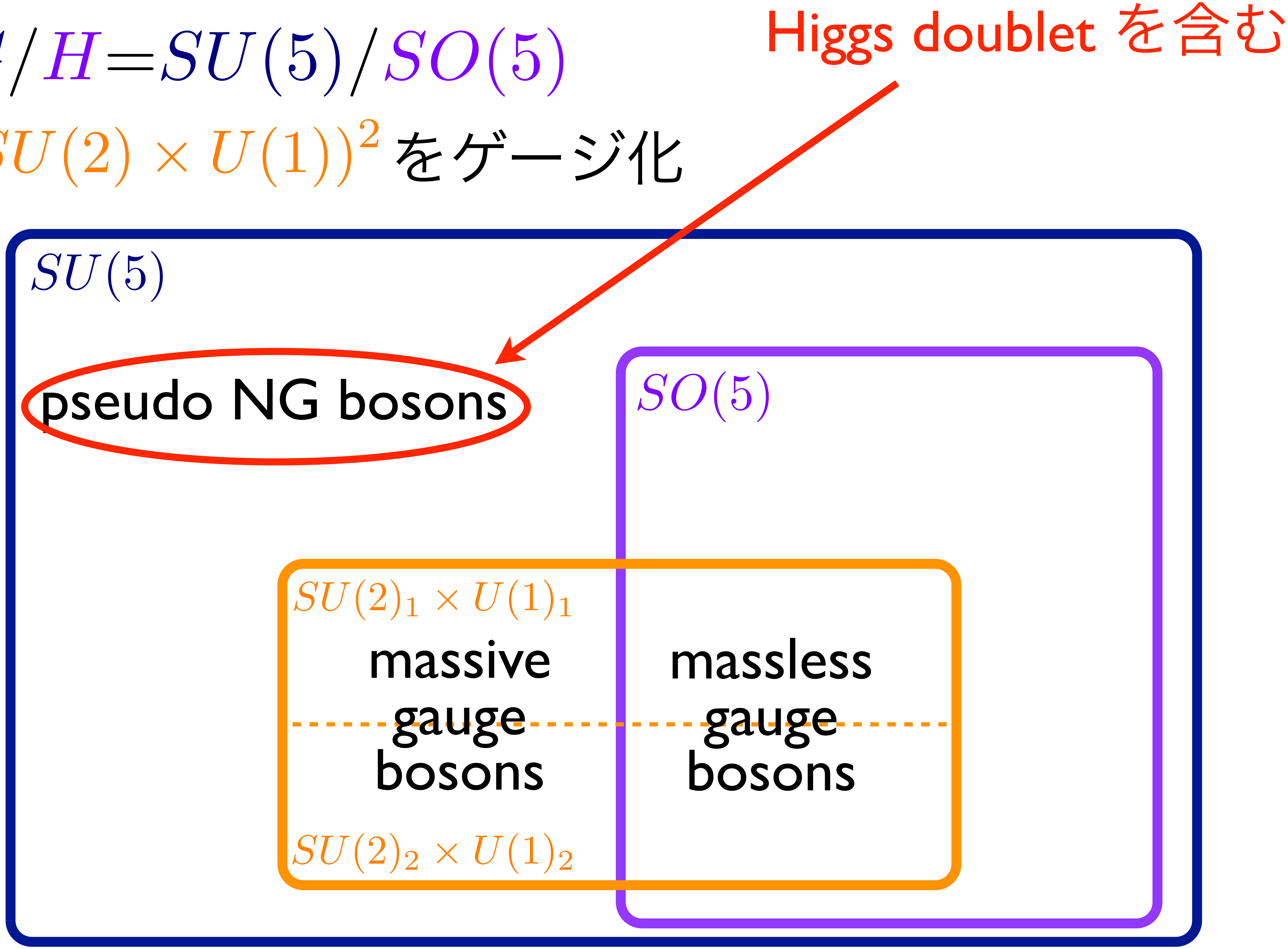

Littlest Higgs model

$$G/H = SU(5)/SO(5)$$

$\Phi \longrightarrow V\Phi V^T$ と SU(5) で変換する

5x5 symmetric matrix の VEV で破れたとする

$$\langle\Phi\rangle \equiv \Sigma_0 = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix}$$

24個の SU(5) generator

$T_a \ (a = 1 \sim 10)$: unbroken $\quad T_a\Sigma_0 + \Sigma_0 T_a^T = 0$

$X_a \ (a = 1 \sim 14)$: broken $\quad X_a\Sigma_0 - \Sigma_0 X_a^T = 0$

NG boson : 真空まわりでの broken 方向への fluctuation

$$\Sigma(x) = e^{i\Pi/f}\Sigma_0 e^{i\Pi^T/f} = e^{2i\Pi/f}\Sigma_0$$

$$(\Pi \equiv \pi^a X^a)$$

破れる generator

$$X_1 = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} & & 1 & & \\ & & 0 & & \\ \hline 1 & 0 & & 1 & 0 \\ \hline & & 1 & & \\ & & 0 & & \end{array} \right)$$

$$X_2 = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} & & -i & & \\ & & 0 & & \\ \hline i & 0 & & -i & 0 \\ \hline & & i & & \\ & & 0 & & \end{array} \right)$$

$$X_3 = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} & & 0 & & \\ & & 1 & & \\ \hline 0 & 1 & & 0 & 1 \\ \hline & & 0 & & \\ & & 1 & & \end{array} \right)$$

$$X_4 = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} & & 0 & & \\ & & -i & & \\ \hline 0 & i & & 0 & -i \\ \hline & & 0 & & \\ & & i & & \end{array} \right)$$

⇒ Higgs doublet h

破れる generator

$$X_5 = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} & & & 0 & 1 \\ & & & 1 & 0 \\ \hline & & & & \\ \hline 0 & 1 & & & \\ 1 & 0 & & & \end{array} \right)$$

$$X_8 = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} & & & -i & 0 \\ & & & 0 & -i \\ \hline & & & & \\ \hline i & 0 & & & \\ 0 & i & & & \end{array} \right)$$

$$X_6 = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} & & & 0 & i \\ & & & i & 0 \\ \hline & & & & \\ \hline 0 & -i & & & \\ -i & 0 & & & \end{array} \right)$$

$$X_9 = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} & & & 1 & 0 \\ & & & 0 & -1 \\ \hline & & & & \\ \hline 1 & 0 & & & \\ 0 & -1 & & & \end{array} \right)$$

$$X_7 = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} & & & 1 & 0 \\ & & & 0 & 1 \\ \hline & & & & \\ \hline 1 & 0 & & & \\ 0 & 1 & & & \end{array} \right)$$

$$X_{10} = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} & & & -i & 0 \\ & & & 0 & i \\ \hline & & & & \\ \hline i & 0 & & & \\ 0 & -i & & & \end{array} \right)$$

massive complex triplet ϕ

破れる generator

$$X_{11} = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} 0 & 1 & & & \\ 1 & 0 & & & \\ \hline & & & & \\ \hline & & & 0 & 1 \\ & & & 1 & 0 \end{array} \right)$$

$$X_{14} = \frac{1}{\sqrt{10}} \left(\begin{array}{cc|c|cc} 1 & & & & \\ & 1 & & & \\ \hline & & -4 & & \\ \hline & & & 1 & \\ & & & & 1 \end{array} \right)$$

$$X_{12} = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} 0 & -i & & & \\ i & 0 & & & \\ \hline & & & & \\ \hline & & & 0 & -i \\ & & & i & 0 \end{array} \right)$$

$$X_{13} = \frac{1}{\sqrt{2}} \left(\begin{array}{cc|c|cc} 1 & 0 & & & \\ 0 & -1 & & & \\ \hline & & & & \\ \hline & & & 1 & 0 \\ & & & 0 & -1 \end{array} \right)$$

$(SU(2) \times U(1))^2$ をゲージ化したときに Higgs 機構で喰われる部分

pseudo NG boson をもう一度まとめると

$$\Pi = \begin{pmatrix} & \frac{h^\dagger}{\sqrt{2}} & \phi^\dagger \\ \frac{h}{\sqrt{2}} & & \frac{h^*}{\sqrt{2}} \\ \phi & \frac{h^T}{\sqrt{2}} & \end{pmatrix}$$

Tree-level Lagrangian: $\mathcal{L} = \mathcal{L}_K + \mathcal{L}_t + \mathcal{L}_\psi$

すべての場の kinetic term

top Yukawa

top 以外の Yukawa

$\mathcal{L}_K$: fermion と gauge 場の kinetic term は普通に入っている

$\mathcal{L}_K$: NG boson の kinetic term

$$\frac{f^2}{4}\,\mathrm{tr}|D_\mu \Sigma|^2$$, where

$$D\Sigma = \partial\Sigma - \sum_j \left\{ i g_j W_j^a (Q_j^a \Sigma + \Sigma Q_j^{aT}) + i g'_j B_j (Y_j \Sigma + \Sigma Y_j^T) \right\}$$

$G_1 = SU(2)_1 \times U(1)_1$

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & \\ & \end{pmatrix}$$

$$Y_1 = \mathrm{diag}(-3,-3,2,2,2)/10$$

$G_2 = SU(2)_2 \times U(1)_2$

$$Q_2^a = \begin{pmatrix} & \\ & -\sigma^{a*}/2 \end{pmatrix}$$

$$Y_2 = \mathrm{diag}(-2,-2,-2,3,3)/10$$

このゲージ相互作用はすべての NG boson に mass を与えるが、、、

$\mathcal{L}_K$：NG boson の kinetic term

$$\frac{f^2}{4}\,\mathrm{tr}|D_\mu\Sigma|^2$$, where

$$D\Sigma = \partial\Sigma - \sum_j \{ig_j W_j^a(Q_j^a\Sigma + \Sigma Q_j^{aT}) + ig_j' B_j(Y_j\Sigma + \Sigma Y_j^T)\}$$

$$G_1 = SU(2)_1 \times U(1)_1$$

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$$Q_2^a = \begin{pmatrix} & \\ & -\sigma^{a*}/2 \end{pmatrix}$$

$$Y_2 = \mathrm{diag}(-2,-2,-2,3,3)/10$$

もし G_1 がなければ $SU(3)_1$ 対称性をもち

$$\Pi = \begin{pmatrix} & \frac{h^\dagger}{\sqrt{2}} & \phi^\dagger \\ \frac{h}{\sqrt{2}} & & \frac{h^*}{\sqrt{2}} \\ \phi & \frac{h^T}{\sqrt{2}} & \end{pmatrix}$$

h が exact NG boson であることを保証

$\mathcal{L}_K$: NG boson の kinetic term

$$\frac{f^2}{4}\,\mathrm{tr}|D_\mu\Sigma|^2$$, where

$$D\Sigma = \partial\Sigma - \sum_j \{ig_j W_j^a(Q_j^a\Sigma + \Sigma Q_j^{aT}) + ig'_j B_j(Y_j\Sigma + \Sigma Y_j^T)\}$$

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$$Q_1^a = \begin{pmatrix} \sigma^a/2 & & \\ & & \\ & & \end{pmatrix}$$

$$Y_1 = \mathrm{diag}(-3,-3,2,2,2)/10$$

$G_2 = SU(2)_2 \times U(1)_2$

$$Q_2^a = \begin{pmatrix} & & \\ & & \\ & & -\sigma^{a*}/2 \end{pmatrix}$$

$$Y_2 = \mathrm{diag}(-2,-2,-2,3,3)/10$$

もし G_2 がなければ $SU(3)_2$ 対称性をもち

$$\Pi = \begin{pmatrix} & \frac{h^\dagger}{\sqrt{2}} & \phi^\dagger \\ \frac{h}{\sqrt{2}} & & \frac{h^*}{\sqrt{2}} \\ \phi & \frac{h^T}{\sqrt{2}} & \end{pmatrix}$$

h が exact NG boson であることを保証

$\mathcal{L}_K$: NG boson の kinetic term

$$\frac{f^2}{4}\,\mathrm{tr}|D_\mu \Sigma|^2$$, where

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$$G_2 = SU(2)_2 \times U(1)_2$$

$$Q_2^a = \begin{pmatrix} & \\ & \\ & -\sigma^{a*}/2 \end{pmatrix}$$

$$Y_2 = \mathrm{diag}(-2,-2,-2,3,3)/10$$

G_1、G_2 の両方が存在してはじめて

$$\Pi = \begin{pmatrix} & \frac{h^\dagger}{\sqrt{2}} & \phi^\dagger \\ \frac{h}{\sqrt{2}} & & \frac{h^*}{\sqrt{2}} \\ \phi & \frac{h^T}{\sqrt{2}} & \end{pmatrix}$$

h が pseudo NG boson になる

Collective symmetry breaking

$\mathcal{L}_K$: NG boson の kinetic term

$$\frac{f^2}{4}\,\mathrm{tr}|D_\mu \Sigma|^2$$, where

$$D\Sigma = \partial\Sigma - \sum_j \left\{ i g_j W_j^a (Q_j^a \Sigma + \Sigma Q_j^{aT}) + i g_j' B_j (Y_j \Sigma + \Sigma Y_j^T) \right\}$$

$G_1 = SU(2)_1 \times U(1)_1$

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & \\ & 0 \end{pmatrix}$$

$$Y_1 = \mathrm{diag}(-3,-3,2,2,2)/10$$

$G_2 = SU(2)_2 \times U(1)_2$

$$Q_2^a = \begin{pmatrix} 0 & \\ & -\sigma^{a*}/2 \end{pmatrix}$$

$$Y_2 = \mathrm{diag}(-2,-2,-2,3,3)/10$$

ちなみに、、、 ϕ はどちらの symmetry enhancement の恩恵もうけない

$$\Pi = \begin{pmatrix} 0 & \frac{h^\dagger}{\sqrt{2}} & \phi^\dagger \\ \frac{h}{\sqrt{2}} & 0 & \frac{h^*}{\sqrt{2}} \\ \phi & \frac{h^T}{\sqrt{2}} & 0 \end{pmatrix}$$

$\mathcal{L}_t$: Top Yukawa coupling

$q_3 = (t_3, b_3)$: SM left-handed SU(2) doublet

${u'_3}^c$: SM right-handed SU(2) singlet

$\tilde{t}, \tilde{t}^c$: a new pair of Weyl fermions

これらで $SU(3)_1$ triplet $\chi = (b_3\, t_3\, \tilde{t})$ を組む

$$\mathcal{L}_t = \lambda_1 f \epsilon_{ijk}\epsilon_{xy}\chi_i \Sigma_{jx}\Sigma_{ky}{u'_3}^c + \lambda_2 f \tilde{t}\tilde{t}^c + \text{h.c.}$$

$$(i, j, k = 1, 2, 3, \quad x, y = 4, 5)$$

λ_1 は $SU(3)_1$ を保ち $SU(3)_2$ を explicit に破る

λ_2 は $SU(3)_2$ を保ち $SU(3)_1$ を explicit に破る

Collective symmetry breaking

$\mathcal{L}_t$: Top Yukawa coupling

Σ を展開 $\quad \mathcal{L}_t = \lambda_1 (q_3 h + f\tilde{t}) u_3'^{\,c} + \lambda_2 f \tilde{t}\tilde{t}^c + \cdots$

field redefinition: $$\begin{pmatrix} \tilde{t}'^{\,c} \\ u_3^c \end{pmatrix} = \frac{1}{\sqrt{\lambda_1^2 + \lambda_2^2}} \begin{pmatrix} \lambda_1 & -\lambda_2 \\ \lambda_2 & \lambda_1 \end{pmatrix} \begin{pmatrix} \tilde{t}^c \\ u'^{\,c}_3 \end{pmatrix}$$

$$\mathcal{L}_t = \boxed{\frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}}}\, q_3\, h\, u_3^c + \boxed{\sqrt{\lambda_1^2 + \lambda_2^2}\, f}\, \tilde{t}\, \tilde{t}'^{\,c} + \cdots$$

$\equiv \lambda_t$: top Yukawa

$\equiv m'$: heavy fermion mass

$\mathcal{L}_t$ ： Top Yukawa coupling

Σ を展開 $\quad \mathcal{L}_t = \lambda_1 (q_3 h + f\tilde{t}) u_3'^{\,c} + \lambda_2 f \tilde{t}\tilde{t}^c + \cdots$

field redefinition: $\begin{pmatrix} \tilde{t}'^{\,c} \\ u_3^c \end{pmatrix} = \frac{1}{\sqrt{\lambda_1^2 + \lambda_2^2}} \begin{pmatrix} \lambda_1 & -\lambda_2 \\ \lambda_2 & \lambda_1 \end{pmatrix} \begin{pmatrix} \tilde{t}^c \\ u'^{\,c}_3 \end{pmatrix}$

$$\mathcal{L}_t = \boxed{\frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}}}\, q_3\, h\, u_3^c + \boxed{\sqrt{\lambda_1^2 + \lambda_2^2}\, f}\, \tilde{t}\, \tilde{t}'^{\,c} + \cdots$$

λ_t : top Yukawa

m' : heavy fermion mass

$\longrightarrow \; 2\lambda_t < \sqrt{\lambda_1^2 + \lambda_2^2} \;\xrightarrow{\lambda_t \sim 1}\; m' > 2f$

Electroweak Symmetry Breaking

At tree level, there is no EWSB
EW symmetry is broken through radiative corrections

Coleman-Weinberg potential を計算

quartic coupling

$$\lambda (h^\dagger h)^2, \quad \text{where} \quad \lambda = c \frac{(g_1^2 + {g'_1}^2 - c'/c \lambda_1^2)(g_2^2 + {g'_2}^2)}{g_1^2 + {g'_1}^2 - c'/c \lambda_1^2 + g_2^2 + {g'_2}^2}$$

$c, \ c'$ は UV physics に sensitive な O(1) constant

Electroweak Symmetry Breaking

At tree level, there is no EWSB
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Coleman-Weinberg potential を計算

quadratic term

gauge : $$\frac{3}{64\pi^2}\left\{3g^2 {M'_W}^2 \log\frac{\Lambda^2}{{M'_W}^2} + {g'}^2 {M'_B}^2 \log\frac{\Lambda^2}{{M'_B}^2}\right\}$$

scalar : $$\frac{\lambda}{16\pi^2} M_\phi^2 \log\frac{\Lambda^2}{M_\phi^2}$$

fermion : $$-\frac{3\lambda_t^2}{8\pi^2} m'^2 \log\frac{\Lambda^2}{m'^2}$$

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scalar : $$\frac{\lambda}{16\pi^2} M_\phi^2 \log\frac{\Lambda^2}{M_\phi^2}$$

fermion : $$-\frac{3\lambda_t^2}{8\pi^2} {m'}^2 \log\frac{\Lambda^2}{{m'}^2}$$ ← EWSB を trigger する

10% fine tuning

$$m' \lesssim 2 \text{ TeV} \left(\frac{m_H}{200 \text{ GeV}}\right)^2 \qquad \left(f \lesssim 1 \text{ TeV} \left(\frac{m_H}{200 \text{ GeV}}\right)^2 \right)$$

$$M'_W \lesssim 6 \text{ TeV} \left(\frac{m_H}{200 \text{ GeV}}\right)^2$$

$$M_\phi \lesssim 10 \text{ TeV}$$

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$$M'_W \lesssim 6\ \mathrm{TeV} \left(\frac{m_H}{200\ \mathrm{GeV}}\right)^2$$

$$M_\phi \lesssim 10\ \mathrm{TeV}$$

W' などの tree-level exchange のせいでprecision EW test からの制限がきついことを考えると、かなり厳しいのでは？

例えば： Csaki, Hubisz, Kribs, Meade, Terning, ``Big corrections from a little Higgs,'' Phys. Rev. D67, 115002 (2003) [arXiv:hep-ph/0211124].

$\Rightarrow$ $f > 4\ \mathrm{TeV}$

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$$\Rightarrow\ f > 4\ \mathrm{TeV}$$

Imposing T-parity cures the problem

4. Discussion

SLAC Summer Institute 2002, H. Georgi ---

Why didn't I find this model long ago, rather than having to learn it from my students recently?

Partly stupidity.
Partly I didn't know the t quark is so heavy.
Partly the kissing Mexican hat (KMH) mechanism is subtle.

But MOSTLY - this represents a slightly different way of thinking about the symmetries. If you must impose a global symmetry, you are actually doing fine tuning.

UV complition?

Littest

$SU(5)/SO(5)$

$$SU(5) \longrightarrow SO(5)$$

$\langle qq^T \rangle \neq 0$

↑

SO(N) dynamics

これはまだ想像できる

UV complition?

Littlest

$SU(5)/SO(5)$ $\quad\quad$ $SU(5) \xrightarrow[\langle qq^T \rangle \neq 0]{} SO(5)$

Kaplan-Schmaltz

$(SU(3)/SU(2))^2$ $\quad\quad$ $SU(N) \xrightarrow{?} SU(N-1)$

hard to imagine...

カイラルゲージ理論によるタンブリング？

UV complition?

Littlest

$SU(5)/SO(5)$ $\qquad SU(5) \xrightarrow[\langle qq^T \rangle \neq 0]{} SO(5)$

Kaplan-Schmaltz

$(SU(3)/SU(2))^2$ $\qquad SU(N) \xrightarrow{?} SU(N-1)$

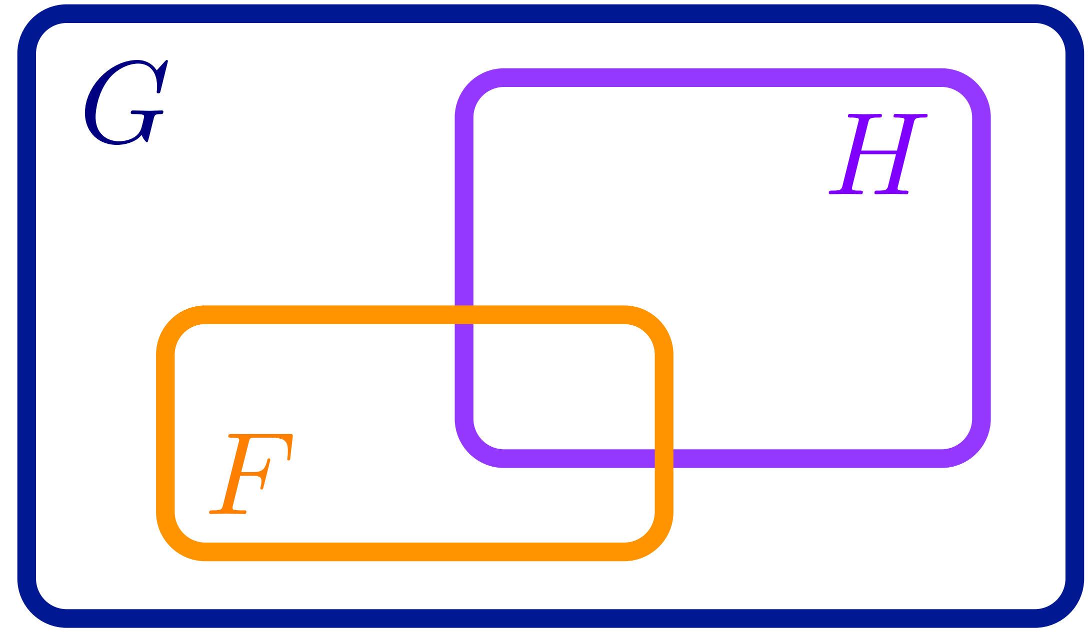
実は、G が $(SU(N))^n$ の場合、
little Higgs をいつでも QCD-like に
UV complete する方法があります

J. Thaler,
``Little technicolor,''
JHEP 0507, 024 (2005)
[arXiv:hep-ph/0502175]

UV complition?

global: G/H

local: F



いったん global を $G \times G$ に拡張する

$(G \times G)/G$ の SSB
が起こったとする

こっちの G の部分群 H をゲージ化

こっちの G の部分群 F をゲージ化

H 部分のゲージ場の質量を無限大にとばす

この破れは QCD-like な力学で起こせる

Signals (qualitative features)

・Weakly coupled light Higgs の存在

・No new strong interaction below ~10 TeV

・新粒子は ~TeV に存在

（Z', W', heavy top, EW triplet scalar）

LHC phenomenology

S. Matsumoto, T. Moroi and K. Tobe,

``Testing the Littlest Higgs Model with T-parity at the Large Hadron Collider,''

Phys. Rev. D78, 055018 (2008)
[arXiv:0806.3837 [hep-ph]]

ILC phenomenology

E. Asakawa, M. Asano, K. Fujii, T. Kusano, S. Matsumoto, R. Sasaki, Y. Takubo and H. Yamamoto

``Precision Measurements of Little Higgs Parameters at the International Linear Collider,''

Phys. Rev. D79, 075013 (2009)
[arXiv:0901.1081 [hep-ph]]

Summary

Little Higgs 模型は Higgs as a pseudo NG boson
という魅力的なアイディアを復活させた

naturalness と密接に関連して、
TeV 領域にnew particle

Cutoff は 10 TeV

でも結局 T parity なしだとつらい？

global 対称性、local 対称性、T-parity...
set-up 自体がけっこう artificial？

一番大事な、top-loop の２次発散をキャンセル
するところのラグランジアンが複雑すぎる？

Summary

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続きは Discussion session で。